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# Spray Automated Balancing of Rotors: Methods and Materials

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US ARMY
AVIATION
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# SUMMARY

A survey has been performed to assess the present state of the art in rotor balancing technology as it applies to Army helicopter gas turbine engines and associated power transmission hardware. A further investigation has evaluated alternative methods of applying balancing correction weights for possible use in automated balancing procedures. A weight addition process based on thermal spraying has been selected for evaluation; its bond strength and fatigue strength performance have been tested; and a method of implementing the approach in an automated balancing facility has been outlined.

The industry survey, performed at five engine manufacturers, one helicopter airframe manufacturer, and two military overhaul facilities, revealed that (1) computerized balancing equipment can be of significant aid in eliminating errors and improving quality and documentation in the process of balancing; (2) central balancing shops staffed by well-trained specialists is a very effective mode of operation used in many of the facilities surveyed; (3) low-speed balancing is performed exclusively, with no foreseeable need for production high-speed balancing; (4) there is a need for an automated balancing procedure applicable to a large percentage of the parts and assemblies balanced in the production and overhaul of helicopter gas turbine engines and drive trains; (5) laser balancing is viewed with concern when suggested for use on flight propulsion hardware; and (6) thermal spray balancing is viewed with cautious optimism when suggested for use in flight propulsion hardware.

A spray automated balancing methodology has been defined based upon a survey of available thermal spray processes, typical materials used in helicopter gas turbines and drive gearing and shafting, and fatigue and bond strength testing of representative materials applied by the selected spray process. The FARE (Fuel/Air Repetitive Explosion) gun is the process selected because it is a high-velocity pulsed spray process which is adaptable to computer control for automation. It can apply a wide range of metal alloys or ceramics with good bond strengths and surface finishes. Tungsten carbide sprayed on 17-4 PH stainless had an average bond strength of 62 MPa (8900 psi) and an endurance fatigue limit better than that for hand-ground specimens of 17-4 PH. The average bond strength of Inconel 718 powder sprayed on Inconel 718 was 35 MPa (5100 psi) with a fatigue endurance limit equivalent to hand-ground specimens of the same material. Bond strength tests of Triballoy 800 sprayed on Inconel 718 averaged 34 MPa (5000 psi) with a fatigue endurance value somewhat lower than the comparable value for hand-ground Inconel specimens. Thus, the fatigue and bond strengths have shown that tungsten carbide sprayed on 17-4 PH stainless steel is an acceptable material combination for use with spray automated balancing in the compressor sections of turbine engines, and Inconel 718 sprayed on Inconel 718 is an acceptable material for spray balancing in the hot turbine sections of engines.

The proposed methodology for Spray Automated Balancing of Rotors (SABOR) is envisaged as a combination of a hard bearing balancing machine, a FARE thermal spray gun, an interface controller, and a master computer. The system would operate in closed-loop to set the balance machine speed, sense the one- or two-plane vibration vectors, calculate the amount and location of correction needed, control the FARE gun to spray metal onto the rotating target at the proper angular location, and rapidly repeat the cycle, calibrating itself as necessary to achieve the minimum or target unbalance in the minimum time. It is estimated that such an automated system would reduce procedural errors, maximize the quality of balance, and achieve high productivity.

Further evaluations and applications engineering are needed to implement the complete SABOR concept into a production or overhaul balancing facility. These include FARE gun enhancements for application to balancing, design of automation machinery for gun positioning and balance machine loading/unloading, and creation of software algorithms for closed-loop balancing.

# INTRODUCTION

Power generation and transmission by rotating parts is critical to the function of the Army helicopter fleet. All Army helicopters are powered by gas turbine engines, some of which rotate at over 50,000 rpm. Gear boxes and shafting transmit power to the main and tail rotors. In each rotating part, any mass eccentricity resulting from fabrication or assembly tolerances causes rotating forces, which increase with the square of speed and are amplified when critical speeds are reached. The consequences of rotating forces which are too high include: wear and over stressing of engine components, reduced fatigue life, discomfort to crew, and noise.

All rotating parts must be periodically overhauled, particularly engines, which are critical to flight safety and are exposed to high temperatures and high stresses in service. Overhaul of engines is a significant cost of ownership and one important but inconvenient step in the overhaul process is balancing to reduce mass eccentricity and its associated dynamic forces.

A recent study addresses the balancing operation in Army helicopter overhaul facilities; it identifies potential approaches to enhancing the efficient and cost-effective production of quality parts within the balancing operation, and initiates development of a method for improved efficiency of balance weight correction. The study is documented in this report.

The U.S. Army helicopter fleet depends, predominantly, on four engines. The Textron Lycoming T-53 and T-55, the Allison T-63, and the General Electric T-700. In addition, under development by two teams, for future helicopter applications, is the T-800. Of currently used helicopter engines, the T-700 represents a new departure in its use of flexible rotor dynamics technology, whereby both gas producer and power turbine run well above rotor critical speeds, some of which involve significant bending of the shaft. All the earlier engines had critical speeds which involved much less flexure of rotor shafting.

Although some helicopter components, such as transmission shafting and gyroscopes for helicopters are balanced at or above their running speed (over 5,000 rpm for some shafting and 27,000 rpm for gyroscopes), all engine parts are balanced within manufacturing and overhaul shops, by two-plane "low-speed" balancing techniques instead of multiplane, flexible rotor techniques. No attempt is made in the balancing process to drive the rotors to speeds where flexure of the rotor becomes a factor. With the T-700 came significant concern that flexible rotor balancing techniques would be needed, but effective design, tight tolerances, and vibration control by squeeze film dampers have avoided the need for techniques beyond the capabilities of conventional balancing machines. It is expected that the same situation will apply to the T-800 engine when it is in production.

Thus, efforts to enhance the balancing operation should concentrate on maximizing the effectiveness of low-speed, one- and two-plane balancing, and improving the ability of operators to perform high quality balancing. Tight low-speed balancing and assembly tolerances help avoid the need for high-speed balancing. There is very limited near-term payoff to be obtained from active pursuit of high- speed balancing technology in the engine overhaul process.

As part of the investigation reported here, visits were made to five engine manufacturers, one helicopter airframe manufacturer, and to both Corpus Christi Army Depot and Kelly Air Force Base (in San Antonio) overhaul facilities. Based on these visits, the following techniques practiced in industry deserve serious consideration for implementation in Army helicopter balancing operations, or for expansion, if they are already in use.

- Use of computer-aided balancing equipment

- Organization of balancing facilities into centralized balancing shops
- Enhanced communication of balancing requirements between engine manufacturer and overhaul shop
- Incorporation of balancing specifications and setup information into a computerized data base
- Exploitation of computer-aided assembly techniques
- Automation of the balancing process
- Computerized documentation and record keeping
- Application of knowledge-based techniques.

These points are discussed in some detail in the next section.

Low-speed balancing, by definition, means mass-eccentricity correction at a speed well below operating speed of the engine and below any critical speeds of the rotor.

As a result, the forces transmitted to the balancing machine's bearing supports are proportional to unbalance multiplied by the square of speed. The balancing machine most commonly senses the transmitted force in terms of the vibration response of the support. Once calibrated to a known unbalance, the balancing machine provides a consistent readout of unbalance level. The phase difference between the vibration signal and a once per revolution phase reference signal indicates the angle of the unbalance.

To reduce unbalance, the balancing operator changes the mass eccentricity at one or two preselected planes in the rotor. On relatively large rotors, such as the high- or low-speed turbine or the fan of a wide-body aircraft engine, the corrections are made by discrete weights which are clipped or bolted in place. On smaller engines, such as for helicopters, the corrections are made by grinding on the turbine wheel, disk, blisk, or shaft.

In all these weight correction methods, the rotor must be brought to rest from its balancing speed, the balancing machine must be opened, and the weight correction must be made. With add-on discrete weights, the correction is usually made while the rotor is on the balancing machine. In the case of grinding, it is most common to remove the rotor to a separate grinding booth for weight changes.

The grinding process is almost always manual. In other words, the operator must apply the grinding wheel to the rotor or wheel for a period of time judged appropriate to make the necessary change in mass eccentricity. The angle for correction is usually marked with reasonable accuracy, but the amount of metal removed is strictly a matter of judgement. To bring the indicated level of unbalance within tolerance frequently requires a number of iterations between balancing machine and grinding booth. The number of iterations generally increases as the specified level of residual unbalance reduces. Some shops are balancing aircraft engine parts to within 0.0004 oz-in.

Computers and calculators have enchanced the low-speed balancing process and the use of computer-assisted balancing machines is increasing. The computer allows setup information, tolerances, etc., to be stored and provides a digital readout of residual unbalance weight and angle. It can subtract out tooling unbalance if required. It provides for record keeping and documentation, but with limited exceptions does not automate the weight change process. There are one or two examples in high volume production where the computer is being used to provide grinding depth and angle information to a grinder for the balancing of specific parts. However, the part must still be transferred from balancing machine to grinder, and a check balance must still be performed. For the most part, low-speed balancing of engines has resisted closed loop automation because of the difficulty of automatic weight correction.

There is a distinct need to fully automate the weight correction process, such that mass eccentricity can be changed while the rotor is spinning. Such automatic weight change would include immediate feedback in terms of the change in recorded vibration. High production rate manufacturing and overhaul processes would benefit greatly.

In order to effectively design an automated balancing system, the process requirements must be defined. Some of these are general in nature, and some of them particular to the specific applications. Following is a list of considerations which must be addressed.

- What is the maximum weight of material to be added?
- What is the minimum weight of material to be added?
- To what thickness must material be deposited to achieve the maximum possible required weight?
- At what speed should the rotor be balanced?
- What is the access to the area for weight addition?
- Will the process produce a concentration of weight at a selected angle?
- How repeatable is process timing?
- Will the deposited material stay in place under the operating environment of the rotor?
- Will the deposited material reduce the fatigue resistance of the part?
- What combination of rotor and spray materials are appropriate for likely applications?
- What are the needs of a production automated balancing system?
- What additional development is necessary to produce an efficient thermal spray automated balancing system?

These and other important questions are addressed in the investigations discussed in the following sections.

# SURVEY RESULTS AND ANALYSIS

This section discusses significant findings from a survey of five engine manufacturers, two engine overhaul centers, and one helicopter manufacturer, supplemented by discussions with suppliers of drive train components and balancing equipment. Table I presents the list of sites visited:

**TABLE I**
**SITES VISITED**

Kelly Air Force Base ALC (San Antonio)
Corpus Christi Army Depot (Corpus Christi)
GE (Lynn)
GE (Evandale)
Garrett (Phoenix)
Textron Lycoming (Stratford)
Allison (Indianapolis)
McDonnell Douglas (Mesa)

This discussion is presented under a series of sub-headings, as follows.

## HIGH-SPEED BALANCING

High-speed balancing with its potential benefits and disadvantages was discussed with several engineers at each of the five engine manufacturers, two overhaul facilities, and one helicopter manufacturer that we visited in our survey. The opinion was unanimous that there is no present or foreseen future need for high-speed balancing of engines. In fact, there was consensus that engine design should incorporate methods which avoid the need for high-speed balancing. Some of the manufacturers had high-speed balancing facilities for research and development work, but did not apply them to production.

At Corpus Christi Army Depot, we did find that some components such as helicopter drive shafts and gyroscope armatures were balanced at their normal operating speeds, which were as high as 8,000 rpm for the drive shafts and 27,000 rpm for the gyros. There was no indication that the number of correction planes exceeds two. Discussions with Bendix indicate that high-speed "multi-plane" balancing is performed on the Apache tail rotor shaft.

Specifically, we found the following facts related to high-speed engine balancing as justification for the opinions expressed. The facts include older engines, advanced current inventory engines, and future engines.

The T-53, T-55, and T-63 engines would appear to have no need for high-speed balancing. The manufacturers say this is true and the experience of Corpus Christi Army Depot is that they are selling engines with very few rejects using low-speed balancing. In a recent study, Martin (1984) concludes that the T-53 needs no high-speed balancing. The T-63 runs at substantially higher speed (53,500 rpm) than the T-53 or T-55, but, it is claimed, has no severe bending modes and is subjected to balancing procedures where assemblies are balanced, in most cases, including the inner race of the bearings. The turbine to compressor shaft ("peashooter") of the T-63 is suspended purely on splines, but appears to maintain tight enough tolerances that low-speed balancing is satisfactory.

The TPE 331, 731, and F-109 engines produced currently by Garrett are successfully balanced for commercial aviation requirements by using a combination of tight tolerances for manufacturing, curvic coupling assembly, and balancing *to the limit of* low-speed balancing *machine capability*. They also two-plane balance some narrow wheels, even though such detail is not absolutely needed. Garrett achieves 0.5 to 0.7 ips vibration levels in the test cell, which is about half the acceptable levels of other comparable military aircraft engines.

The T-700, which is the most advanced engine in the current Army helicopter inventory, does not appear to need high-speed balancing. A number of test cell records which we reviewed indicated that the engine is comfortably meeting its vibration criteria; however, there is probably insufficient data as yet to be conclusive. The approach being taken by the Army to have some high-speed balancing work done on the T-700 is certainly prudent. It is probably also prudent to seek evidence of need before undertaking a major development effort to produce, implement, and train for high-speed balancing capabilities in the CCAD operation.

The T-800, by reports, is being engineered to have no need for high-speed balancing both by the Allison and Garrett joint engine program (LHTEC) and by the Textron Lycoming and Pratt & Whitney joint engine program (APW) teams. The LHTEC version will have a supercritical power turbine but will employ a squeeze film damper and, it appears, will rely on past experience with the F-109 fan engine which operates satisfactorily using only low-speed balancing. One comment offered during the survey is that supercritical engine rotors, which are appropriately engineered to have critical speeds only well below or well above the operating speed range, run more smoothly in that range than engines whose critical speeds are more in the nature of rigid body mode criticals. Since helicopter service calls for a constant speed power turbine and a limited speed range for the gas producer, time at the criticals should be very short.

At the same time, the data pertaining to the T-800 balancing requirements should be critically reviewed by the Army. A dynamic simulator rig may help to build confidence that low-speed balancing techniques will be effective for the T-800.

There are some disadvantages to the use of high-speed balancing in engines which inhibit its acceptance by manufacturers and by overhaul centers:

(1) It appears to require more complicated facilities.

(2) Each run tends to take longer than a low-speed balancing run and it may be necessary to balance at more than one speed.

(3) It may not be as effective as low-speed balancing of components and partial assemblies in eliminating built-in couples (reference here is made to a statement by Martin (1984) in his report on T-53 and T-55 balancing in which he states that high-speed balancing is less effective than low-speed balancing in eliminating the power turbine couple unbalance).

(4) It requires more operator knowledge and skill which is not directly derived from low-speed balancing technology.

(5) Balance stand resonances contribute to requirements for increased skill and knowledge.

## BALANCING ALGORITHMS

Industry-wide resistance to high-speed balancing could be reduced by automatic balancing, but this would essentially require a machine to handle dynamic interpretation problems, which presently require the skill of experienced vibration engineers. *If there is a need* for high-speed automated balancing, then there is a need for the development and application of some advanced high-speed balancing algorithms and techniques. These algorithms need to be able to recognize when a rotor is approaching a resonance, even if that resonance varies from one rotor build to the next. When the rotor passes through the resonance, the algorithms need to be able to identify the resonant frequency and damping ratio. There is a need to handle balance weight sensitivities which apply as a function of speed ratio (speed/resonant frequency) as opposed to a function of absolute speed.

There is a need in high-speed balancing to distinguish shaft and balance stand resonances. A powerful technique is modal impact testing, which can rapidly identify the dynamic characteristics of a rotor and its supports. A further technique which is sometimes helpful is shaker testing over a frequency range while the rotor is running at a constant speed. The basic point here is that a shaker is a better calibrated source of excitation than the rotor itself.

Once the balance stand is fully characterized, it is possible to distinguish rotor and balance stand resonances as they occur during balancing efforts.

Variants on the modal balancing technique (Bishop and Parkinson, 1963; Parkinson, Darlow, Smalley, and Badgley, 1979) can be very useful in balancing. Combinations of weights can be used selectively to control one mode and to avoid affecting other modes.

In general, it is noted that, if the Army is to further pursue high-speed balancing, then techniques such as those discussed above should be developed in combination with automation to make high-speed balancing deployable in a production environment. The need is not clear for engines, but for flexible transmission shafts, which in the Apache helicopter run at supercritical speeds, there is a clear need to enhance the state of the art.

## BALANCING AT CCAD

Based upon our review of the industry survey findings, discussions of problems with CCAD and AVSCOM personnel, and SwRI's knowledge of the balancing industry state of the art, we recommend the following topics be considered for application in the CCAD balancing operation.

### Balancing Specifications

To ensure uniformity and effectiveness of balancing specifications provided by manufacturers for use in overhaul, there would be benefit to a set of guidelines on the subject. Items to be addressed would include the following:

- A range of acceptable speeds at which the part may be balanced. On some balancing machines, certain speeds, such as harmonics, produce unsteady vibration data for balancing. CCAD needs the flexibility to choose the specific speed which fits their equipment, from the specified range.

- The balance correction planes should be specified along with the balance tolerance for each plane. The location of the plane is important because of the modes of vibration the likely unbalance distributions can cause and because it directly impacts the location where the weight is to be corrected. This specification should give the unbalance tolerance in in-ounces or in-grams for each plane and a further note as to how the weight is to be changed (grinding, screws, etc.). Additional helpful information would specify limits on the amount of weight that should be removed (or added) and how it should be distributed or contoured, when practical.

- The axis of rotation of the part for balancing should be specified. For a simple gear or disk, this axis can be trivial, but for shafts or long assemblies, the location of the support points used in the balancing machine can determine an axis of rotation which is not co-linear with the axis of rotation in the engine. Machining tolerances at various points along a shaft or assembly are not all referenced to the shaft axis of rotation and usually have different tolerances and residual runout values. Differences in the accuracy of the axis of rotation can also occur when parts are spun on arbor or tooling surfaces instead of their own surfaces.

- Realistic balance tolerances should be specified. In the specification of both unbalance tolerances and axis of rotation, consideration should be given to rework tolerances of parts, as well as their new condition. Also balance tolerances should take into account assembly and alignment tolerances, and vice-versa.

- Consideration should be given to the fact that, when a balance plane on a part is also a balance plane for an assembly, it may be undesirable to remove weight during both part and assembly balance operations. During the component balancing operation, it may be preferable to simply mark the amount and location of the unbalance and take that into consideration in the assembly indexing of the parts. The net weight should then be removed in the final assembly balancing operation.

## Balancing Machines

In our industry survey, we saw highly-automated, computer controlled balancing machines, and very manually-oriented machines with rudimentary readouts. It appears that many of the shortcomings of manual machines can be overcome with computer control. The computer can be programmed to check any number of parameters before and during the balancing process to ensure that the best and most accurate balance is achieved. The system can verify balancing speed, sensitivity, acceptance tolerances, plane separation, and support separation distances by part number. There can even be interlock checks that the correct fixture is being used and is correctly adjusted. Printout and permanent file records can document data such as the time and date, duration of task, weight correction steps performed, and confirm that the final balance condition meets or exceeds tolerances; quality assurance can be built in. The amount of operator-initiated record keeping would be reduced, yet the amount of valuable data stored would increase. Computers could eliminate the need for shop floor specification sheets which operators presently use to implement the DMWR's.

The balancing equipment and procedures at CCAD should be upgraded in an evolutionary manner to control the impact on production schedules, but in a definite trend toward enchanced quality control, productivity, and record keeping. At each step in the evolution, an evaluation of the benefits and problems should be performed.

A viable approach is to initiate a pilot program which would acquire one or two computerized balancing machines to be installed in areas where they would receive continuous use and evaluation. These new machines could form the nucleus of what would eventually become a balancing shop for one or more engines or helicopters. Although it is productive to combine balancing tasks into concentrated areas where good equipment is given maximum utilization by trained and knowledgeable operators, it is not necessary to centralize *all* balancing operations into *one* shop. The optimum number of balancing areas should be determined by work load, logistics of moving parts between assembly areas, and management structure for supervising related activities.

A multi-year plan should be developed to gradually replace or upgrade all balancing machines to computer control. Many of the present machines, though old, are still adequate for the hardware aspects of the job, if they can be modified with new control, readout, and storage features.

In some large production facilities, we saw particular balancing machines dedicated to particular parts or assemblies which never changed. In these cases, it appeared that the *capacity* for production throughput was maximized by eliminating setup or change-over time, but considerable capital was invested in excess machines which were not kept in continuous (or even frequent) operation. During the period of our visits, production did not appear to warrant the excess capacity. We suggest that greater utilization of capital investment would be attained by having computerized machines which have stored setups for numerous similar parts or assemblies and can be changed over quickly without causing errors. "Help" menus could probably be built-in which would guide an operator through balancing a part which is only balanced occasionally. The expertise needed to handle problem situations could eventually be added -- leading to a "knowledge-based" system.

A need in order to implement computer-aided balancing is the development and installation of a data base upon which the computer can operate. This information should consist of the present or modified balancing specifications for the parts to be run on the computerized balancing machine. The data should include, but not be limited to, the part designation, appropriate dimensions, sensitivities, and acceptance criteria. Additional preparation for setting up the computer could require some custom software development, either by the machine vendor, the user, or a consultant.

All balancing machines should be equipped with shrouds or shields to protect the operator and surroundings from potential damage due to contact with rotating parts. Bladed wheels should also be shrouded to reduce windage effects during balancing operations. The drawback to shrouding all balancing machines is that this could potentially limit the flexibility of a machine to be applied to several different components. We saw, during the survey, balancing machines which had a barrel-shaped enclosure that shrouded most of the machine and any shaped rotor inside it. The lid also engaged the drive belt and a power interlock switch when it was closed to ensure that the cover cannot be opened when the rotor is moving and that the rotor cannot be driven when the cover is open.

## Test Cell Vibrations

We learned that all engines pass the test cell vibrations test eventually, and balancing is not seen as a problem. No engines are returned from the field specifically for unbalance vibration problems, although some are returned for rotor dynamics problems such as rubs, bad bearings, or unbalance due to foreign object ingestion.

The test cell does experience vibration problems on engines, however. The first preventive measure is to index the power output shaft with respect to the rest of the engine. If that is not successful in reducing the vibrations to an acceptable level, the engine is sent back for inspection and rework as necessary.

Occasionally, a group of similar problems will occur on an engine model which may be traced to procedural problems. Some data is saved from the test cell runs and could be retrieved to identify problems. Data from the balancing operations are not available for correlation with test cell data. More plant-wide collection of data for each engine from each step in the overhaul process would allow direct correlation and identification of problems that are identified in the test cell.

In some manufacturers shops, magnitude and angle of residual unbalance are recorded. Mostly, the data is just filed away, but it provides valuable documentation for checking when a quality control problem occurs.

## Automated Balancing

A long-range plan for balancing at the Corpus Christi Army Depot should include not only computer-aided balancing, but a natural progression into automated balancing and automation of other functions associated with the overhaul process. While overall plant automation is beyond the scope of the present study, the balancing process can be designed so that it is adaptable to such a system, if it should be developed in the future. Any plant automation plans at CCAD should give careful attention to integrating the balancing operation.

Automated balancing appears to be the best possibility for reducing the amount of time consumed in balancing components and assemblies, and for ensuring the consistency of the balancing performed. Furthermore, it is a natural extension of computer-aided balancing which performs functions such as storage of setup and calibration parameters, and documentation and storage of results.

The step from computer-aided balancing to automated balancing requires the addition of a computer controllable method of making weight changes to a variety of parts and assemblies of varying shapes and materials. A desirable but not essential component of automated balancing is the ability to make weight changes while the rotor is spinning. The two prominent methods of doing this are the laser balancing technique, which has been under development by other programs supported by NASA and the Army, and the thermal spray technique, which is to be initially investigated by subsequent tasks of this program.

Our review of the state-of-the-art balancing machine technology has identified that a number of automatic or semi-automatic weight removal techniques utilizing a grinder have been sold commercially. These involve a computer-controlled balancing machine (or two) coupled with a grinding tool, machine, or robot operating off of the balancing machine computer to position the part and remove the appropriate amount of metal. The advantage of such methods for use at CCAD would be that they are currently available for installation for application to selected parts; even development to deal with needed refinements would have shorter lead time than the development of a new process.

## Laser Balancing

Laser balancing has definite benefits and has been developed to the extent that it is in commercial production, however, it has some limitations for aircraft rotating equipment applications.

The benefits of laser weight removal for balancing include:

- It is controllable for use on spinning rotors. Martin (1986) reports that laser balancing was performed at 1500 rpm with a laser pulse duration of 0.9 milliseconds. As rotor speed goes up, the amount of material removed per shot decreases.
- It is adaptable to automation. Lasers are intrinsically controlled by electronic circuitry, which can be made adaptable to computer triggering.
- It removes small discrete weights at a time (1 to 9 mg per shot). This is of greatest benefit when small parts are being balanced for operation at high speeds. The amount of material removed per shot is decreased as the rotor speed is increased because the pulse duration must be correspondingly decreased.

The presently perceived disadvantages in the use of laser weight removal include:

- The need for a high powered laser is a safety and expense problem. Higher power lasers remove more material per shot, but, in so doing, may create a larger heat affected zone and higher stress concentrations. A fixed position laser with constant beam path can be made efficient; but a laser which has additional optics, such as in robotics applications, can lose considerable energy before getting to the target.

- The laser affected zone in the material can have fatigue strength reduction factors as high as 7, as reported by DeMuth and Zorzi (1981). More recent work by Martin (1986) reports this factor as high as 3.2 when compared to hand-ground specimens, rather than undisturbed material.

- There is some distinct resistance to the method by some engine manufacturers, at least for the present state of the art. The method is unacceptable because of the problems of stress risers and reduced fatigue life.

## Thermal Spray Balancing

Balance weight correction using SABOR has yet to be proven as a viable balancing process, but it has potential as a successful technique. The main benefit is the inherent ability to add mass only where it is needed, rather than removing mass from a sacrificial ring. Other advantages of thermal spray balancing appear to be:

- The absence of stress concentration areas. Since no heat affected zone is created, and no material is removed, stress riser areas are not expected to occur.

- The ability to apply relatively small discrete weights, yet apply them at a rate which is reasonable for large corrections. Present thermal spray techniques are designed to maximize the amount of material deposited; however, development work is possible to reduce the deposition for small sensitive rotors. Depending upon the material and process used, a minimum application is less than 100 mg. per shot. When rapid weight addition is needed, thermal spray processes can deposit 4 or more pounds per hour with present technology.

- The apparent ability to apply a variety of film materials to a variety of substrates. The thermal spray industry has proven its ability to deposit many different materials to many different substrates. Limitations on bond, fatigue, and differential thermal growth stresses, however, may limit the total range of useful and reliable combinations, for high stress or high temperature applications. It is further proven by the industry that certain processes can spray abrasive materials which can remove metal.

The potential disadvantages of thermal spray balancing include the following:

- The need to grit blast the surface to be sprayed before spraying. In standard industrial applications of thermally sprayed deposits, the surface to be coated must be grit blasted and then sprayed in a relatively short time to avoid recontamination. This is done to maximize bond strength.

- The noise environment of thermal spraying. Because thermal spraying is a combustion process, it is inherently noisy and is normally performed within a sound insulated enclosure.

- Some (not all) thermal spray processes and materials involve risk of explosion, and rather high pressure material delivery.

The problems listed above for laser balancing are likely to inhibit its application to flight propulsion engines for many years. The technique may be viable for noncritical equipment; in fact, it is currently used for balancing of small gyroscopes. The gas turbine engine industry, however, gave clear indication that there is a need to develop other automated balancing options for flight propulsion engines. A favorable alternative at this point is thermal spray weight addition for balance weight correction.

## Data Storage

Computerization or automation of balancing and perhaps other processes at CCAD provide the ability to painlessly collect and save additional data in the form of temporary records (paper printouts) and permanent storage (magnetic media). The data saved on magnetic media makes efficient use of space and provides rapid recall and manipulation of the data for future uses which may not even be anticipated at the present.

In addition to saving data directly generated from balancing operations, such data records allow comparison of data from different phases of the assembly operations, such as correlation of component balancing records with test cell vibration responses. Additional data which could be placed into computer storage in text format includes the solution and documentation of particular balancing problems, and the validation of DMWR's. Such information could provide a "corporate knowledge base" for balancing, regardless of the personnel performing the task of corporate balancing responsibility. This information would also form the basis of a future "expert system" in balancing.

## Alternatives to Mass Addition/Removal

Weight correction in stacked rotors can be minimized by several assembly techniques which use the residual component tolerances and residual unbalances to compensate for assembly unbalances. Among these methods are blade stacking and rotating, part indexing, and straight stacking.

Blade stacking can be used in either of two ways to compensate for component or assembly unbalance. One method is to use a computer program to stack the blades on the disk with a collective unbalance which compensates for the measured unbalance in the disk. The second method is to use this blade unbalance to advantage to make small corrections in assembly unbalance by rotating the blades with respect to the disk to readjust the assembly unbalance.

Part indexing is a closely related technique which documents the residual unbalance of parts after balancing and orients the parts of an assembly (usually aided by computer program) to distribute the unbalances to counteract each other. A less sophisticated, or secondary, application of the method is to rotate the various (especially larger) parts with respect to the assembly, one at a time, in an attempt to minimize the assembly vibration due to unbalance.

Straight stacking of components involves using measured runouts and tolerances of components in an assembly to minimize the unbalance generated when parts are assembled into a rotor. The straighter a rotor can be stacked, the less eccentricity will be generated. The use of curvic couplings has been shown to be an effective measure in minimizing assembly eccentricities.

# DEFINITION OF REQUIREMENTS AND SELECTION OF PROCESS AND MATERIALS

In order to balance gas turbine engines, transmission gears, and helicopter drive shafting, the selected thermal spray process and materials must produce acceptable characteristics with regard to:

- The maximum and minimum magnitude of correction weights that must be applied relative to requirements for the classes of turbine engines and drive components used by the Army.
- Thermal and centrifugal stresses at all locations in the deposited material and at the interface between the deposited material and substrate.
- The range of component materials used in both hot and cold sections of helicopter engine and drive trains.
- The operating environment of the part, including temperatures, corrosion, speeds, and acceleration.

These requirements are discussed below.

## DISCUSSION OF REQUIREMENTS

### Correction Weight Sizes

The largest correction weights used in Army helicopter gas turbines for balancing are about 7 grams at a typical radius of 100 mm (4 inches). Unbalances of 250 to 750 gram-mm (10 to 30 gram-inches) are about the worst initial unbalance conditions we were able to identify. Conditions worse than these are dealt with by measures other than weight change. Some typical balance tolerances on small, high-speed turbine components are in the range of 0.1 grams; for this application, a *goal* for minimum discrete weights should be on the order of 10 - 25 milligrams.

### Stresses

Calculations of stresses created in the sprayed layer or substrate due to centrifugal forces acting on the added mass, or acceleration forces due to the maximum rate of increase in engine rotational speed are generally small in magnitude (highest estimated stress is 7 MPa, or 1,000 psi). See Appendix A, Spray Film-Substrate Stresses. Stresses significant enough to cause separation of the sprayed layer and the substrate can be created, however, when materials of dissimilar coefficients of thermal expansion are exposed to temperatures as found in the hot section of aircraft gas turbines.

Another stress condition identified, but which is more difficult to quantify, is the residual stress set up when the hot spray is applied to the cool substrate and the spray cools and shrinks rather rapidly; spray materials with smaller thermal shrinkages make the best bonds. Since the spray materials usually consist of complex alloy and binder combinations, it is not common to find material properties such as the coefficient of thermal expansion, or modulus of elasticity for them. Tests and microscopic inspections are usually used to identify the integrity and residual stress state of sprayed layers. In the absence of good engineering data for many sprayed films, operating experience is a valid substitute.

## Substrate Candidate Engine Materials

Based upon our survey of Army inventory helicopter gas turbines (T-53, T-55, T-63, and T-700), two basic types of materials were found to be used. These are (1) stainless steels of the 17-4 PH type, including GEAM 350 and 355, and A 286 and 321 stainless, and (2) high nickel base alloys of which Inconel 718 is the most common, and is similar to D979 and Rene 41. The stainless steels are found to predominate in the compressor section of the engines while the nickel alloys are used in the hot section. An additional important point favoring the selection of 17-4 PH and Inconel 718 is the fact that comparable data is available for laser balancing (Martin, 1986), and therein provide fatigue life data for the uncoated specimens. These combined facts provide strong justification for use of 17-4 PH and Inconel 718 as substrate materials for the fatigue and bond strength tests.

## Corrosion

Corrosion in the hot section of combustion turbines is a form of accelerated oxidation induced by impurities brought into the combustion gases from the fuel or environment. Two distinct forms of hot corrosion are recognized; high-temperature (Type I) and low-temperature (Type II). Type I hot corrosion is observed at temperatures between 800°C to 900°C (1500°F and 1700°F) in the presence of sodium sulfate. The sodium sulfate is generated in the combustion process by the reaction of sodium and sulfur impurities from the fuel with oxygen. Type I hot corrosion features intergranular attack, sulfide particles, and a denuded zone of base metal. Above 900°C (1700°F), sulfidation is generally less severe and oxidation predominates. Type II hot corrosion occurs in the 600°C to 750°C (1100°F to 1400°F) range, and is caused by the formation of low-melting eutectics of alkali metals and base alloy metal sulfates. Type II hot corrosion is characterized by a layered corrosion scale with no intergranular attack and no denuded zone. In general, the properties of the turbine materials are selected to avoid the problem of hot corrosion.

In the cold section of turbines, wet corrosion or oxidation can occur. Again, this effect is primarily influenced by the environment from chlorides (salt water environments), and most materials used in aircraft turbines are selected partially for their resistance to corrosive attacks.

In general, corrosion attack on sprayed balance weight material can be avoided by spraying materials the same as the substrate material, or with equal or better corrosion resistance properties. Any spray material which is proven compatible with the substrate for the corrosion and thermal environments of the gas turbine should also serve effectively for balance weight correction.

## Erosion

Erosion is sometimes a problem in turbines; it is unlikely to be a significant problem for balancing, however, since the balance weight correction areas are usually not located in the main gas flow path of the engine. As in the case of corrosion, any spray material which prevents or retards erosion and is otherwise compatible in the area it is to be applied can be also used for unbalance correction.

## Thermal Spray Requirements

The term *thermal spray process* is used as a generic term to describe a whole class of devices that project molten metal spray from a gun which melts metal material in various forms by various heating techniques. Among the techniques used in industry are plasma spray, flame spray, arc spray, and detonation spray processes. These processes melt metals in the form of wire or powder. Detailed descriptions of the processes are provided in Appendix B.

The spray process requirements for automated balancing are high velocity, good adhesion, pulsed timing control, and accurately placed deposition. High velocity reduces the timing lag for accurate placement of the spray on a moving target, and also improves the adhesion of the spray particles on the substrate. Good adhesion is related to particle size and temperature in addition to velocity. In order to accurately time the placement of spray material, the process should have the ability to be turned off and on quickly, precisely, and repeatably; pulsed spray processes are inherently better adapted to this requirement than continuous processes which may require shields, rotating windows, or timing shutters. Accurately placed deposition refers to the ability to spray onto a narrow track on the spinning disk with a minimum of adhesive or nonadhesive overspray; this is based primarily on nozzle size.

Any process selected is expected to need some engineering development to adapt it from the process of applying maximum material in minimum time without regard to timing, to the process of automated balancing where timing is most important and the amount of metal applied per shot becomes a variable with desirable applications for both high and low deposition rates. Other expected development needs include customizing spray nozzles to apply material to surfaces where perpendicular line-of-sight is not possible.

### Balancing Speeds

Our industry survey was unanimous in its rational resistance to the present or foreseen future need for high-speed balancing. Nearly all engine component and assembly balancing is presently performed at speeds below 3,000 rpm. In only a few isolated cases we identified, helicopter drive shafts and gyroscopes were balanced at their operating speeds in the range between 3,000 and 27,000 rpm.

It should be possible to balance at speeds below 3,000 rpm, using either a pulsed process, or a rotating window or shield and a continuous spray process. However, the engineering design requirements of rotating windows or timing shutters at this point appear to be unnecessary encumbrances in view of the fact that pulsed spray systems can perform the timing task without them. This direction does not rule out addressing high-speed balancing in the future through further development of stationary shields, rotating windows, timing shutters, shortened pulse width development, or temporary slowing for weight addition as needed. *The primary and immediate need, however, is for balancing at speeds below 3,000 rpm with a mechanically simple system which can be applied to a completely automated design for use by operators with limited technical skill.*

## SELECTION OF PROCESS AND MATERIALS

### Thermal Spray Process Selection

Table II shows the thermal spray processes identified and investigated for application to spray automated balancing. This table describes the factors considered important in the selection of a spray process for automated balancing. Although there are some blanks that could not be filled from available data, we feel that the information is sufficiently complete to make an intelligent and informed selection of a thermal spray process that can best be adapted to automated balancing. Our selection is the FARE gun.

The FARE gun seems to be adaptable in its present configuration, into a closed loop system. This automated system would use computers and a balancing machine to automate the process of adding material onto a rotating disk at the proper location to steadily reduce its unbalance to a predetermined tolerance. The FARE gun is a detonation spray process which is inherently pulsed. It produces high-velocity, high-temperature spray with reportedly good adhesion characteristics. The spray material is fed into the gun in powder form in pre-measured quantities encapsulated in a paper tape.

TABLE IIA

THERMAL SPRAY PROCESS EVALUATION FOR AUTOMATED DYNAMIC BALANCING*

| 1<br>Thermal Spray Coating Method Equipment Type | 2<br>Equipment Cost & Availability | 3<br>Equipment Application Capability | 4<br>Typical Choices of Coating Material | 5<br>Average Metal Deposition Rate lb/hr | 6<br>Approximate Area of Deposit (control area) | 7<br>Powder Feed/ & Firing Method |
|---|---|---|---|---|---|---|
| DC Plasma Arc 40 Kw Unit | \$30 - \$70K | Metallic, Ceramic & Fusible Coatings | Any powder mixture that melts; limited by particle bond in coating | 4 - 20 | 1/2 in. dia. | Continuous/ Continuous |
| Powder Flame Spray (unfused) | <\$10K | Metallic, Ceramic, Plastics & Compounds | Nonreactive metals; refractories with melting point less than 5000°F | 4 - 20 | 1/2 in. dia. | Continuous/ Continuous |
| Wire Flame Spray (unfused) | <\$10K | Metallic | " | 5 - 65 | 3/4 in. dia. | Continuous/ Continuous |
| (2) Wire Electric Arc | \$10 - \$15K | Metallic | 1/8 in. & > Wire | 5 - 65 | 1 in. dia. | Continuous/ Continuous |
| D-Gun | Service Center | Metallic, Ceramic | Tungsten carbide with selected matrices; selected oxides | 7 | 3/4 to 1 in. dia. | Continuous/Discrete Time Firing |
| FARE | \$25K + Spray Room \$3,500 | Metallic, Ceramic | " | 4<br>1 - 5 shots/sec. (0.057 g/shot) | 0.11 sq. in.<br>3/8 in. dia. | Metered tape pellets Shot coating period |
| JETCOAT | Complete with Course \$34,155 | Metallic, Ceramic | WC & CrC with/ Selected Matrices | 7 - 15 | 1/2 in. dia. | Continuous/ Continuous |
| GATOR-GARD Plasma | | Metallic, Ceramic, Plastics & Compounds | Any powder mixture that melts; selected oxides | 7 - 20 | 1/2 in. dia. | Continuous/ Continuous |

*References for information in this chart are listed in Appendix B. Brief process descriptions are also provided.

TABLE IIA
THERMAL SPRAY PROCESS EVALUATION FOR AUTOMATED DYNAMIC BALANCING*
(Cont'd)

| 1 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|
| Thermal Spray Coating Method Equipment Type | Normal Processing Temperature at The Base Material | Flame Temperature | Type of Bond | Dimensional Limits on Base** | Coating Thickness & Tolerances, in. Max./Min. Control | Particle Velocity, M/S | Particle Temperature, Control |
| DC Plasma Arc 40 Kw Unit | Usually less than 250 to 500°F for a few coatings | Usually 10-15,000 As High as 20,000 | Mechanical, somtimes quasi-metallurgical | 0.025 in. dia. min., No max. limit | 0.002 - 0.1 in. +/-0.001 | 150 - 400 M/sec | High/Temp. Med. Control |
| Powder Flame Spray (unfused) | 200 - 250°F | About 5,000 | Mechanical | 0.004 in. dia. min., No max. limit | 0.005 - 0.2 in. +/-0.003 | Powder 100 - 120 M/sec | 1100 - 2760°C Little control |
| Wire Flame Spray (unfused) | 200 - 250°F | About 5,000 | Mechanical | 0.004 in. dia. min., No max. limit | 0.005 - 0.2 in. +/-0.003 | 100 - 150 M/sec | 1100 - 2760°C Little control |
| (2) Wire Electric Arc | Room - 100°F | About 10,000 | Mechanical | 0.004 in. dia. min., No max. limit | 0.005 - 0.2 in. +/-0.003 | - | High/Temp. No control |
| D-Gun | 300°F | About 5,000 | Intimate Mechanical | 0.002 in. dia. min., 60 in. max. limit | 0.001 - 0.012 in. +/-0.001 | ~100 M/sec. | Good control |
| FARE | 300°F | More than 4000 | Intimate Mechanical | 0.025 in. dia. min., No max. limit | 0.001 - 0.2 in. +/-0.001 | ~2500 ft/sec 760 M/sec | Good control |
| JETCOAT | 300°F | About 5,000 | Intimate Mechanical | 0.005 in. dia. min., No max. | 0.001 - 0.015 +/-0.0005 | 200 - 700 M/sec (1000)ft/sec | Good control |
| GATOR-GARD Plasma | <400°F | About 4,000 | Intimate Mechanical | Add | 0.001 - 0.010 +/-0.001 | 200 M/sec. 1200 - 1520 ft/sec | 1510°C Good control |

** - Depends on the base material.

*References for information in this chart are listed in Appendix B. Brief process descriptions are also provided.

TABLE IIB

THERMAL SPRAY MATERIAL EVALUATION FOR AUTOMATED DYNAMIC BALANCING

| 1<br>Thermal Spray Coating Method Equipment Type | 2<br>High Density Material | 3<br>Coating Efficiency | 4<br>Bond * Strength Static-Dynamic Shear-Tensile | 5<br>Coating* Porosity, % /Oxide, % | 6<br>Residual Stress (coating) *** | 7<br>Smoothness (as deposited) | 8<br>Cost of Operation | 9<br>Miscellaneous |
|---|---|---|---|---|---|---|---|---|
| DC Plasma Arc 40 Kw Unit | WC - 12% Co = 12.5 g/cm3 | 40% | Avg. 8,000 | Up to 15% /up to 10% | | Approx. 250 RMS | $18/hr. & $62/ .010 in./ sq. ft. WC-88 | |
| Powder Flame Spray (unfused) | | 40% | | Up to 20% /up to 10% | | | | |
| Wire Flame Spray (unfused) | | | | Up 20% /up to 10% | | | | |
| (2) Wire Electric Arc | | | | | | | | |
| D-Gun | WC - 13%Co = 13.5g/cm3 | | > 10,000 psi | 1% /1% | | Approx. 120 - 150 | | |
| FARE | 88WC - 12Co | 28.50% | " | 1% /1% | | Approx. 250 RMS | | |
| JETCOAT | WC - 12Co = 13.5g/cm3<br>WC - 17%Co = 12.6g/cm3 | 72% | > 10,000 psi | 1% /1% | | 160 - 240<br>140 - 240 | $31/hr. & $37/.010 in./7in. sq. ft. WC-88 | Stand Off |
| GATOR-GARD Plasma | | 40% | > 10,000 psi | 1% /1% | | | | |
| | | | * with WC Coating | * with WC Coating | *** - Hard to measure & depends on technique | | | |

## Materials Selection

Based upon the discussion above under *Substrate Candidate Engine Materials*, we have selected Inconel 718, and 17-4 PH stainless as common representatives of the two basic types of materials found in helicopter turbine engines. Thermal spray materials have been selected which are compatible with these substrates. The substrate and spray material combinations selected for evaluation under fatigue and bond strength tests are:

- Tungsten carbide sprayed on 17-4 PH stainless
- Inconel 718 sprayed on Inconel 718
- Triballoy 800 sprayed on Inconel 718.

Tungsten carbide was selected as a coating material for the cold section of the aircraft turbine because it is a high density material which should maximize the mass for the volume of material applied. It has a good history of performance as a sprayed material on stainless substrates for the environmental conditions found in the "cold" sections of gas turbines. It has the further advantage of being a hard coating material.

In the "hot" sections of gas turbines, the important compatibility parameters for a sprayed substance are its oxidation resistance and its thermal shrinkage on cooling compared to the substrate material. Inconel 718 has high resistance to oxidation for use in hot atmospheres. The thermal shrinkage for a spray powder is very near to that for the contiguous material of the same alloy. For these reasons, Inconel was selected for spraying on Inconel as the ideal material match for bond and fatigue strength evaluation.

Triballoy 800 is a material commonly used in aircraft applications as a hard facing in high temperature environments. It has good oxidation resistance and low thermal shrinkage characteristics. These characteristics make Triballoy a good choice for another material for spraying onto Inconel for evaluation as a candidate for balance correction in the "hot" gas turbine sections of helicopter engines.

# TESTING OF CANDIDATE PROCESS AND MATERIALS

Screening tests were performed on selected samples of spray and substrate materials to determine the adequacy of the coating bond and its effect upon the fatigue life of the material combination. The spray coatings were applied to the substrate materials by the FARE process (Figure 1, page 31). The material combinations tested were:

- Tungsten Carbide on 17-4 PH Stainless
- Inconel 718 on Inconel 718
- Triballoy 800 on Inconel 718.

The tests performed on these material combinations were:

- Bond strength tests
- Fatigue life tests
- Metallurgical examinations of selected failures
- Surface roughness measurements.

In order to apply thermal spray automated balancing to aircraft propulsion components, it is necessary to prove that the strength of the parts will not be degraded by the process. Naturally it is better to secure this confidence before money is spent on developing the automated balancing process.

## MATERIAL QUALITY CONTROL

The substrate materials were ordered from the manufacturers with alloy certification (Appendix C). After fabrication of the fatigue test bars from the raw stock, the specimens were marked on both ends with a designation of the substrate material and a sequence number. They were also marked with the spray material designation during that process. The bond test specimens were similarly marked. The designation used consisted of the following:

- 17 — 17-4 PH stainless steel substrate material
- IN — Inconel 718 steel substrate material
- B — Inconel 718 sprayed coating
- T — Triballoy T-800 sprayed coating.

The 17-4 PH samples are only sprayed with tungsten carbide (FG112 powder), so no specific coating designation is used. The final notation is a number assigned to the particular sample within the material and coating designation. Examples are:

- 17-9 — 17-4 PH stainless steel substrate coated with tungsten carbide - specimen number 9.
- INB-1 — Inconel 718 substrate coated with Inconel 718 - specimen number 1.
- INT-2 — Inconel 718 substrate coated with Triballoy T-800 - specimen number 2.

## FATIGUE PROGRAM

Under this test program, a fatigue life curve for each material combination was developed using eight test specimens to generate data for failures between 10,000 and 10,000,000 cycles. The tests were performed according to standard engineering practice and quality control using four point bending. The four point bending provides sufficient uniform stress over the entire test area to evaluate substrate to coating bond integrity and the effect, if any, of the coating on the behavior of the substrate material under cyclic loading.

## Test Preparation

### Fatigue Specimens

The test bars prepared for evaluation were short, rectangular beams with dimensions as shown in Figures 2 and 3. The sprayed area is indicated. In order to properly spray coat the bars, they had to be grit blasted immediately before spraying, to produce a clean, roughened surface for spray adhesion. The spray was applied by the FARE process, building up the coating in several layers. The bar was mounted in a motorized, movable table which continuously cycled the surface to be sprayed under the gun nozzle to contour the surface as evenly as possible (Figures 4 and 5). The completed fatigue bars are shown in Figures 6 and 7. Refer to Appendix D, *Thermal Spray Fatigue Bar Data Summary*, showing the spray coating parameters, dimensions, and surface finish results.

### Surface Roughness

The spray deposited surfaces were measured using a Surtronic-3 brand profilometer in the RA range with 0.25mm (0.01 inch) of reading area. The unit is self-powered for travel and stylus pressure and makes a measurement along a path approximately 13mm (1/2 inch) long across the specimen. The average of three readings was recorded for each of the fatigue bar specimens shown in the Fatigue Bar Data Summary included in Appendix D.

Results of the three alloy combinations can be summarized by comparing the combined averages of each combination as follows.

(1) The Triballoy 800 alloy spray deposit was the smoothest deposit with an average RMS 163 surface finish.

(2) The Inconel 718 alloy was the roughest with an average of RMS 568. This is attributed to the powder material being a rather coarse 325 mesh.

(3) The tungsten carbide alloy spray deposit was RMS 175.

A graphic view of these comparisons is also shown in the metallographic examination to follow at various magnifications from 2X to 5000X, in Figures 19, 20, 23, 24, and 32.

It is evident that the coarseness or fineness of the original powder used directly affects the final spray deposit surface finish. Deposit density is also directly affected by the spray powder particle size as shown in the metallographic cross sections to follow.

### Deposit Efficiency

The thickness of deposited spray metal per layer was estimated for the fatigue bars on the Appendix D data sheets. The most buildup per shot was made by the larger metal particles of the Inconel 718 deposits with 0.018 grams per shot or 0.2 mm (8 mils) of thickness per shot, while the tungsten carbide coating efficiency was only about 28 percent of the original shot weight and the buildup of 0.025 mm (0.1 mils) per shot thickness of deposit. The Triballoy T-800 deposited approximately 0.1 mm (4 mils) per shot.

### Test Machine and Fixture

The bending fatigue tests were conducted in a closed-loop, servo-controlled, hydraulic testing machine. The four point bending fixture with its pertinent dimensions is presented schematically in Figure 8, and the actual laboratory test setup is shown in Figure 9. The lower loading anvil of the bending fixture was directly attached to the hydraulic actuator shaft, while the upper anvil was reacting against the load transducer of the testing machine through a ball adapter. Line contact loads were delivered to the bar specimens through hardened pins. This alignment prevents asymmetric loading of the test specimen.

During test performance, the machine automatically recorded the number of cycles and controlled the load reached. A displacement transducer monitored the maximum movement with each cycle. An increase in this deflection indicated that a crack was present and growing; failure was imminent in a few hundred cycles. The output of the displacement transducer was recorded on a strip chart to document the crack generation and final failure (Appendix E).

### Calibration

There are two calibration procedures commonly used for fatigue tests -- calculation, or testing. We elected to perform the calibration by testing because it yields more reliable data and because the thickness to length ratio of the test bars would yield better data by testing.

Calibration was performed using an uncoated beam of 17-4 PH stainless steel. The beam was instrumented with four 350 ohm, single element strain gages on the tension side of the calibration beam, as shown in Figure 10. This layout was chosen to obtain both applied load vs strain amplitude in the test section, and verification of the actual uniformity of the strain (and stress) distribution. Average strain vs load values for the calibration beam are presented in graphical form in Figure 11.

Conversion of the average strain values to stress was made using the elastic stress-strain relation:

$$\sigma = \varepsilon \times E$$

where $\sigma$ = Elastic fiber stress
$\varepsilon$ = Average bending strain
$E$ = Elastic Modulus.

To maintain the accuracy gained by testing, over the assumptions used in calculation, the conversion of the experimentally generated load-strain curve to load-stress values requires that the elastic modulus value be tested rather than using reference book values. One 6.4 mm (0.250 inch) diameter tensile specimen of the configuration shown in Figure 12 was tested for each of the beam materials. Elastic modulus values obtained in these tensile tests were as follows:

| Material | Elastic Modulus (psi) | Elastic Modulus (GPa) |
|---|---|---|
| 17-4 PH | $29.1 \times 10^6$ | 201 |
| Inconel 718 | $28.9 \times 10^6$ | 199 |

## Test Results

The S/N curves generated for each of the substrate-coating combinations are shown in Figures 13-15. The data are compared to that given by Martin (1986). Examination and comparison of these three plots shows that data for the tungsten carbide coated 17-4 PH stainless steel samples lies directly in line with the data for hand-ground surfaces. The data for Inconel 718 on Inconel 718 has greater scatter but is comparable to the data for Inconel with hand-ground contours. The data for the Triballoy coated Inconel is consistent and defines a curve which lies definitely below the one defined by the hand-ground data. The reasons for these results are investigated and discussed further in light of the microscopic examinations of the failures in a later section.

## Microscopic Evaluation of Fatigue Specimens

The fatigue test samples were examined metallographically to determine the nature and extent of the fatigue damage and for evidence of any influence of the spray coatings on the fatigue behavior of the specimens. The specimen evaluation is described in the following paragraphs.

A stereomicroscopic examination was performed on the coated tension surface of all specimens. The surfaces were viewed under 10 to 40X magnification and the degree of cracking was rated. This rating was an arbitrary number from 1 to 10, noted on the fatigue data sheets, to correlate the load levels; a description of the visible cracking was given as remarks. These results are shown in Figure 16. Many cracks probably were not observable since the specimens were not under load during examination.

A scanning electron microscope (SEM) examination was performed on the coated surfaces on selected sections for each coating type (three specimens)( Figures 17-21). The selection was based on the findings of the stereomicroscope examination. Longitudinal metallographic sections were cut from two cracked, but unbroken samples with different deposit-substrate combinations. These were specimens INB-8 and INT-3 shown in Figures 17 and 21 respectively. Sections were also cut from a failed sample, specimen 17-5 shown in Figure 22.

SEM fractographic examination was then made on each of the coating samples selected for examination for both low cycle and high cycle, broken and unbroken specimens. Typical coating surfaces for these fatigue specimens are shown in Figures 23 for specimen 17-1, Figures 24 and 25 for specimen INB-1, and Figures 19 and 20 for specimen INT-3.

Some preparation for the visual and SEM surface examinations was performed. The specimens were cut to a more manageable mounting size for the SEM equipment. The longitudinal sectioning of the selected cracked specimen was performed on the metallurgical abrasive cutoff saw with water cooling. The specimens were then nickel plated to preserve the coatings through further grinding and polishing. The specimens were then etched with ferric chloride to highlight surface features for examination under the light microscope.

## Discussion of Fatigue Test Microscopy

The complete sets of fractured fatigue bars are shown in Figures 26, 27, and 28 for the three material combinations.

### Tungsten Carbide Samples

All of the bars in this set tested to complete fracture. Examination of the failures was made by selecting for comparative evaluation of a high load, low cycle specimen (17-1) and a low load, high cycle specimen (17-6). These bars show the nature of the FG112 tungsten carbide deposit and its effect on the 17-4 PH stainless steel substrate after fatigue testing.

Figure 23 shows the typical coating surfaces after fatigue failure at 100X, and 5000X magnifications respectively for specimen 17-1. Note the very fine particle size of the deposit evident in Figure 23(b). No major cracks were observed other than the main fracture.

SEM fractographs from specimens 17-1 and 17-6 are shown in Figures 29 and 30. In specimen 17-1, a distinct step which is usually present is shown at the deposit-substrate interface. Fracture deposit material exhibited shows typical particulate features. There is no evidence of slow crack growth in the deposit and no features are evident to indicate that the deposit played any role in crack initiation in the substrate. Features of the substrate fracture surface near the bond line are consistent with high cycle fatigue. Some cracking of the deposit parallel to the interface was evident. No major difference was noted for specimen 17-6 except that the step at the interface is not evident. This specimen also showed substrate cracking parallel to the interface.

The metallographic section of 17-5 is shown in Figure 22(a) and no substrate cracking can be observed. A substantial part of the deposit showed no damage as seen in Figure 22(b).

### Inconel Coated Specimens

Typical appearance of the Inconel spray coating surface is shown for specimen INB-1 in Figure 24 characterized by large rounded particle shapes. Stereomicroscopy of INB-8 (unfractured) revealed very tight transverse cracks. SEM micrographs of that crack are shown in Figure 25.

Metallographic sections of INB-8 at the location of the surface cracking are shown in Figure 17. A major deposit crack and debonding are evident in Figure 17(a). Other tight transverse cracks and some evidence of coating failure are shown in Figure 17(b).

Photomicrographs of sections made at the main substrate crack are shown in Figure 18. This crack was found to be 0.6 mm (25 mils) deep at that section. Another (the third) distinct deposit crack was located near the substrate crack but was not associated with the substrate crack.

### Triballoy Coated Specimens

The results of surface examinations show more extensive cracking occurred on the Triballoy coating of the IN-T specimens. Except for one specimen (INT-3) which showed network type cracking, the coating cracks were linear, secondary, and parallel to the fractures.

Typical appearance of the Triballoy spray deposit surface is shown in Figure 19. The dense structure and fine particle size are evident as compared to the Inconel spray specimen. This specimen exhibited a patch of network cracking as shown in Figure 20. Longitudinal sectioning of the deposit cracks are shown in Figure 21. Transverse cracking and debonding are shown in Figure 21(a) as well as coating failure in Figure 21(b). There was no evidence of substrate cracking failure as seen in Figure 31. The depth of this crack was 6 mm (1/4 inch). This substrate crack was located outside the deposit coating area and, therefore, obviously not influenced by the coating deposit.

## BOND TEST PROGRAM

The strength of the bond between a spray deposit and the substrate depends upon many factors including the following:

- Substrate material
- Preparation of the substrate surface

- Preheat treatment
- Bond layer material and its application
- Coating material and its application
- Thickness of the deposit
- Post-spraying thermal treatment
- Design of the bond strength test
- Technique of attachment to the deposit surface
- Effect of the attachment on the deposit properties.

The standard test described in ASTM C633, *Standard Test Method for Adhesion or Cohesive Strength of Flame Sprayed Coatings*, was used for determining the bond strengths in these tests.

## Test Preparation

### Bond Test Specimens

The bond test specimens were 1 inch diameter cylindrical sections prepared for spraying on one end (flat surface) and for test machine attachment on the other (see Figure 32). The flat end of the substrate block was prepared by grit blasting and the deposit was applied to it. Figures 33 and 34 show photographs of the FARE process coating setup for spraying bond test specimens. The deposit was applied flat and uniform in thickness using optimum procedures for the deposit material (see Figures 32(b), (c)). Refer to data sheets 1, 2, and 3 in Appendix D which show the parameters and dimensions. A mating block, identical to the substrate block, except for the absence of spray coating, is adhesive bonded to the flat deposit surface of the substrate block to produce the tension specimens.

A 3-M adhesive was used which produced a bond strength after heat curing in excess of 69MPa (10,000 psi). (Refer to blank test values.)

### Test Machine and Fixture

The fixture and specimen arrangement for the ASTM C633 bond test is shown in Figure 35. In this test, the assembled substrate and loading blocks are loaded into the attachment fixtures of the servo-controlled, hydraulic test machine. The specimens were loaded in tension at a constant rate using the self-aligning device. The load was increased until the two blocks separated. Five specimens minimum were pulled of each of the three spray-substrate combinations. The maximum loads were recorded and the bond strengths (stress) of the deposits were calculated on the data sheets.

## Test Results

The results of the bond strength tests for the three material combinations are shown in Data Sheets 1, 2, and 3 in Appendix D. Although there are more than five tested specimens for the tungsten carbide coating on 17-4 PH stainless, the last five specimens were used as the record data for the project. The earlier tests were performed as part of the process of perfecting our testing technique. In the bond test for each of the two substrate materials, one test was performed on a specimen set prepared without a spray coating on the substrate block. This test was used to evaluate the adhesive bond.

The average of the five bond tests for each of the three material combinations are:

| | | |
|---|---|---|
| • Tungsten carbide on 17-4 PH | 8900 psi | 62 MPa |
| • Inconel 718 on Inconel 718 | 5100 psi | 35 MPa |
| • Triballoy on Inconel 718 | 5000 psi | 34 MPa |

## Microscopic Evaluations of Bond Strength Specimens

Representative bond test samples were selected for metallurgical examination. Two areas of the samples were examined, (1) where the epoxy adhesive had pulled the spray coating away from the substrate specimen, the spray material remaining on the substrate would indicate the nature of the failure and its location, and (2) areas where the coating remained on the substrate. One example of each combination was considered sufficient. The specimens selected were numbers INB-6, 17-9, and INT-7 as mentioned in the following "Discussion of Bond Test Microscopy.".

The areas of the cross sections of spray deposit were viewed on the metallurgical light microscope to select representative areas showing the two conditions mentioned above. The first area, with adherent spray material remaining on the specimen, shows the character of the deposit, including the bonding and the structure of the deposit and the oxides and porosity present. The second area, where the spray deposit was pulled away from the substrate (nonadherent), was considered to show the nature of the remaining spray material that may still be on the surface and give a clue as to where the coating parted.

### Specimen Preparation

The specimens were first cut by slicing off a 1.6 mm (1/16 inch) wafer which included the spray deposit. Then, a cross section was made with the metallurgical cut-off wheel, to include the representative areas selected. The sections were then nickel plated to preserve the specimen edges during subsequent mounting in Bakelite and surface polishing operations. After metallurgical polishing, the specimens were etched using ferric chloride, to emphasize the surface features and grain structure.

## Discussion of Bond Test Microscopy

### Unstressed Spray Coatings

Figures 36 through 39 are sections of deposits made before bond testing. Figures 36 and 37 show an area where some unfilled depressions were found at the roughened substrate surface. Figure 38 shows an area of intimate tungsten carbide bonding, while Figure 39 identifies areas of greater porosity and lack of bonding in an Inconel sprayed specimen. Even though all spray coatings were applied in layers using multiple passes (over a short time duration), it is difficult to identify layering in the cross-sectional views; the multiple layers form a homogeneous coating.

### Tungsten Carbide Coated Specimens

Figure 40 shows the two halves of bond specimen 17-9 where approximately 80 percent of the spray deposit stayed with the substrate side of the bond test specimen.

Shown in Figures 41 through 44 are metallographic sections through the substrate side of specimen 17-9. Figures 41 and 43 show sections in areas of thick layers where the bond line remains intact, similar to that of Figures 36, 37, and 38. Figures 42 and 44 show that failure occurred in the coating and left a thin layer of coating on the substrate. This indicates that the failure occurred by fracture of the coating, rather than by separation at the bond line.

### Inconel Sprayed Specimens

Figures 45 through 49 are metallographic sections through the substrate side of Inconel specimen INB-6 showing nearly all of the deposit pulled away from the substrate, i.e., stayed with the epoxy or dummy side of the specimen.

Figures 47 through 49 show metallographic sections through typical substrate material where the deposit was substantially gone. Portions show complete lack of any deposit remaining. This factor indicates that debonding of the substrate bond occurred. This observation is consistent with the bond line crack conditions noted in the "as sprayed" samples on Inconel shown in Figure 39. The location where the small part of deposit remains represents a localized area where intimate bonding was achieved.

### Triballoy Sprayed Specimens

Figures 50 through 55 are post-bond test specimens for Triballoy sprayed on Inconel 718. Figures 50 through 52 are of specimen INT-7 which is an example of lower bond strength values. The cross sections show a small amount of adherent Triballoy remaining on the surface.

Figures 53 through 55 analyze specimen number INT-3 which had the highest value of bond strength. It also has small areas of adherent Triballoy, but the majority of the material was pulled away from the substrate.

## SUMMARY OF METALLOGRAPHIC INVESTIGATIONS

Metallographic inspection of tungsten carbide and Inconel sprayed specimens that have not been exposed to any stress of bond or fatigue testing showed desirable traits of an intimate bond line and low coating porosity. The larger grain size of the Inconel powder caused these adhesion characteristics to be somewhat lower in the Inconel sprayed specimens than in the tungsten carbide sprayed specimens.

The application of thin spray coatings in multiple layers produced a homogeneous coating, which was evident in the cross-sectional view of unstressed or stressed specimens.

Fractographic examination did not show direct influence of the deposit on cracking in the substrate of failed specimens. In every specimen that was sectioned metallographically, coating cracks were present without associated substrate cracks. In the two cases where the unfractured specimens were examined, the coating cracks clearly did not propagate directly into the substrate material.

Representative examples of each of two bond test substrate materials, 17-4 PH and 718 Inconel, were selected to show both conditions of adherent and nonadherent spray bond deposit on the specimens after the tensile testing was completed. In every case, most of the spray deposits were pulled away from the substrate specimen. The question of whether the spray coating tensile failures occurred at the bond line was resolved by the metallographic study, i.e., some of the spray deposit material remains in the pre-spray gritted surface depressions, while most of the deposit pulled off with the epoxy.

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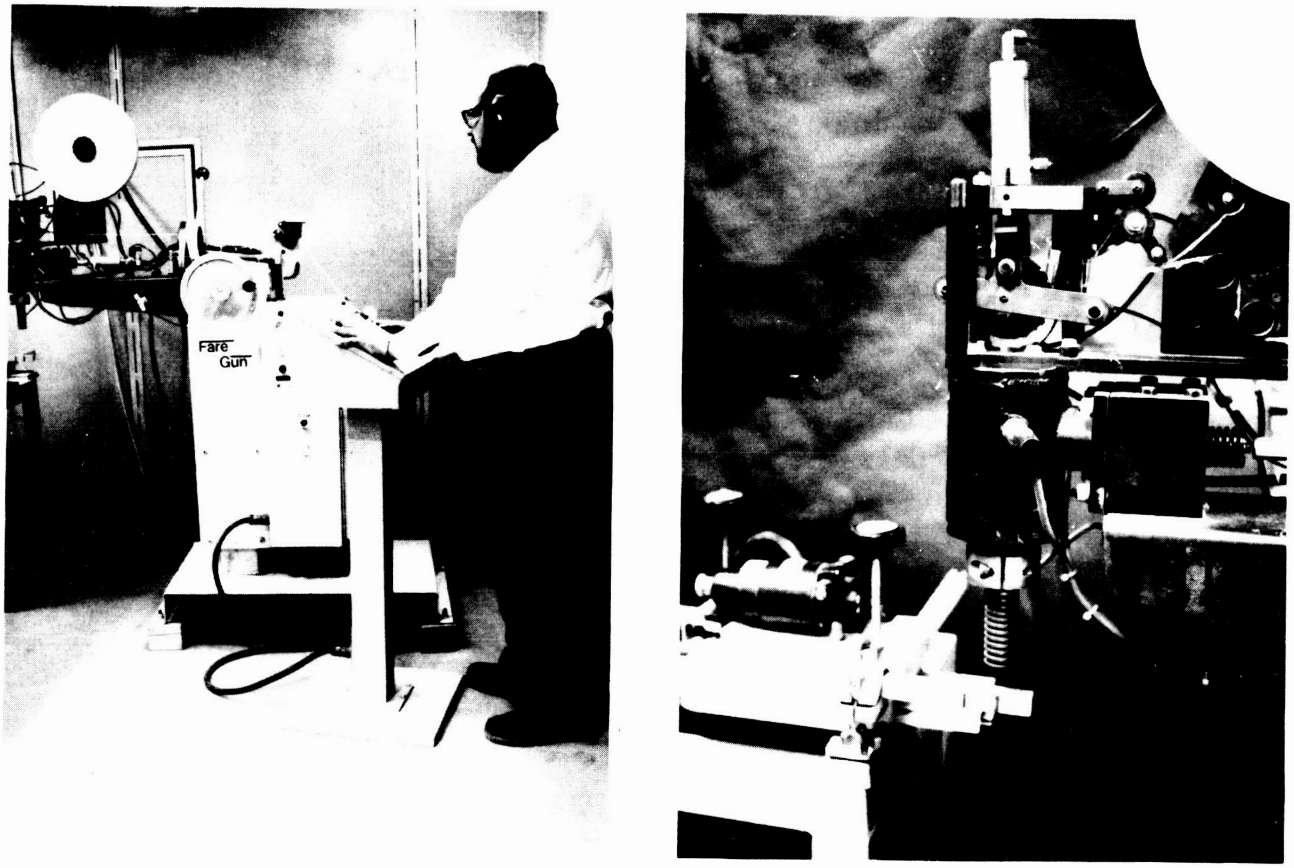
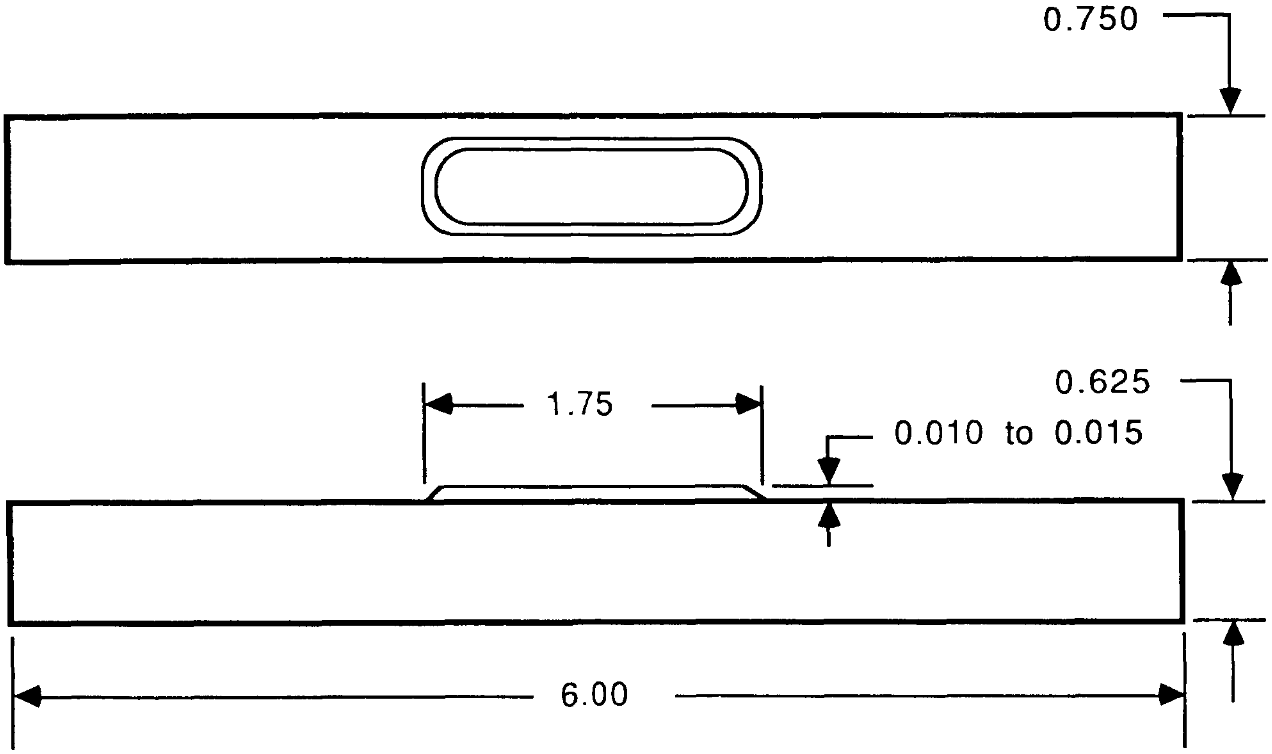
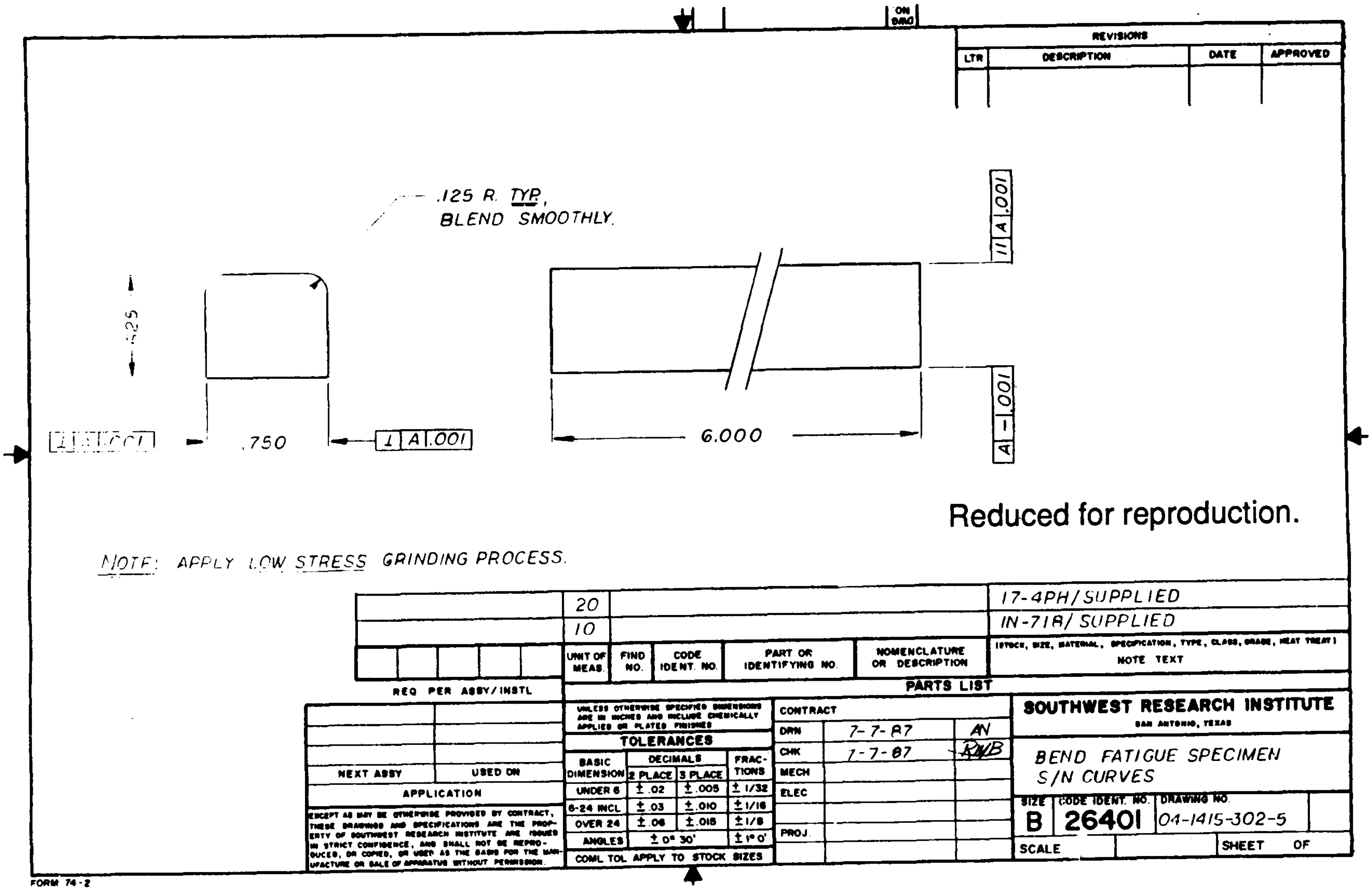



FIGURE 1. THE FARE GUN EQUIPMENT SETUP INSIDE A SPRAY BOOTH




SPRAY DEPOSIT FATIGUE SPECIMEN
FIGURE 2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TOLERANCES
BASIC DIMENSION
DECIMALS
2 PLACE
3 PLACE
FRACTIONS
UNDER 6
± .02
± .005
± 1/32
6-24 INCL
± .03
± .010
± 1/16
OVER 24
± .06
± .015
± 1/8
ANGLES
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FIGURE 3

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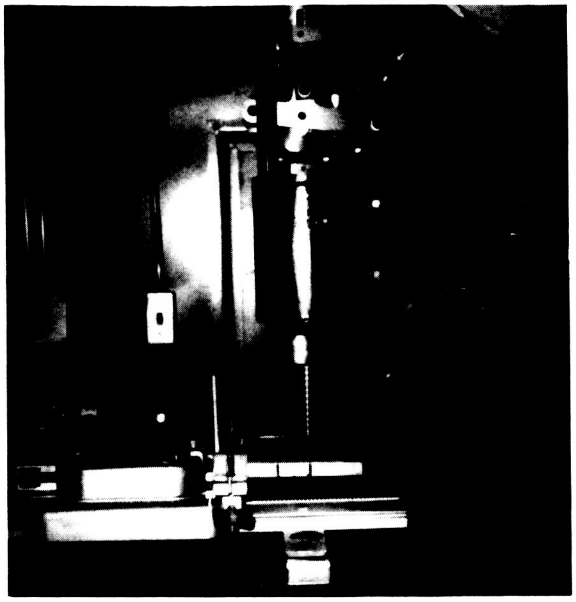

FIGURE 4. MOTORIZED FIXTURING SETUP FOR SPRAYING FATIGUE BAR SPECIMENS

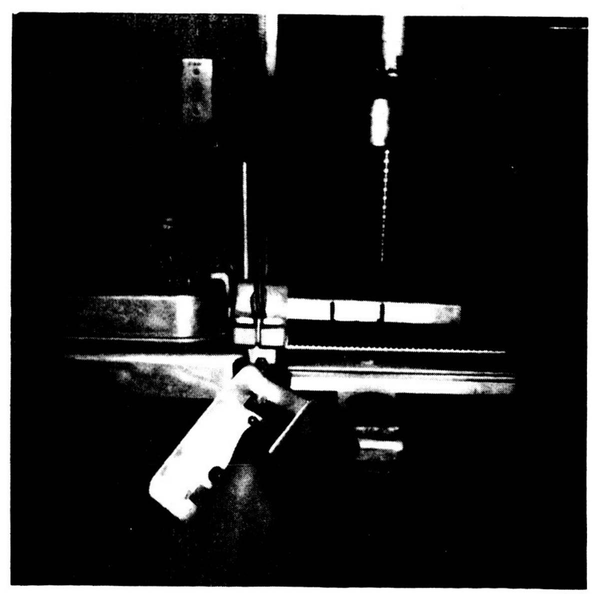

FIGURE 5. CLOSER VIEW OF BAR SPECIMEN SHOWS THE POINTER AND PENDANT FOR HORIZONTAL AND REVERSE CONTROL

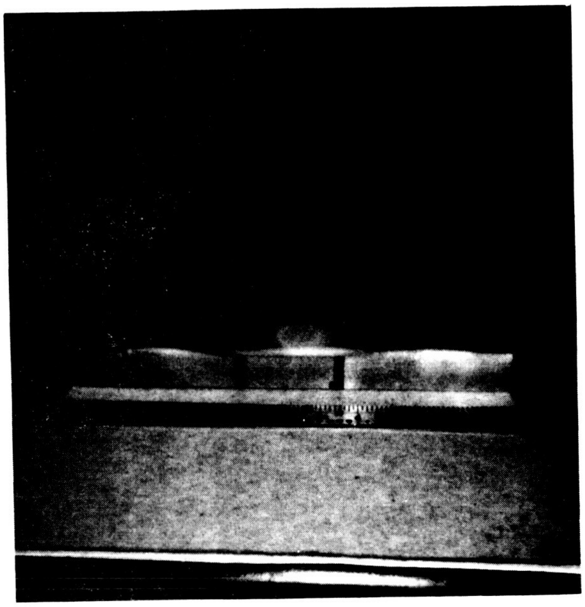

FIGURE 6. COMPLETED BAR WITH APPROXIMATELY 1-1/2 INCH LONG BY .015 INCH BUILDUP

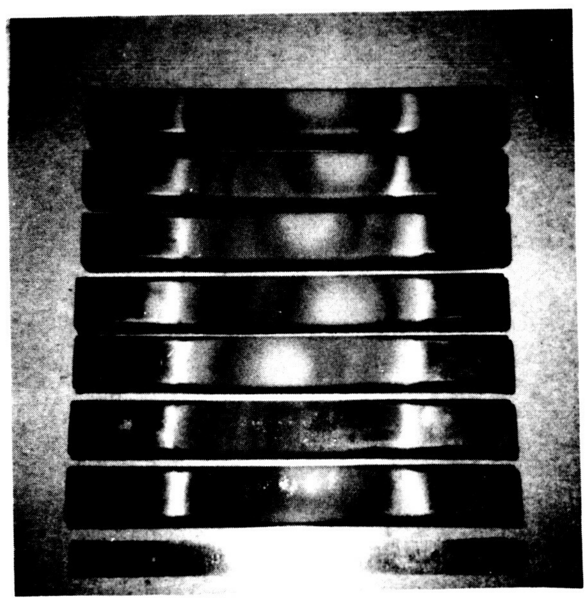

FIGURE 7. COATED FATIGUE BARS FG112 ON 17-4 PH SUBSTRATE

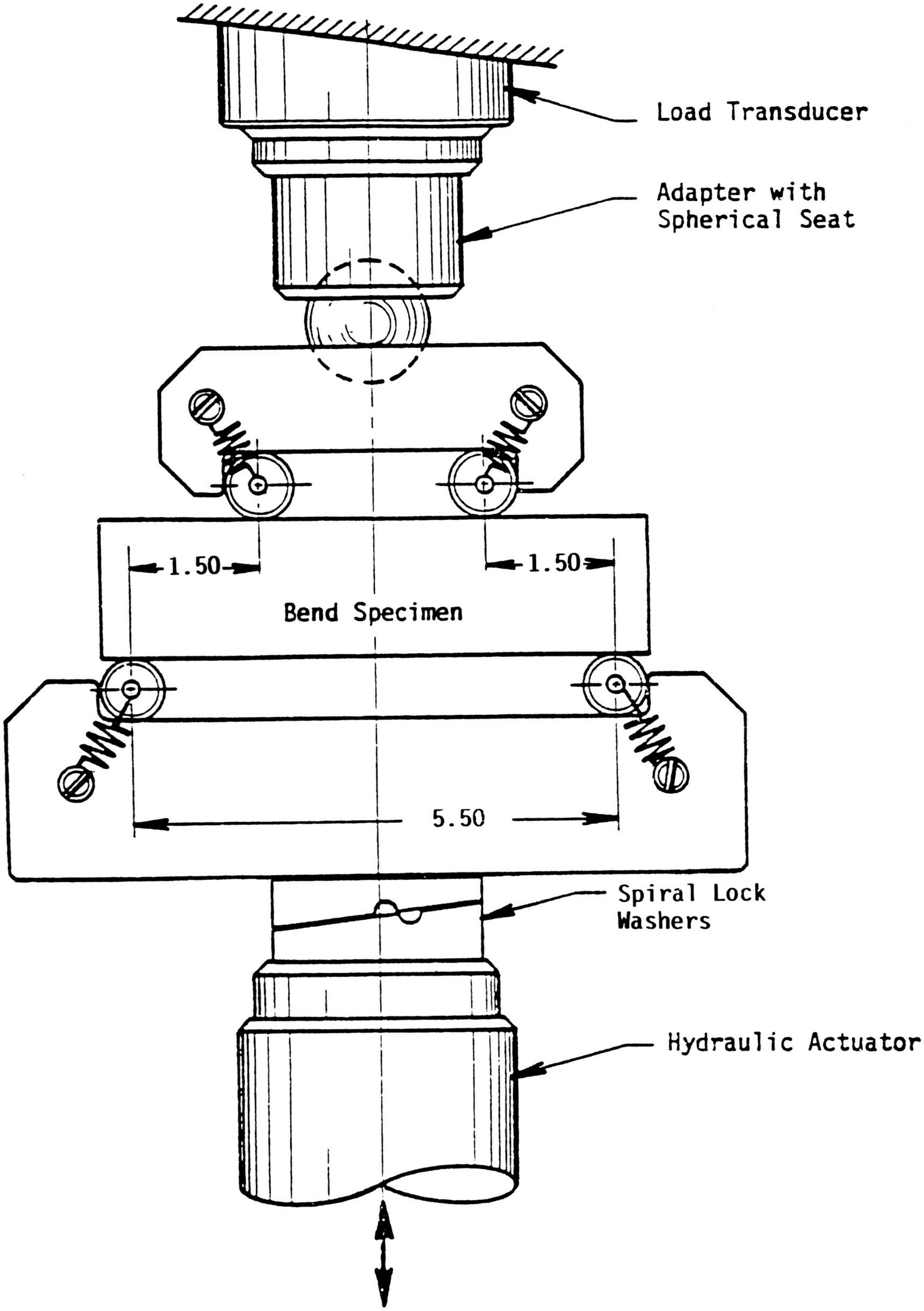


FIGURE 8. FATIGUE TEST SETUP

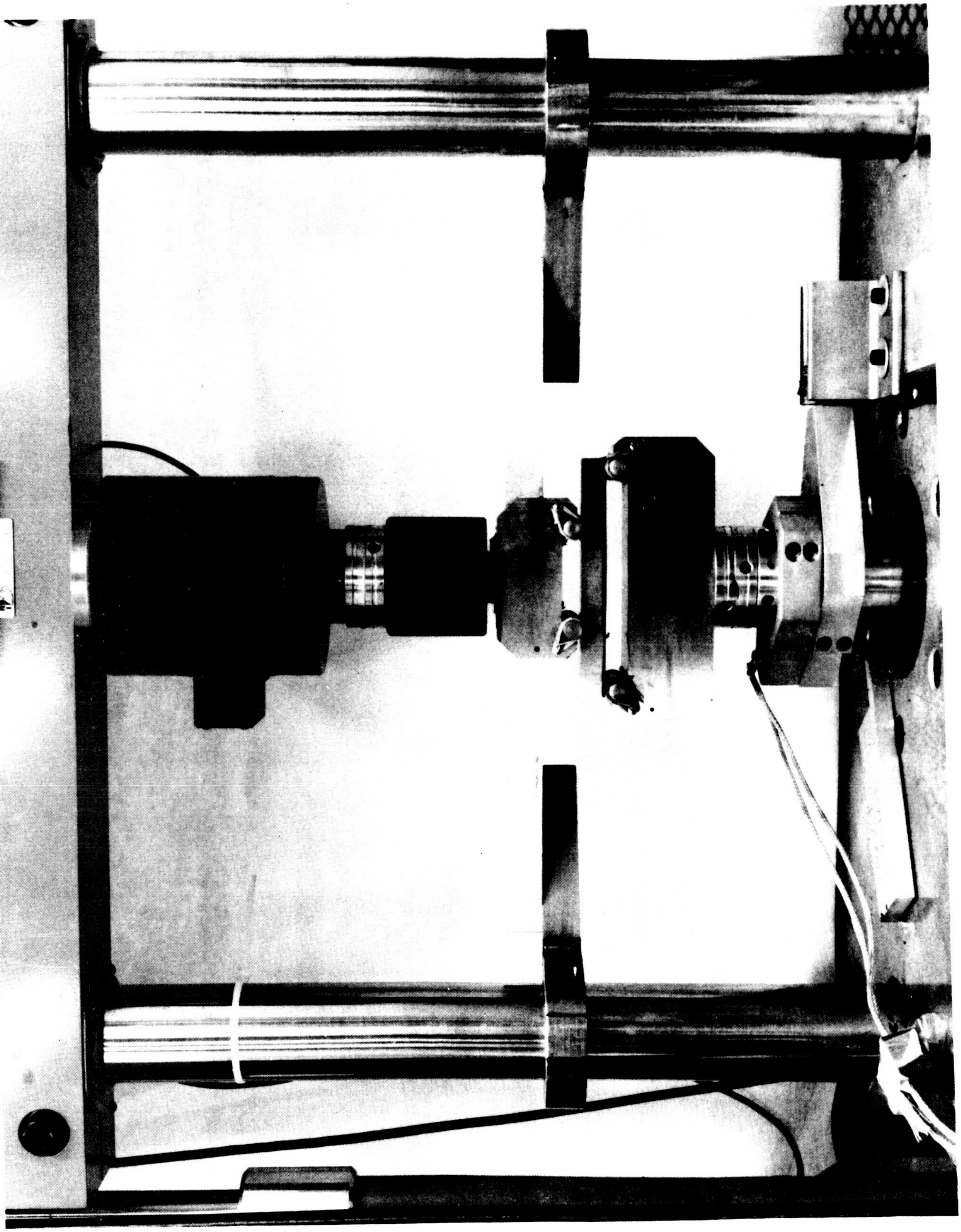

FIGURE 9. FATIGUE TEST MACHINE AS OPERATED WITH SPECIMEN IN PLACE

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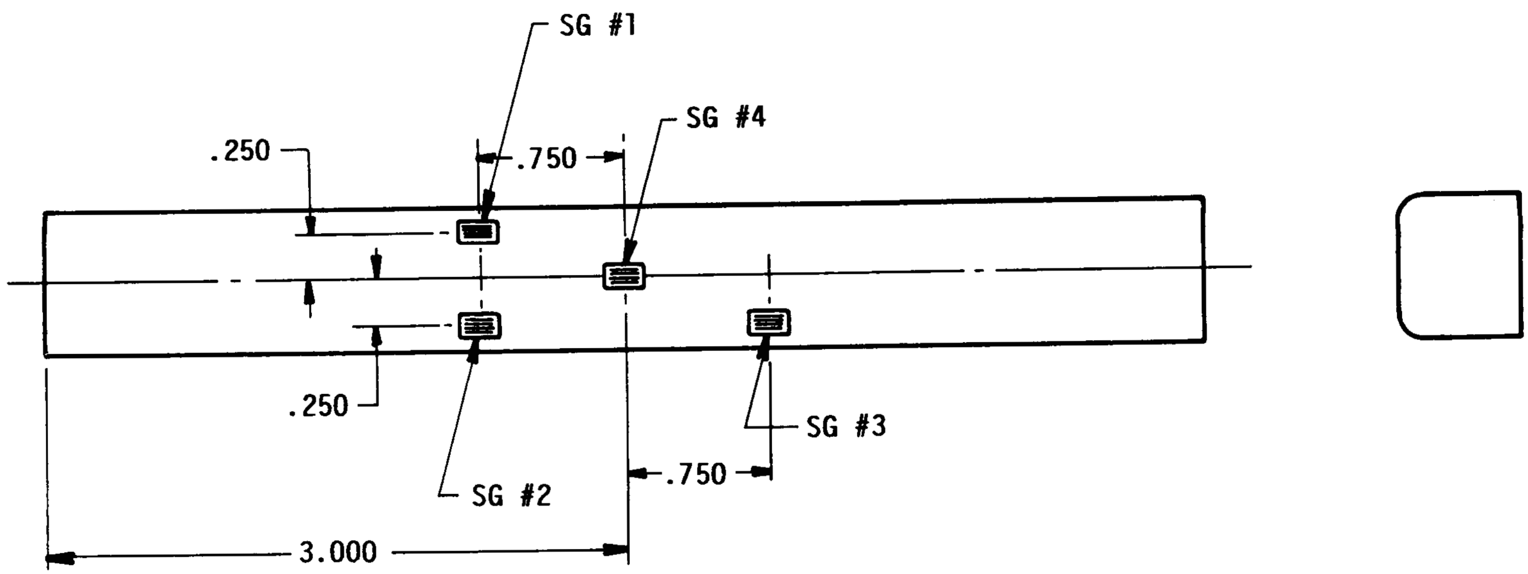



FIGURE 10. STRAIN GAGE PLACEMENT ON FATIGUE CALIBRATION BAR

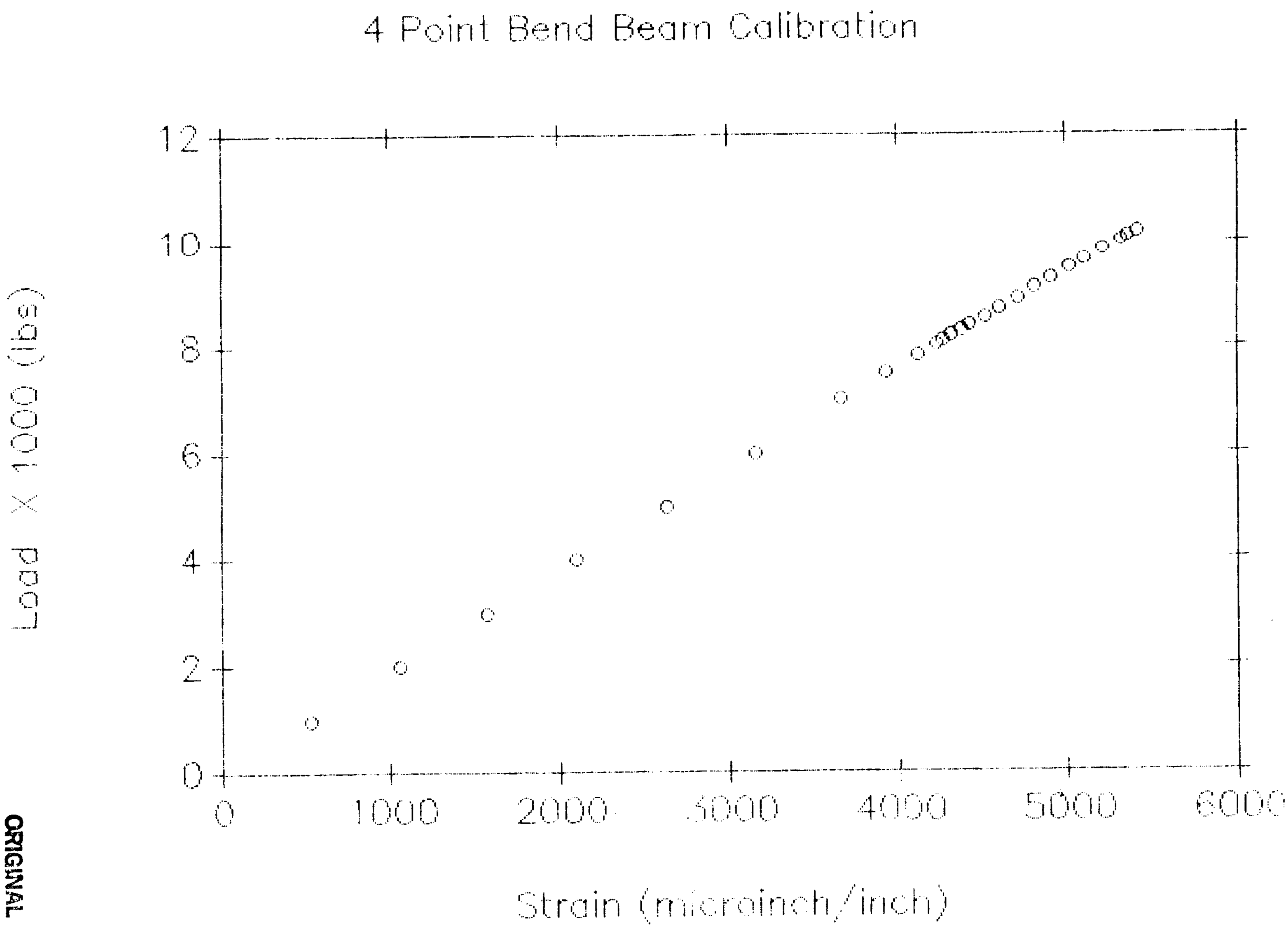
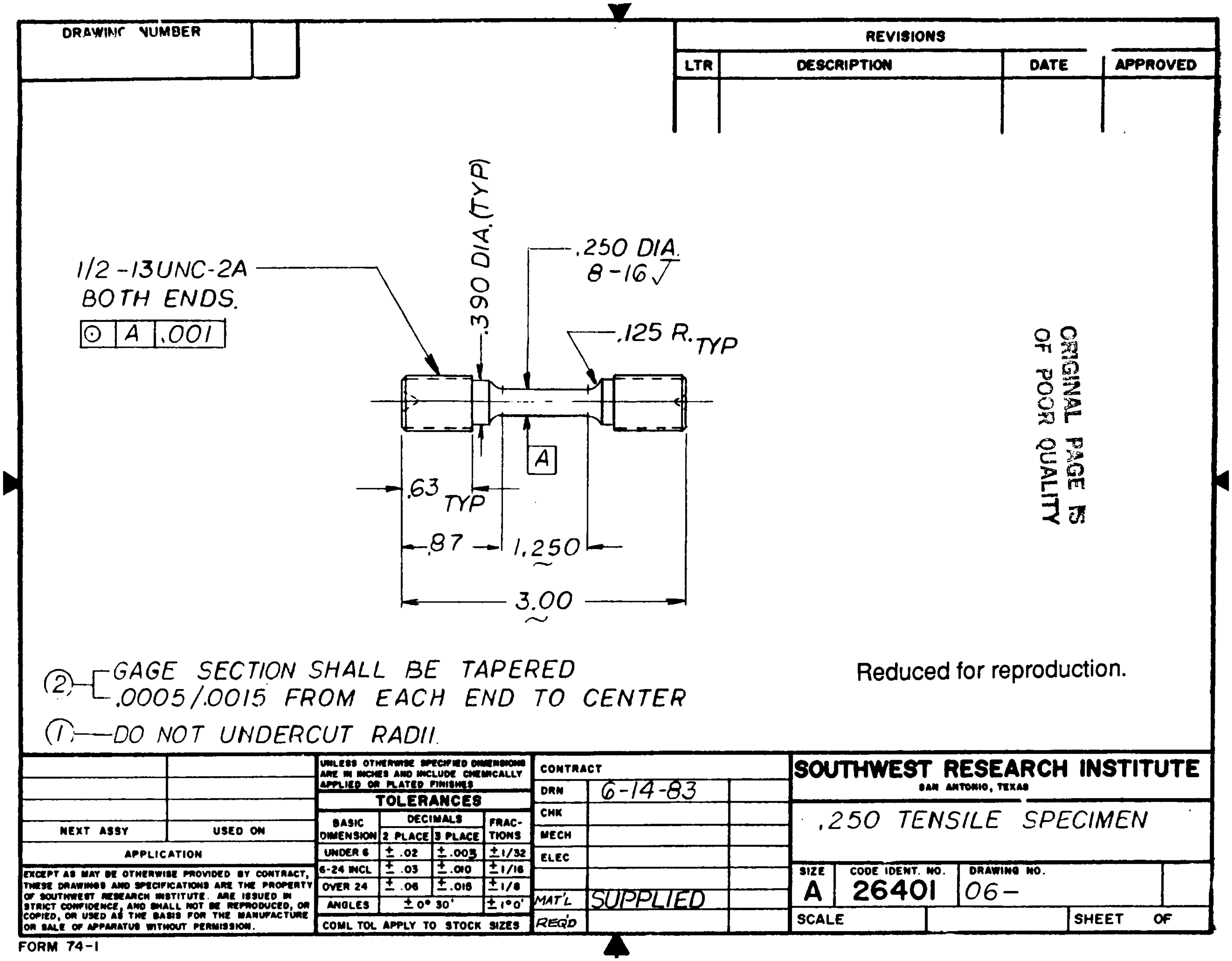



FIGURE 11. TESTED LOAD vs STRAIN RELATIONSHIP FOR FATIGUE TEST



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TOLERANCES
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2 PLACE
3 PLACE
FRACTIONS
UNDER 6 ±.02 ±.005 ±1/32
6-24 INCL ±.03 ±.010 ±1/16
OVER 24 ±.06 ±.015 ±1/8
ANGLES ±0° 30' ±1°0'
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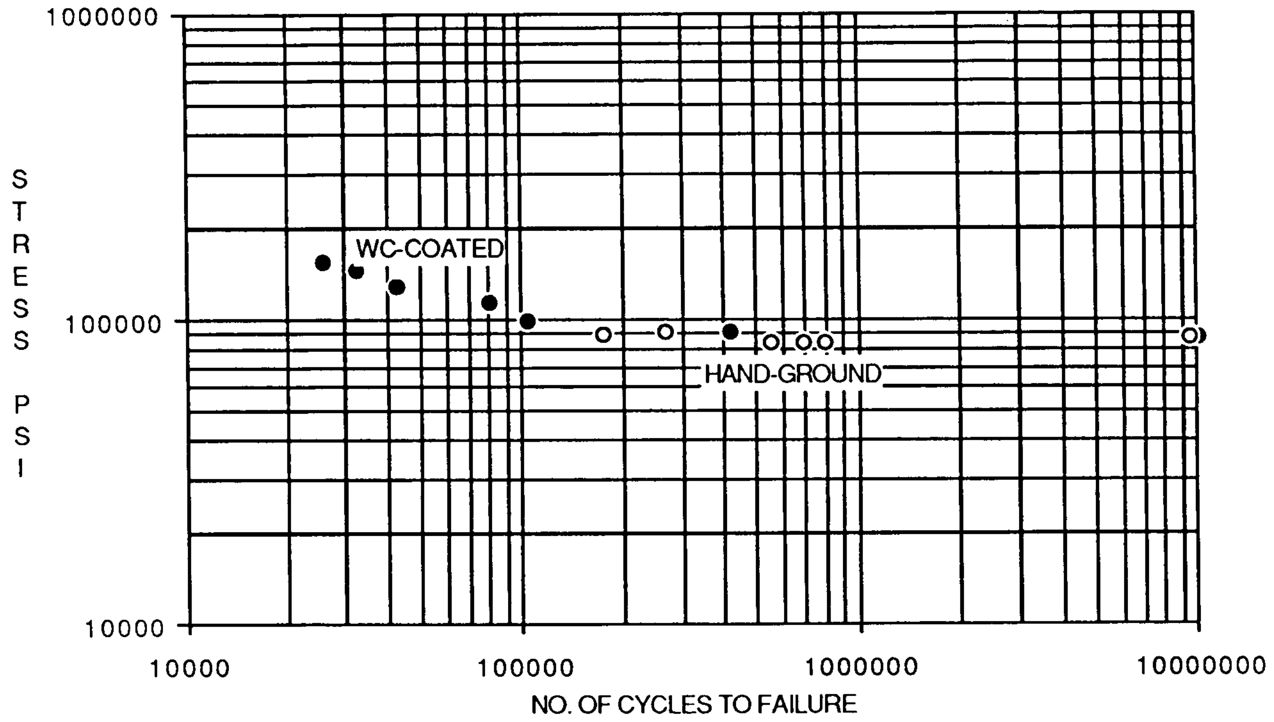
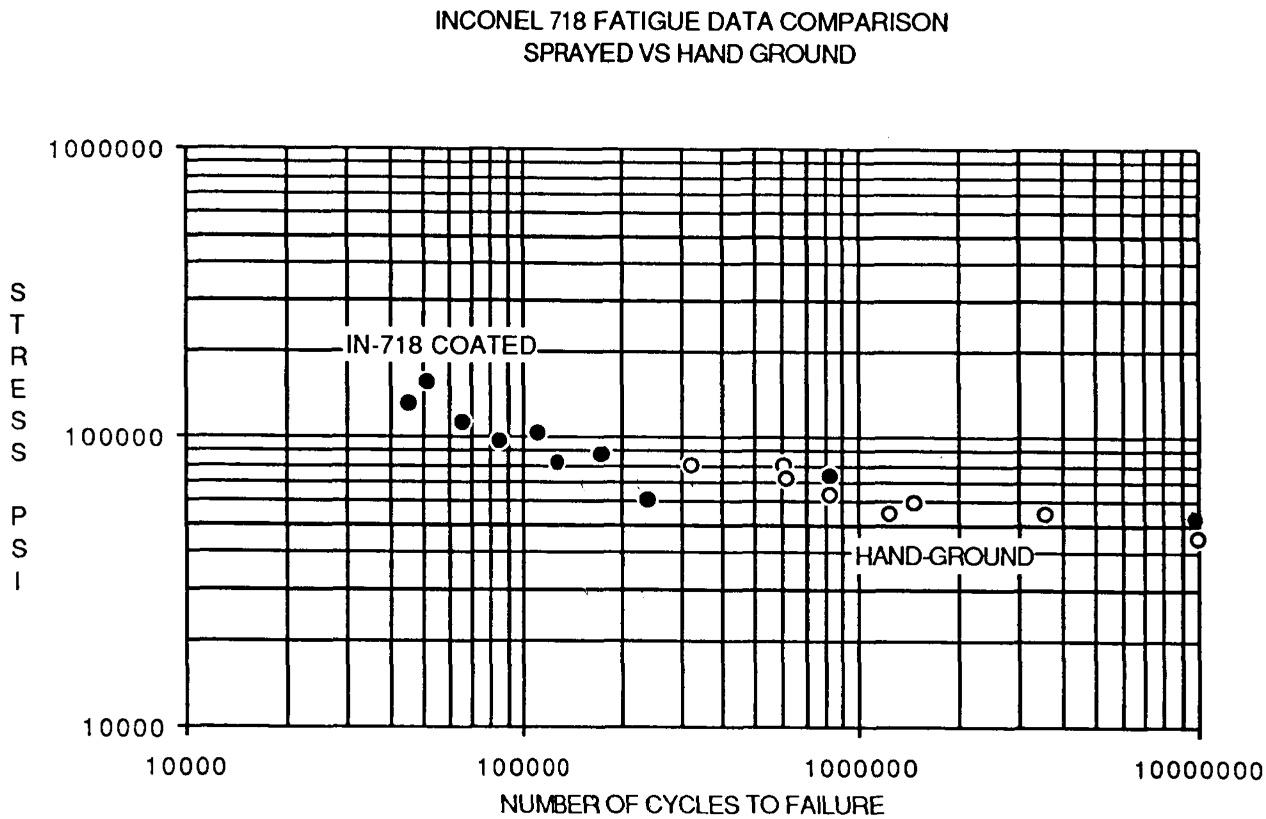
FIGURE 12

17-4 PH STAINLESS FATIGUE DATA COMPARISON
SPRAYED VS HAND GROUND



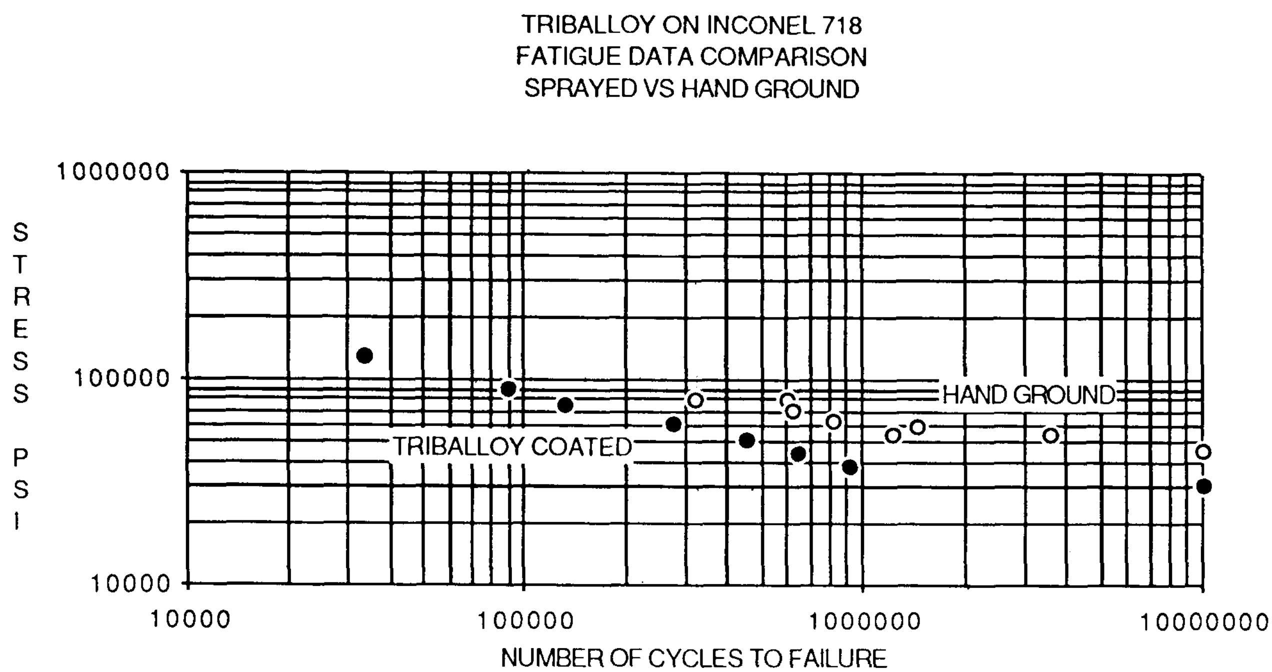

Handground data from Martin, Michael R., *Fatigue Life of Laser Cut Metals*, NASA Contractor Report 179501, Sept. 1986.

**FIGURE 13**




Handground data from Martin, Michael R., *Fatigue Life of Laser Cut Metals*, NASA Contractor Report 179501, Sept. 1986.

FIGURE 14




Handground data from Martin, Michael R., *Fatigue Life of Laser Cut Metals*, NASA Contractor Report 179501, Sept. 1986.

**FIGURE 15**

**Process Data for 17-4PH S/N Curve**
**with FG-112 Tungsten Carbide Deposit**

| Specimen Number | Max. Load (lbs) | Stress (ksi) | Failure Cycles | Coating Rating | Cracking Remarks |
|---|---|---|---|---|---|
| 17-6A | 10000 | 154946 | 25993 | | |
| 17-3 | 9400 | 145144 | 32445 | 3 | Near & 11 to Frac. |
| 17-2 | 8380 | 128560 | 45156 | 4 | 11 to Fracture |
| 17-1 | 7437 | 113268 | 80625 | 2 | Secondary Crack |
| 17-4 | 6500 | 99129 | 104400 | 1 | Small Sec. Crack |
| 17-9 | 5900 | 90067 | 10374500 | 0 | No Visible Cracks |
| 17-7 | 6000 | 91578 | 420290 | 1 | Small Sec. Crack |
| 17-8 | 5800 | 88580 | 10303000 | 2 | Small 11 Cracks |
| 17-6 | 5000 | 76591 | STOPPED | 1 | Small Sec. Crack |
| 17-5 | 4500 | 68880 | 10017200 | 1 | Transverse Crack |

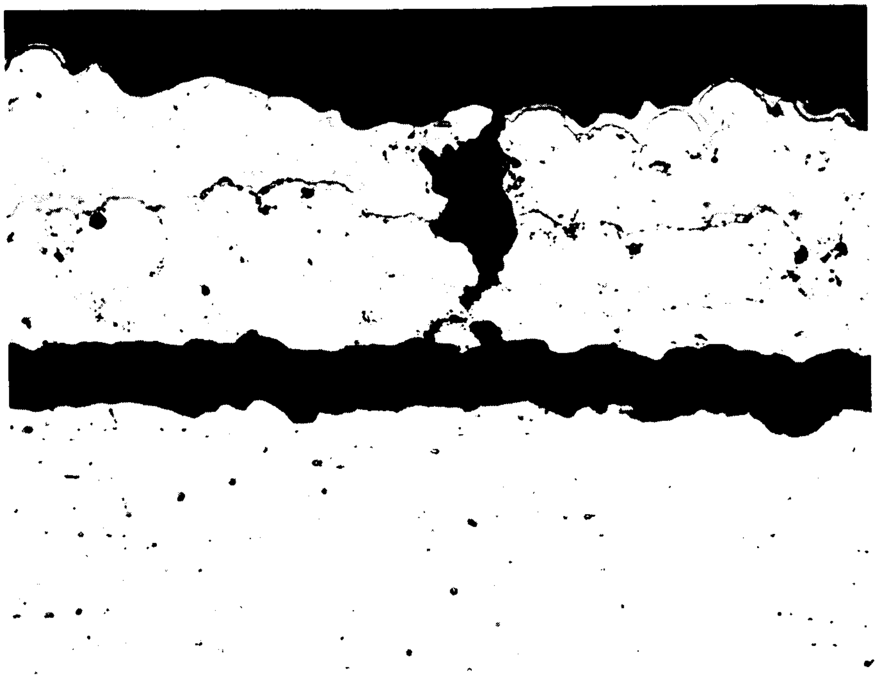
**Process Data for IN-718 S/N Curve**
**with INCONEL Deposit**

| Specimen Number | Max. Load (lbs) | Stress (ksi) | Failure Cycles | Coating Rating | Cracking Remarks |
|---|---|---|---|---|---|
| IN-B-2 | 10000 | 154095 | 51368 | 2 | Near & 11 to frac. |
| IN-B-1 | 8500 | 130265 | 44950 | 1 | Sec. tail crack |
| IN-B-3 | 7400 | 112090 | 82510 | 2 | Sec. 11 to Frac. |
| IN-B-4 | 6800 | 103090 | 108790 | 1 | Sec. 11 to Frac. |
| IN-B-5 | 6400 | 97082 | 85210 | 1 | Sml Sec. tail |
| IN-B-6 | 5800 | 88093 | 174590 | 1 | Sml Sec. tail |
| IN-B-8 | 5400 | 82132 | 127500 | 1 | Trns. Not Failed |
| IN-B-7 | 4800 | 73102 | 826300 | 0 | None Visible |
| IN-B-9 | 4500 | 68501 | 239200 | 1 | Sml. Sec. 11 |
| IN-B-10 | 3300 | 50237 | 10240000 | 0 | Sml. Not Failed |

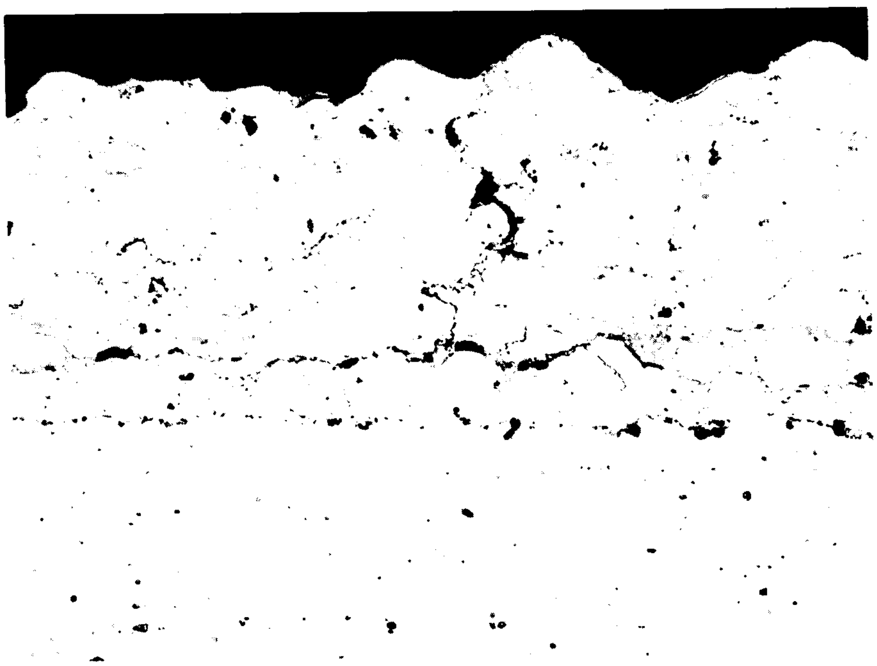
**Process Data for IN-718T S/N Curve**
**with T800 PLASMA DEPOSIT**

| Specimen Number | Max. Load (lbs) | Stress (ksi) | Failure Cycles | Coating Rating | Cracking Remarks |
|---|---|---|---|---|---|
| IN-T-1 | 8500 | 130265 | 34100 | 5 | Near & 11 to frac. |
| IN-T-2 | 6000 | 91074 | 89170 | 5 | Near & 11 to frac. |
| IN-T-3 | 5000 | 76170 | 132800 | 5 | Mud Cracked Not Failed |
| IN-T-4 | 4000 | 60832 | 275700 | 3 | Slight. Sec. at Frac. |
| IN-T-5 | 3300 | 50237 | 453200 | 4 | 3/16 from & 11 to Frac. |
| IN-T-6 | 2900 | 44174 | 650400 | 4 | 3/16 from & 11 to Frac. |
| IN-T-7 | 2500 | 38085 | 923500 | 1 | No Sec.Visible, 1 chip |
| IN-T-8 | 2000 | 30474 | | 0 | None Visible |

**FIGURE 16**



31059 (a) 100X



31060 (b) 100X

**FIGURE 17. PHOTOMICROGRAPH FROM A LONGITUDINAL SECTION OF SPECIMEN NO. INB-8. LOCATION AT SURFACE CRACK SHOWN IN FIGURE 25.**

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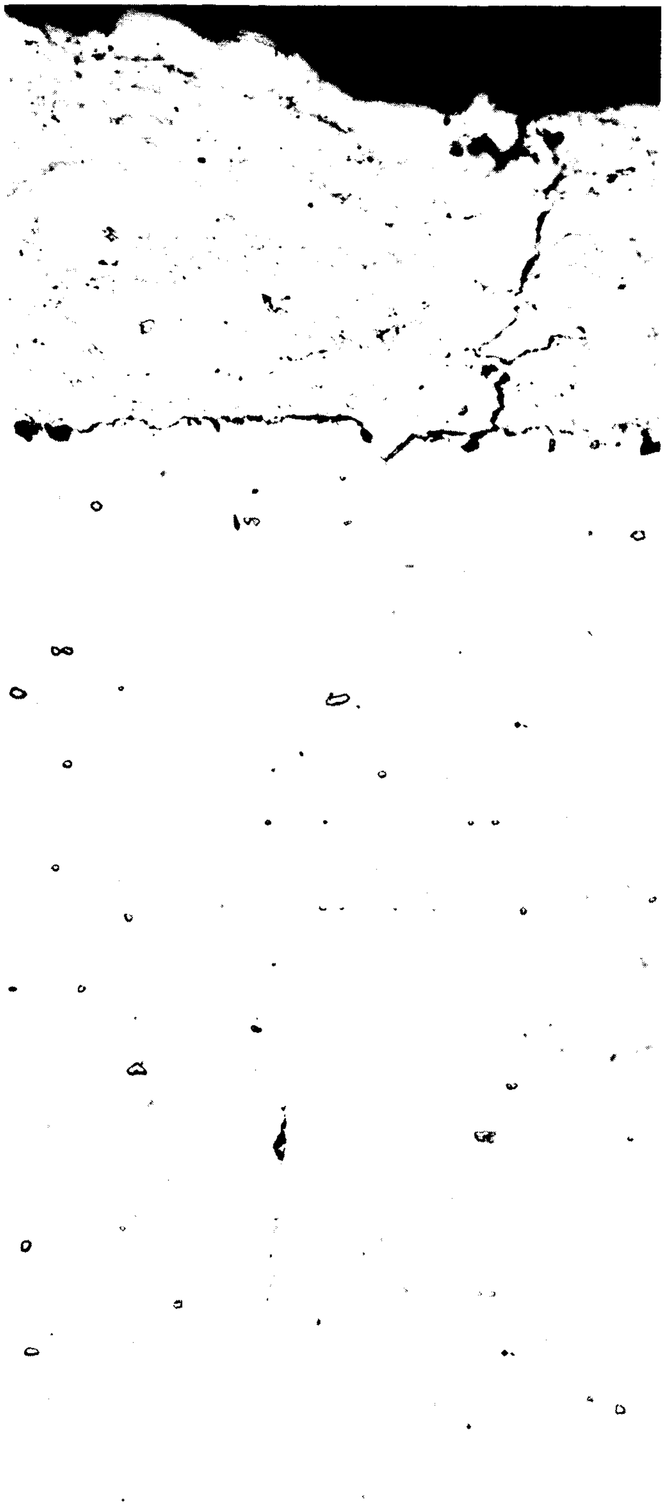
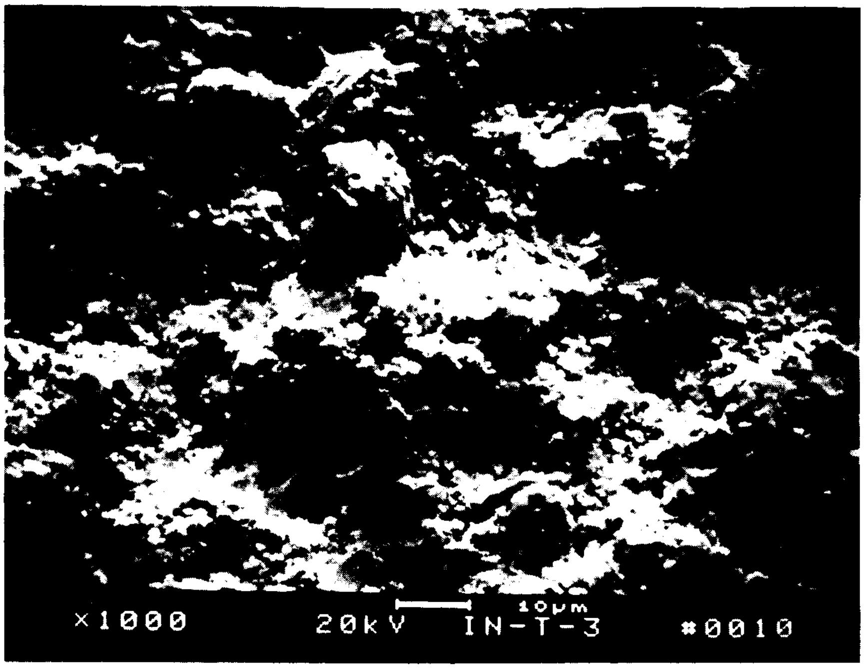


31097-98 200X

FIGURE 18. PHOTOMICROGRAPH FROM LONGITUDINAL SECTION OF SPECIMEN INB-8. LOCATION AT SUBSTRATE CRACK APPROXIMATELY 1/2 INCH FROM LOAD POINT.

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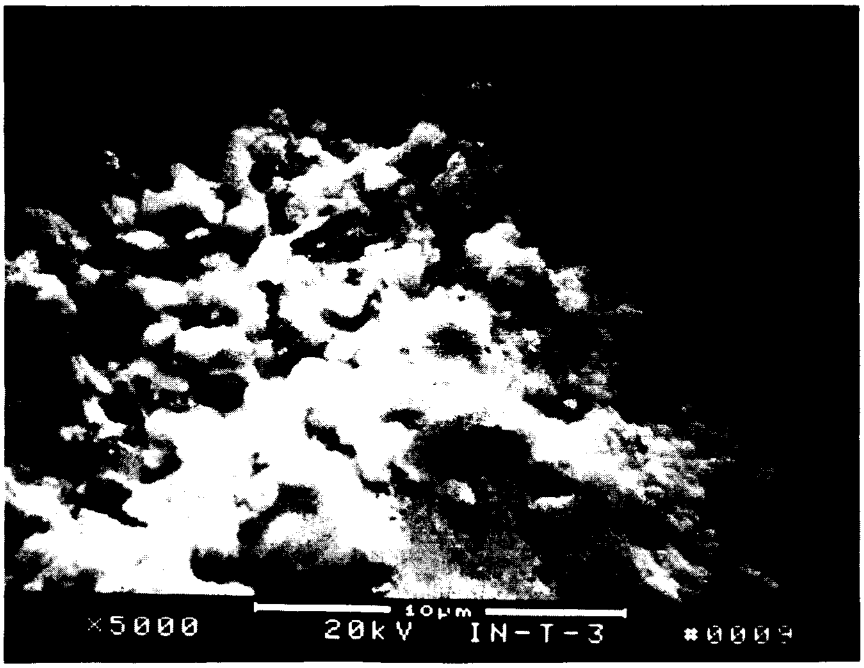


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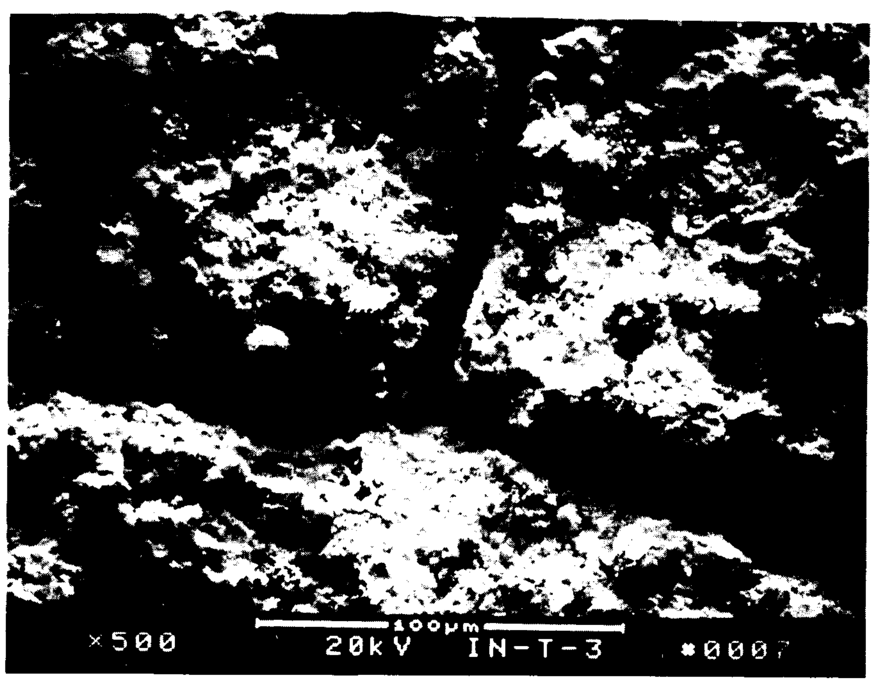
FIGURE 19. TYPICAL FG-T800 SPRAY DEPOSIT SURFACE AFTER FATIGUE TESTING SPECIMEN NO. INT-3

30983 (a) 10X

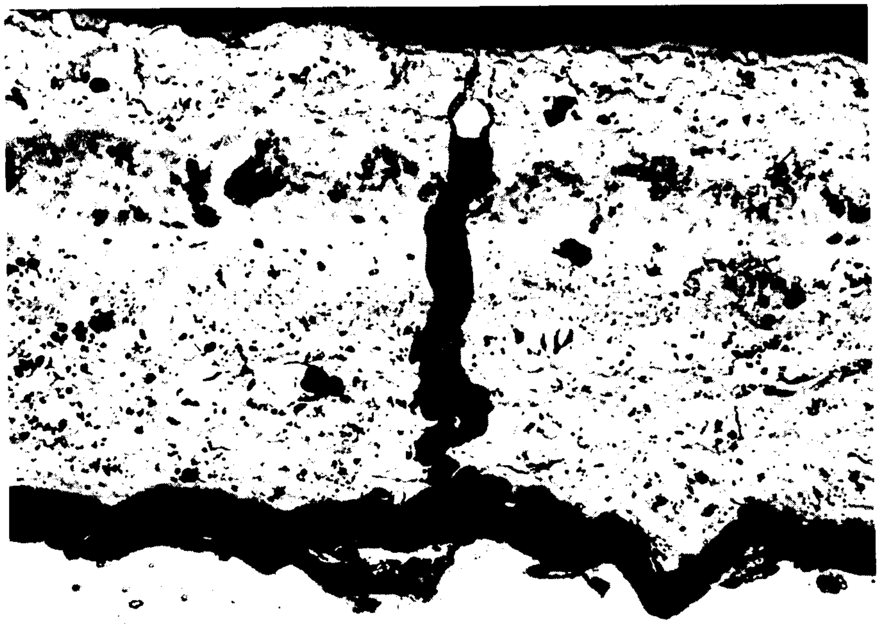



30969 (b)

FIGURE 20. NETWORK CRACKING OF TRIBALLOY SPRAY DEPOSIT ON THE CENTER SURFACE AREA OF SPECIMEN INT-3 AFTER 132,800 CYCLES AT 5000 LBS. LOAD

(a)

31057 200X



(b)

31054 200X

**FIGURE 21. PHOTOMICROGRAPHS FROM LONGITUDINAL SECTIONS OF SPECIMEN NO. INT-3 OF THE DEPOSIT CRACKING SHOWN IN FIGURE 20**

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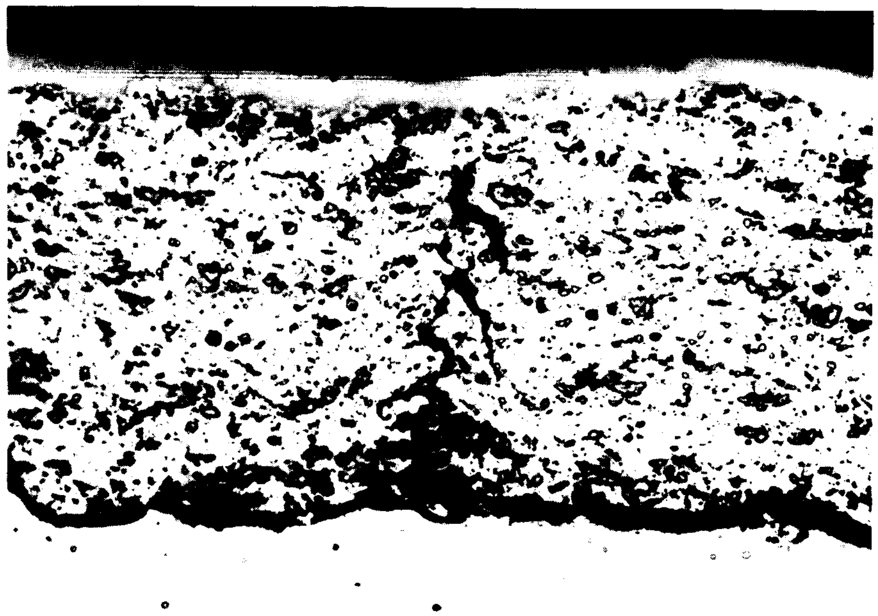
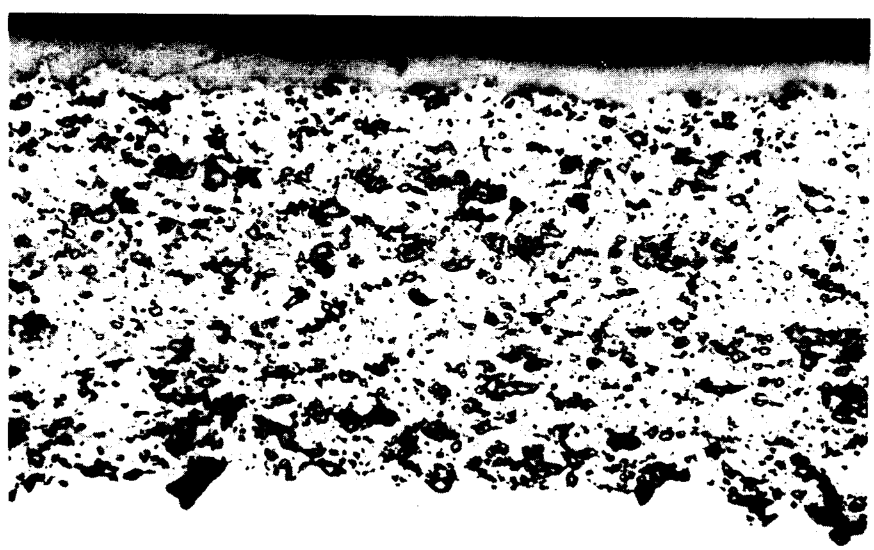


31130 200X

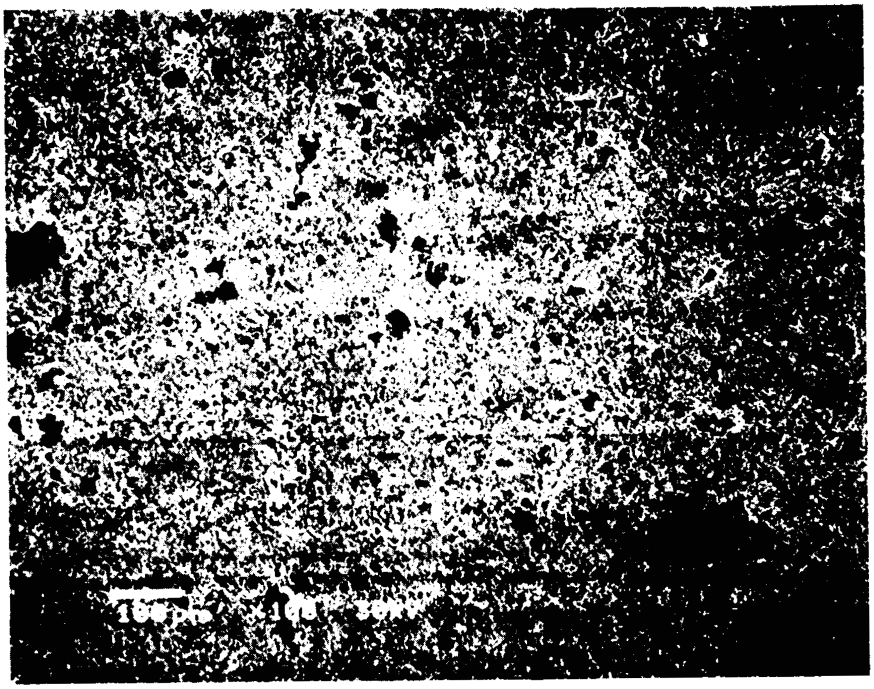
(a) Location of deposit crack.



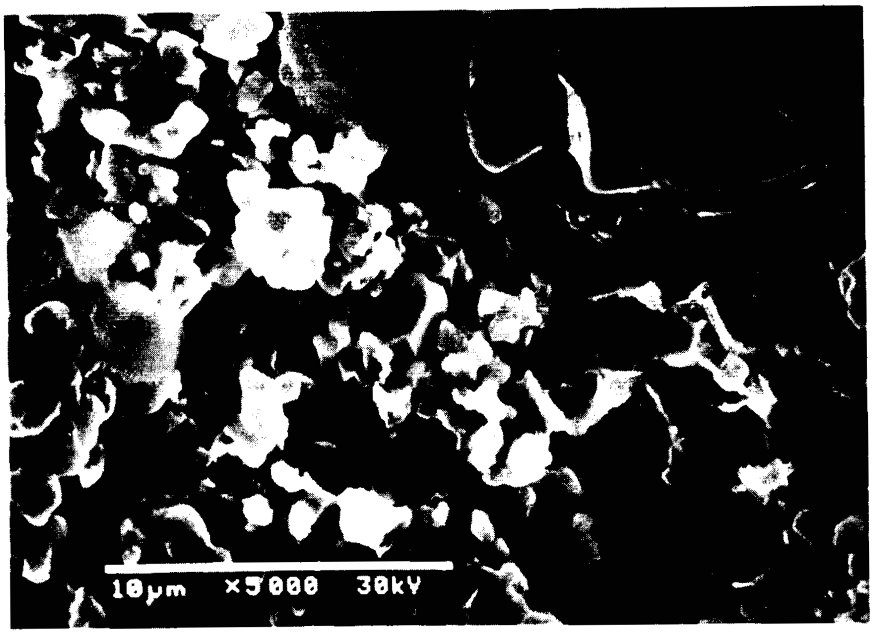
31131 200X

(b) Location of typical intact deposit.

**FIGURE 22. PHOTOMICROGRAPHS FROM LONGITUDINAL SECTIONS OF SPECIMEN NO. 17-5**



29676 (a) 100X




29678 (b) 5000X

FIGURE 23. TYPICAL FG112 SPRAY SURFACE AFTER FATIGUE TESTING SPECIMEN NO. 17-1

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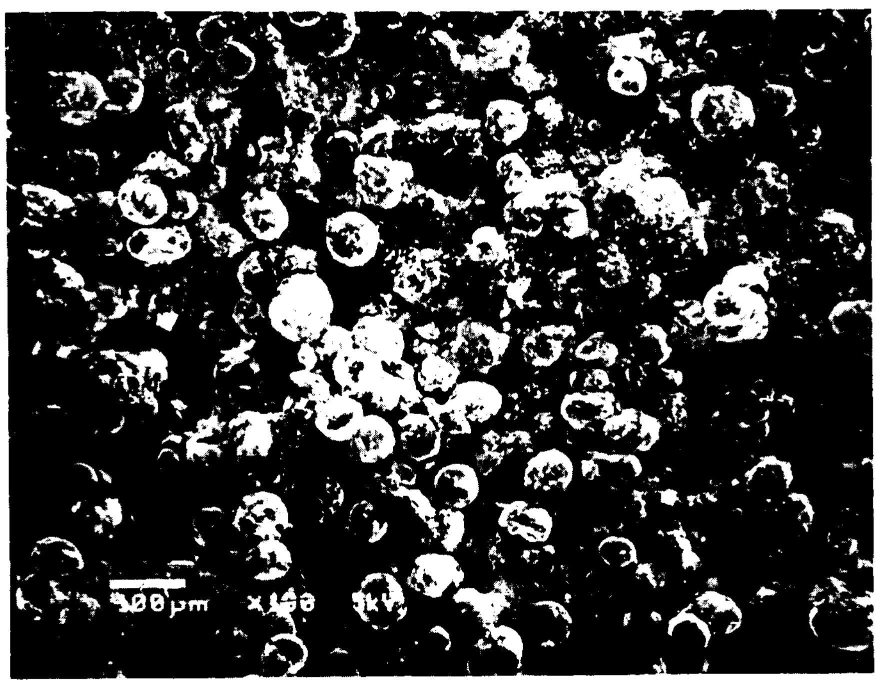
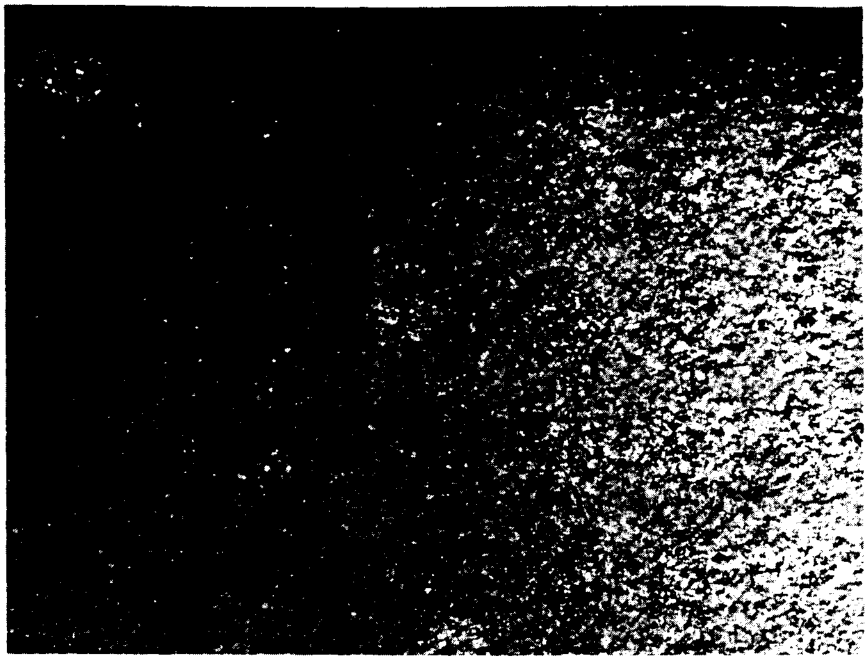


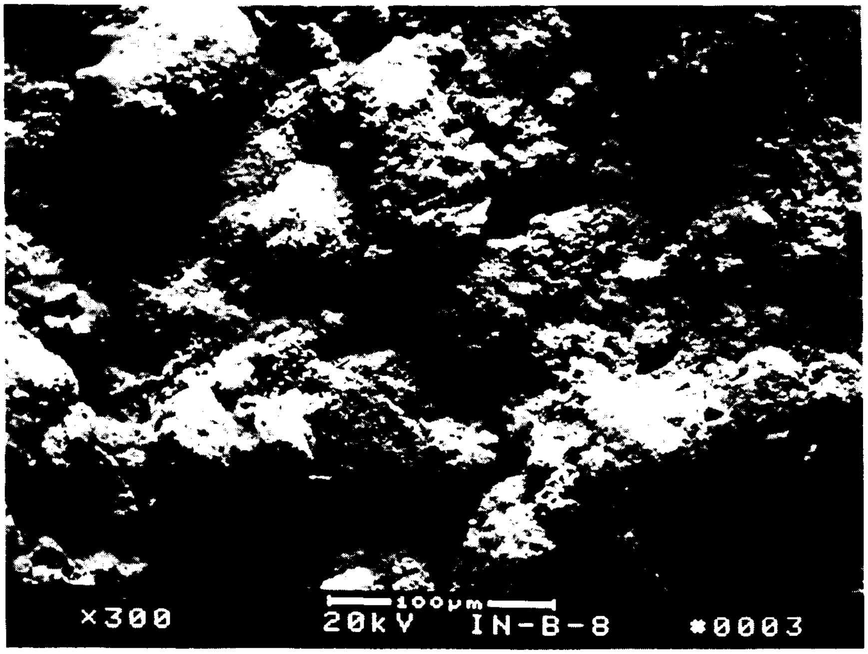

29674

FIGURE 24. TYPICAL COATING SURFACE FOR FATIGUE SPECIMEN INB-1 INCONEL SPRAY DEPOSIT



(a)

30984 10X




(b)

30975

FIGURE 25. DEPOSIT CRACK ON FATIGUE SPECIMEN INB-8 SURFACE NEAR TO CENTER OF BAR

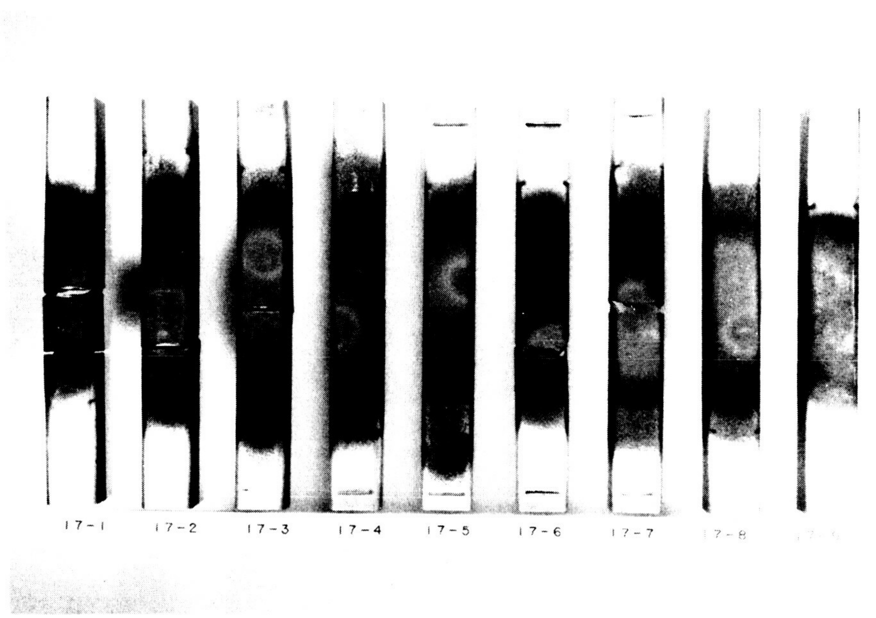



**FIGURE 26. FATIGUE SPECIMEN NOS. 17-1 THROUGH 9 SHOWN WITH SEM SPECIMENS CUT FROM 17-1 AND 17-6**

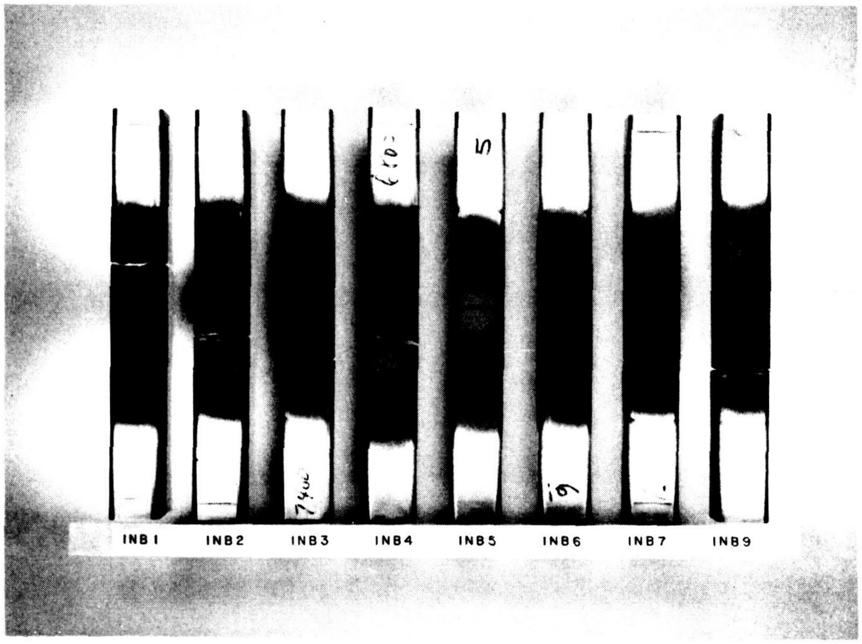



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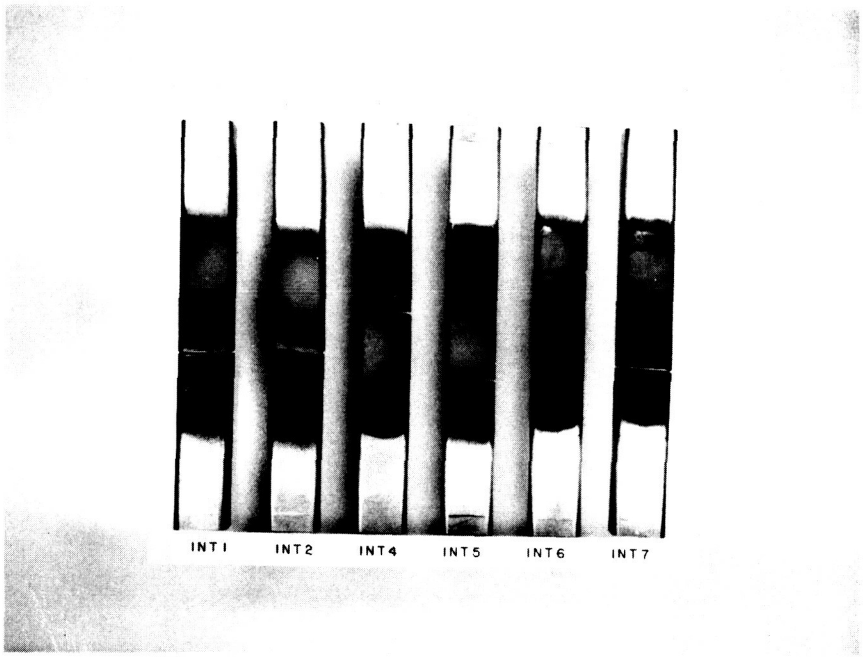
FIGURE 27. FATIGUE SPECIMEN NOS. INB-1 THROUGH 10. SAMPLES USED FOR METALLOGRAPHY ARE NOT SHOWN.




31078 1/3 X

FIGURE 28. FATIGUE SPECIMEN NOS. INT-1 THROUGH 8. SAMPLES USED FOR METALLOGRAPHY ARE NOT SHOWN.

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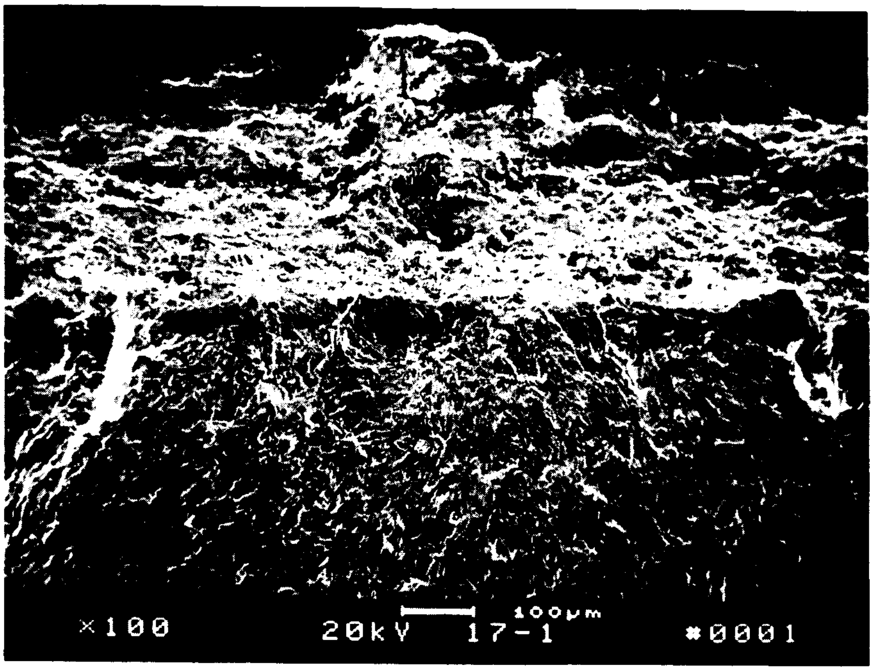



← Deposit

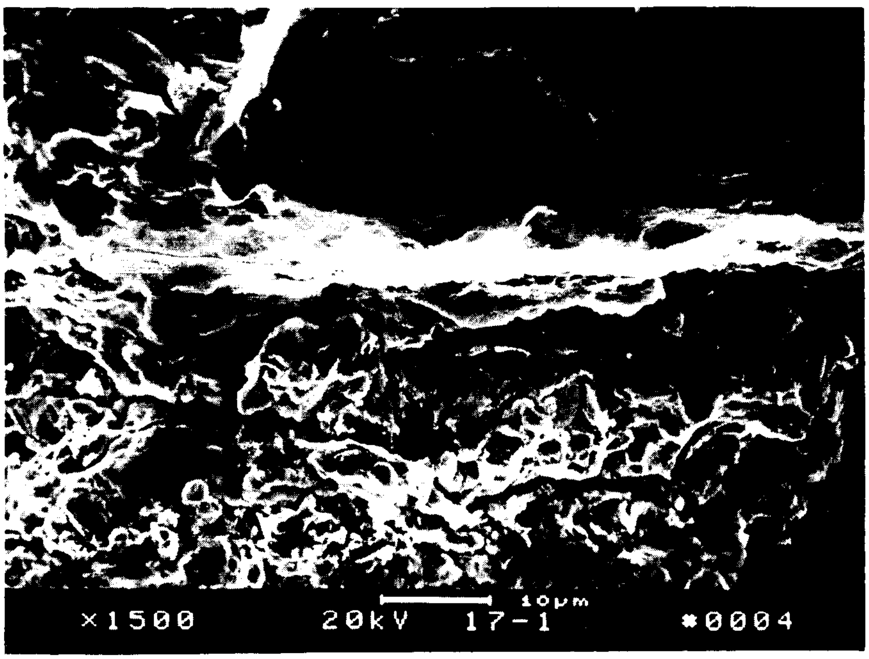
← Substrate

31005

(a)

Substrate →

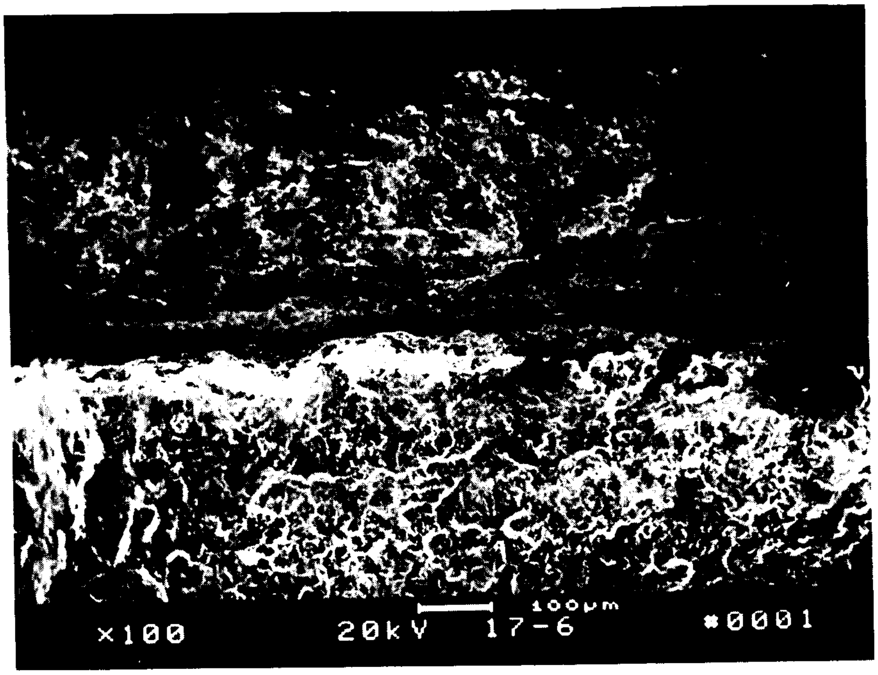
Deposit →



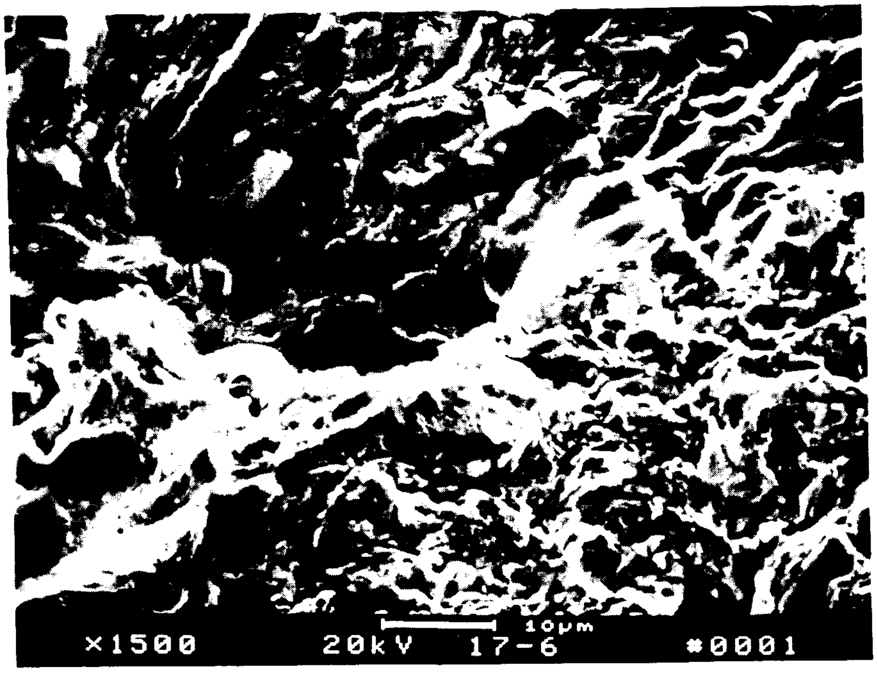

31072

(b)

FIGURE 29. SEM FRACTOGRAPHS FROM FATIGUE SPECIMEN NO. 17-1. DEPOSIT: FG112 TUNGSTEN CARBIDE ALLOY - SUBSTRATE: 17-4PH STAINLESS STEEL.




31002




31071

FIGURE 30. SEM FRACTOGRAPHS FROM FATIGUE SPECIMEN NO. 17-6.
DEPOSIT: FG112 TUNGSTEN CARBIDE ALLOY -
SUBSTRATE: 17-4PH STAINLESS STEEL.

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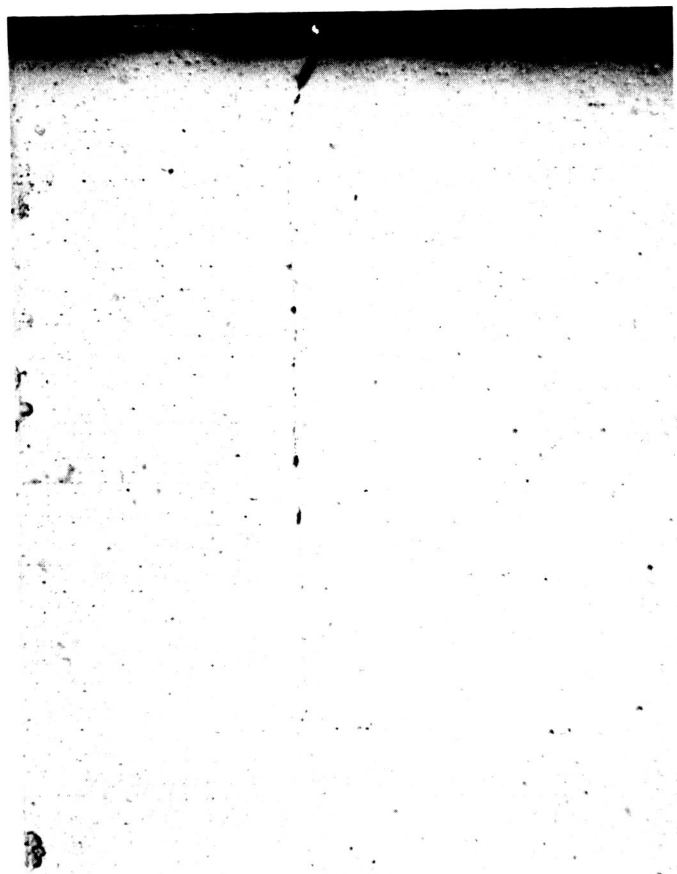
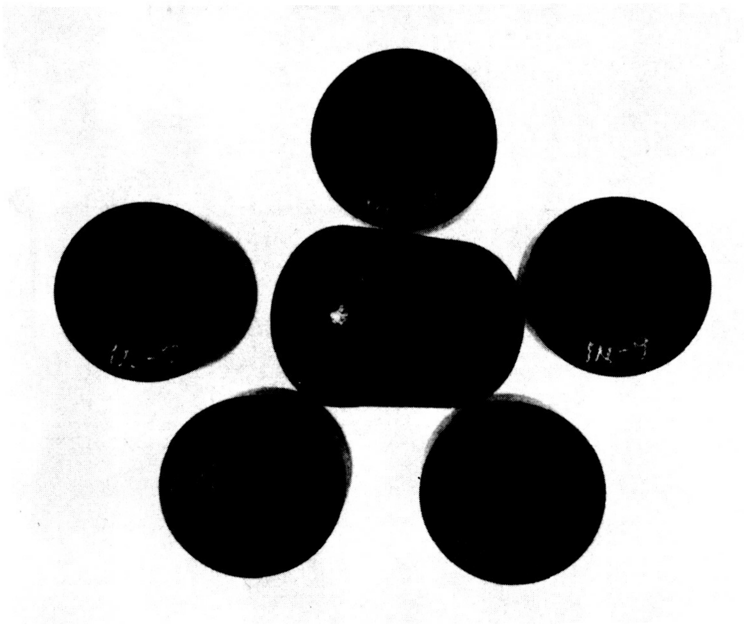


31087 16X

(a)

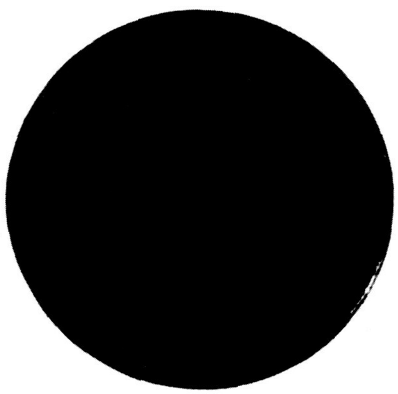
FIGURE 31. PHOTOMICROGRAPH FROM LONGITUDINAL SECTION OF SPECIMEN NO INT-3. LOCATION AT SUBSTRATE CRACK APPROXIMATELY 1/2 INCH FROM LOAD POINT.

BOND TEST SPECIMENS



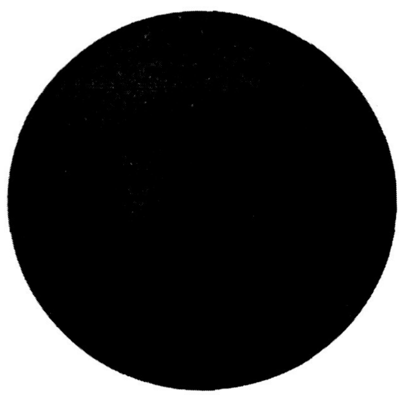
29585 1X

FIGURE 32(a). BOND TEST SPECIMENS FOR INCONEL 718 MATERIAL



29670 2X

FIGURE 32(b). CLOSE-UP OF IN-1 COATING SPECIMEN



29668 2X

FIGURE 32(c). AS DEPOSITED TUNGSTEN CARBIDE ALLOY ON SPECIMEN 17-21

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FIGURE 33. FARE GUN AND ROTATING FIXTURING SETUP FOR SPRAYING BOND TEST SPECIMENS.

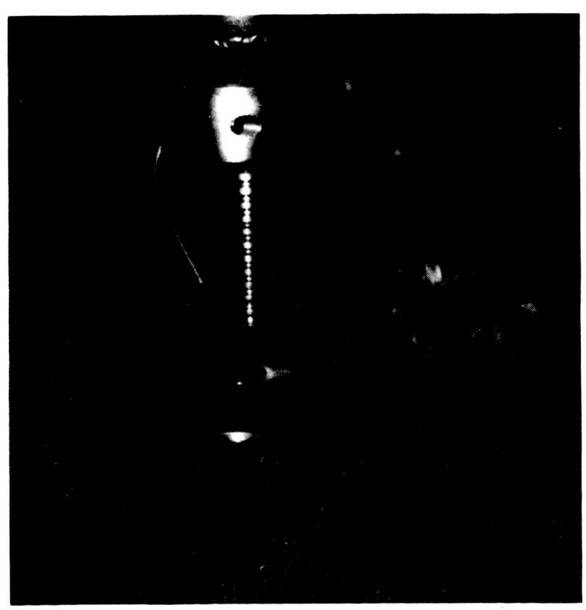

FIGURE 34. ALIGNMENT OF THE GUN BARREL TO 3/16 INCH FROM THE SPECIMEN ID GAVE THE MOST EVEN LAYER DEPOSIT WITH THE TUNGSTEN CARBIDE FG112 ALLOW. NOTE THE COPPER TUBE PROVIDES AIR COOLING OF THE SPECIMEN.

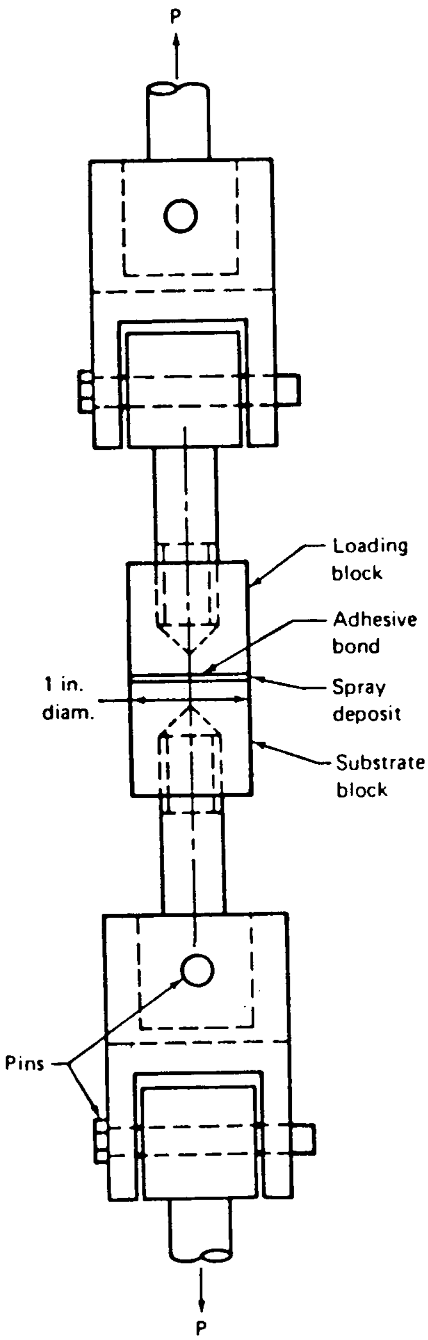


FIGURE 35. BOND STRENGTH TEST ARRANGEMENT

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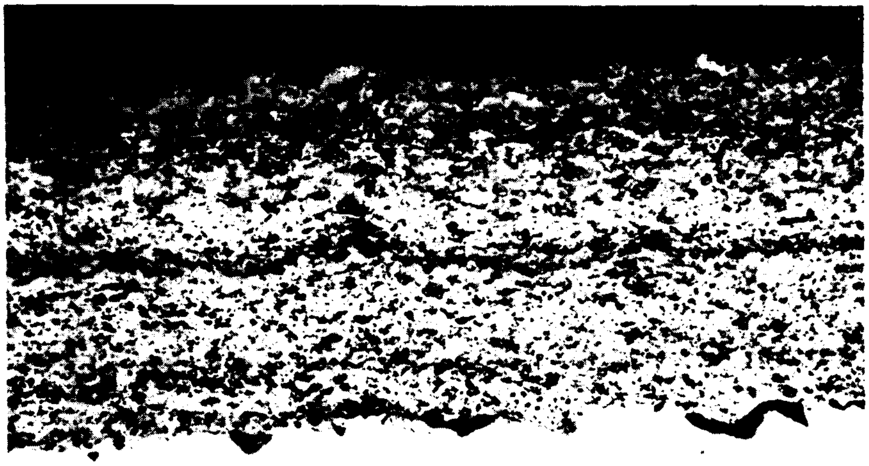
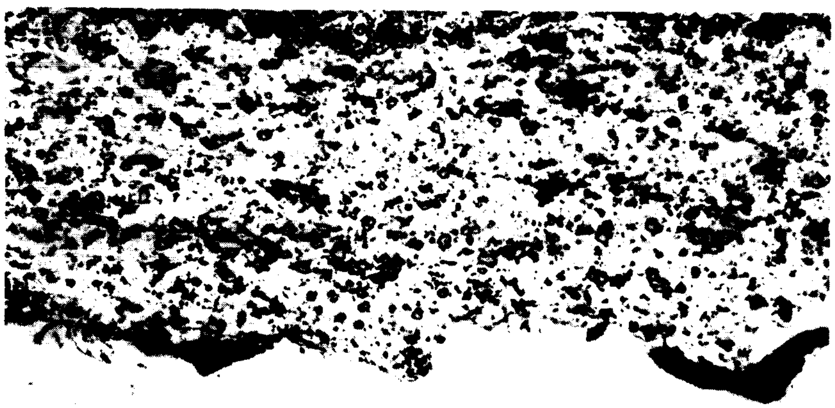


29719 100X

FIGURE 36. CROSS SECTION OF AS-DEPOSITED TUNGSTEN CARBIDE ALLOY FG 112. NOTE THE UNFILLED DEPRESSIONS OF ROUGHENED SUBSTRATE SURFACE.

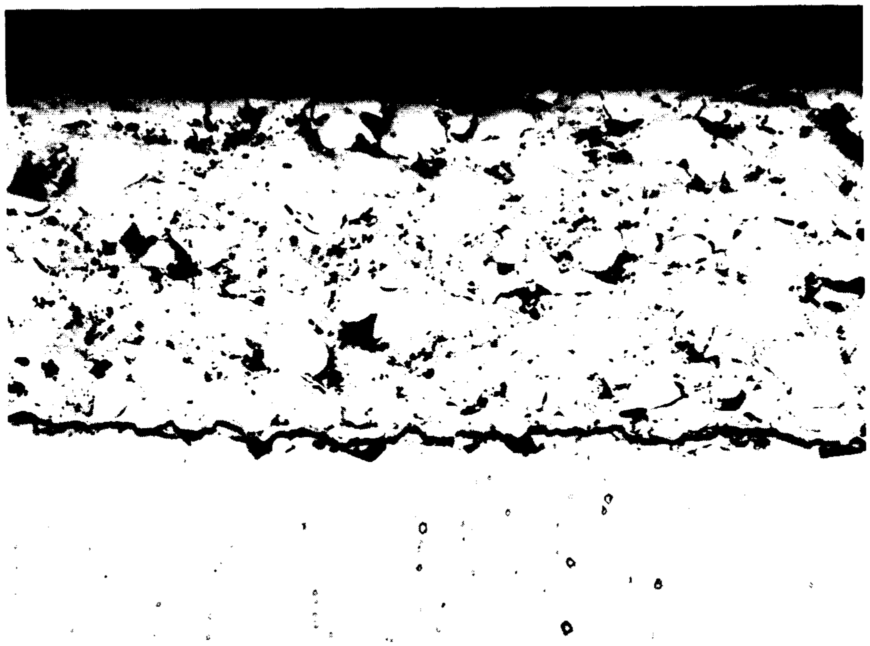


29720 200X

FIGURE 37. TUNGSTEN CARBIDE ON 17-4PH. NOTE THE SMALL AMOUNT OF COATING POROSITY.

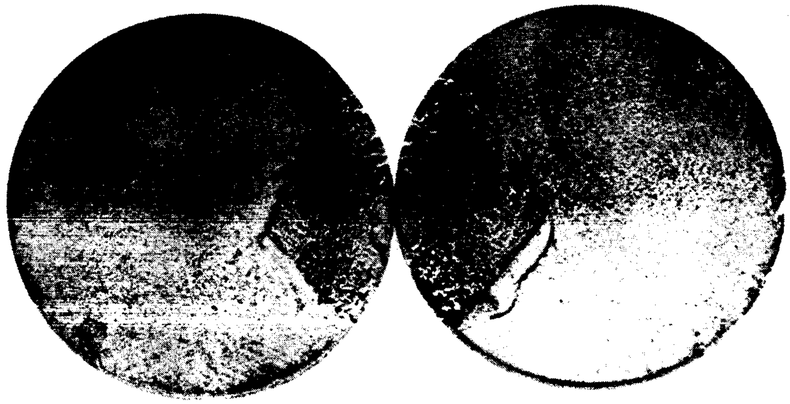
29721 500X

FIGURE 38. TUNGSTEN CARBIDE ON 17-4PH. NOTE THE INTIMATE BOND THAT IS FORMED WITH THE SUBSTRATE.



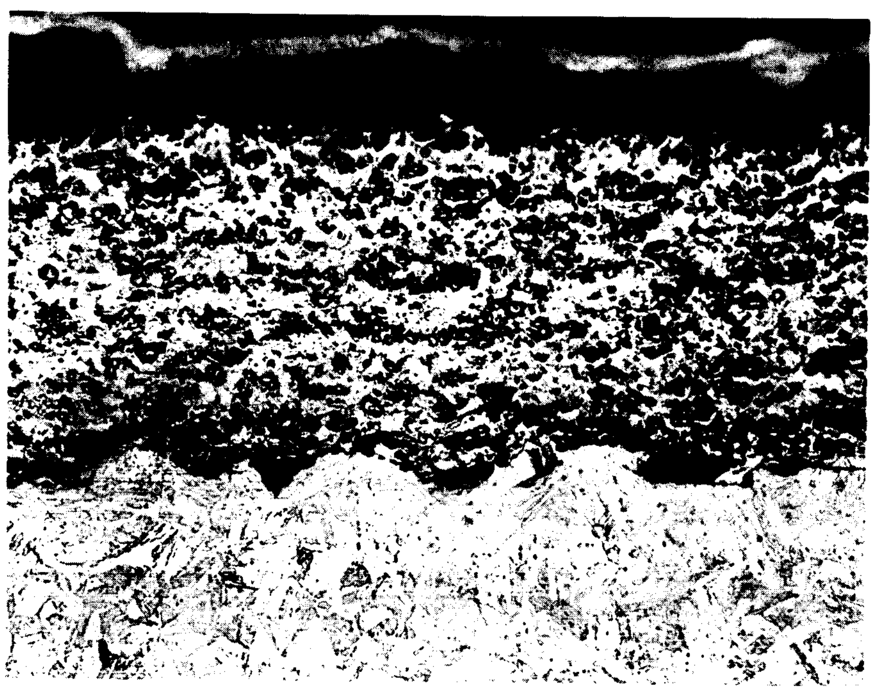
29682 100X

FIGURE 39. CROSS SECTION OF AS-SPRAYED INCONEL ALLOY 718. TRIAL SHOWING POROSITY AND LACK OF BONDING BETWEEN COATING AND SUBSTRATE.



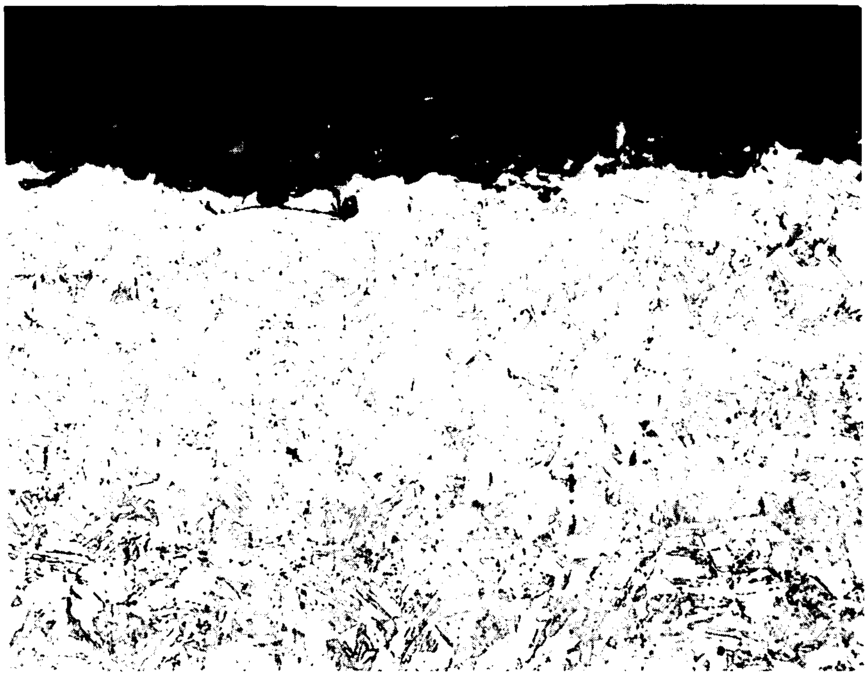
30464 2X

FIGURE 40. BOND TEST SPECIMEN NO. 17-9 WITH FG 112 SPRAY DEPOSITED TUNGSTEN CARBIDE ALLOY ON TYPE 17-4PH STAINLESS STEEL SUBSTRATE



30630 200X

FIGURE 41. SPECIMEN 17-9. CROSS SECTION OF AN AREA WITH ADHERENT TUNGSTEN CARBIDE ALLOY FG 112 FLAME SPRAY DEPOSIT. ELECTROLESS NICKEL PLATED. $FeCl_3$ ETCHANT.



30628 200X

FIGURE 42. SPECIMEN NO. 17-9. CROSS SECTION WHERE COATING HAS MOSTLY PULLED OFF EXCEPT FOR VALLEYS IN THE PRE-SPRAY GRITTED SURFACE. ELECTROLESS NICKEL PLATED $FeCl_3$ ETCHANT.

30631 500X

FIGURE 43. SPECIMEN 17-9. AREA OF ADHERENT FG 112 SPRAY DEPOSIT SHOWN IN FIGURE 41. ELECTROLESS NICKEL PLATED. $FeCl_3$ ETCHANT.

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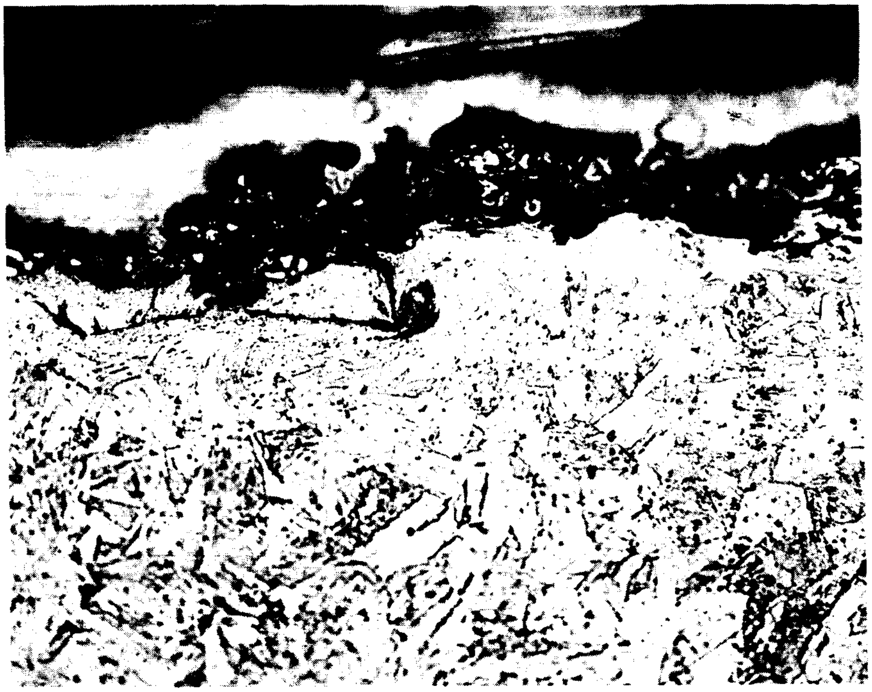
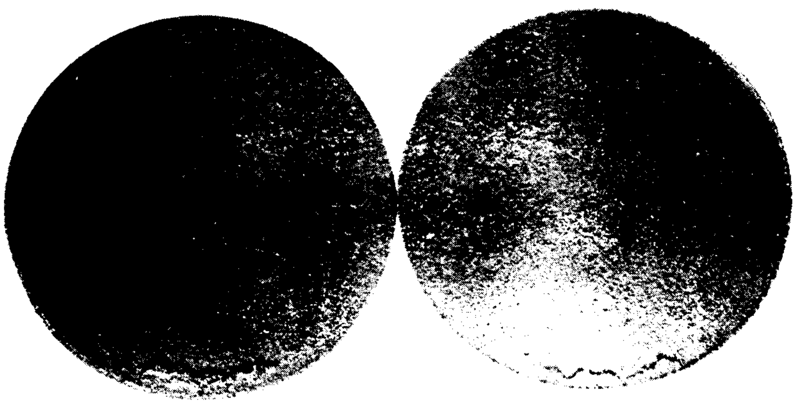


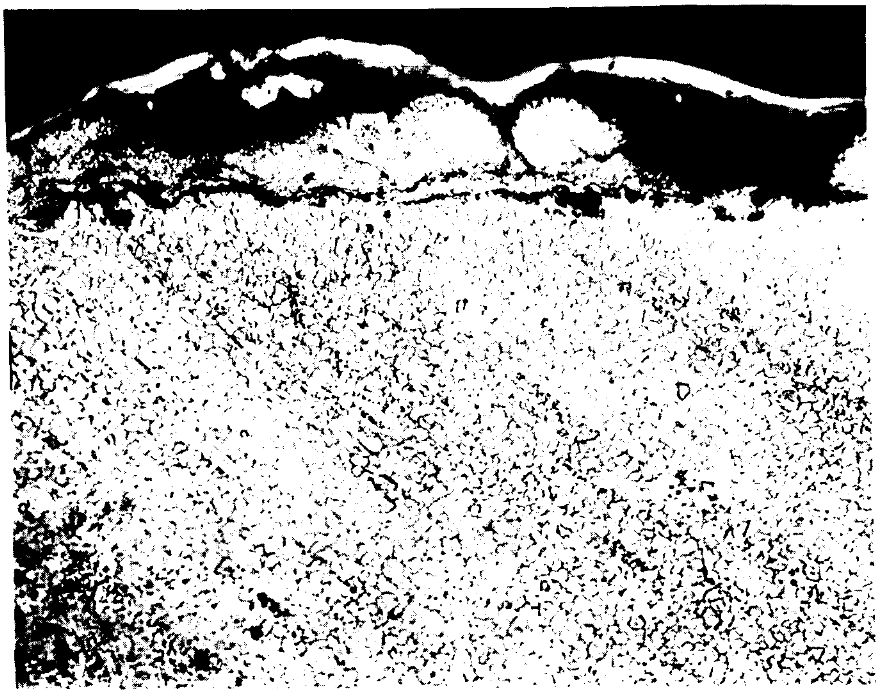
30629 500X

FIGURE 44. SPECIMEN 17-9. AREA OF NONADHERENT SPRAY DEPOSIT SHOWN IN FIGURE 42. ELECTROLESS NICKEL PLATED. $FeCl_3$ ETCHANT.



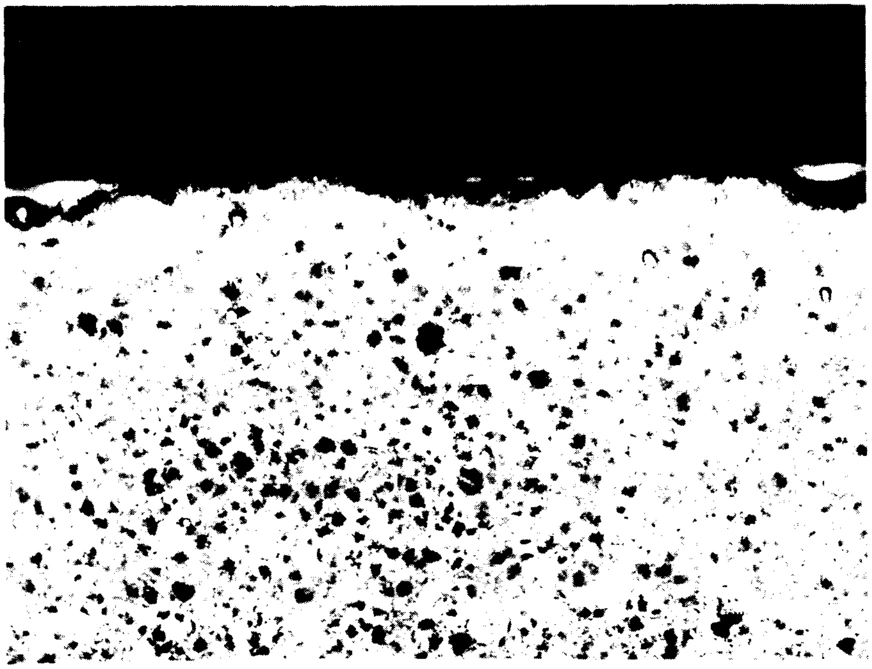
30465 2X

FIGURE 45. SPECIMEN NO. IN-6 WITH FG 718 INCONEL SPRAY DEPOSITED ON TYPE 718 INCONEL SUBSTRATE



30634 200X

FIGURE 46. SPECIMEN IN-6. CROSS SECTION OF AN AREA WITH ADHERENT INCONEL 718 ALLOY FLAME SPRAY DEPOSIT. ELECTROLESS NICKEL PLATED. $FeCl_3$ ETCHANT.

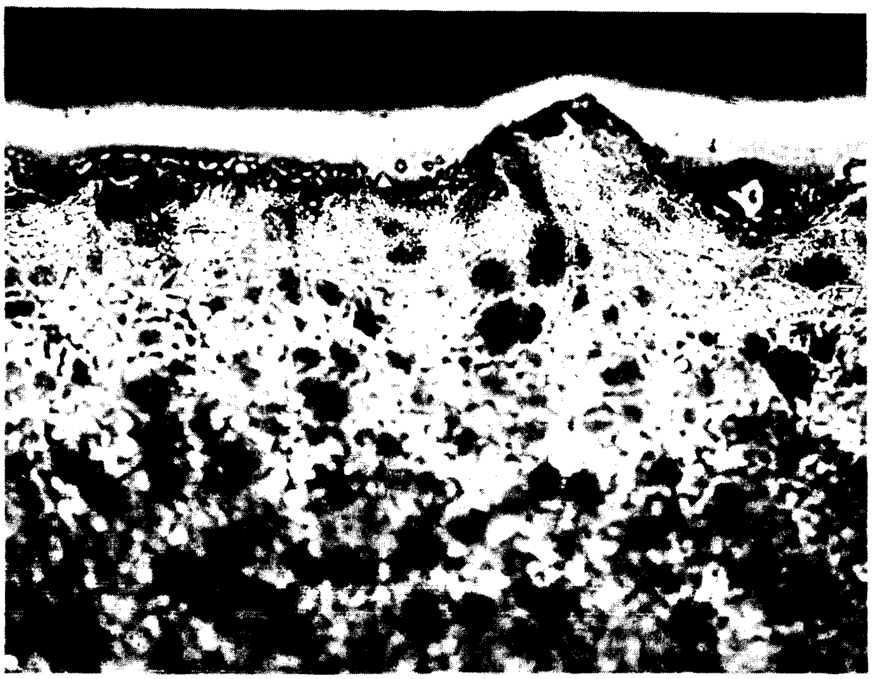


30632 200X

FIGURE 47. SPECIMEN IN-6. CROSS SECTION WHERE COATING HAS PULLED AWAY FROM THE SUBSTRATE. ELECTROLESS NICKEL PLATED. $FeCl_3$ ETCHANT.

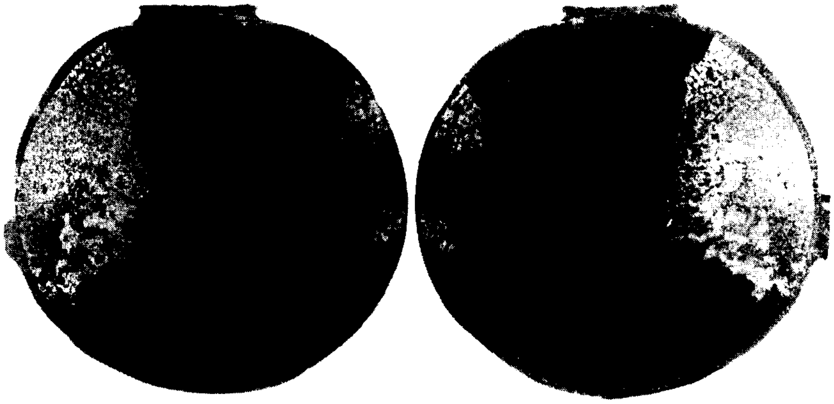
30635 500X

FIGURE 48. AREA OF ADHERENT SPRAY FG 718 DEPOSIT SHOWN IN FIGURE 46. ELECTROLESS NICKEL PLATED. $FeCl_3$ ETCHANT.



30633 500X

FIGURE 49. AREA OF NONADHERENT SPRAY FG 718 DEPOSIT SHOWN IN FIGURE 47. ELECTROLESS NICKEL PLATED. $FeCl_3$ ETCHANT.



31010 2X

FIGURE 50. AFTER BOND TESTING. SPECIMEN NO. INT-7 WITH FG T-800 SPRAY DEPOSITED TRIBALLOY ON TYPE 718 INCONEL SUBSTRATE. EXAMPLE OF A LOWER BOND STRENGTH SPECIMEN SHOWING AREAS OF PULLED-AWAY DEPOSIT.

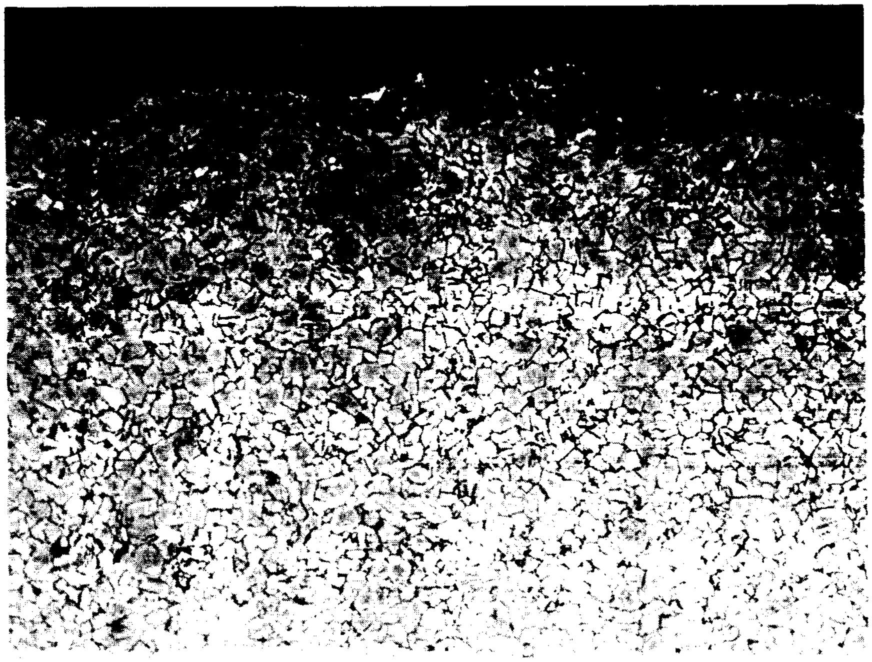


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FIGURE 51. SPECIMEN INT-7. CROSS SECTION SHOWING AN AREA WITH SOME REMAINING ADHERENT FT T-800 DEPOSIT. ELECTROLESS NICKEL PLATED. $FeCl_3$ ETCHANT.

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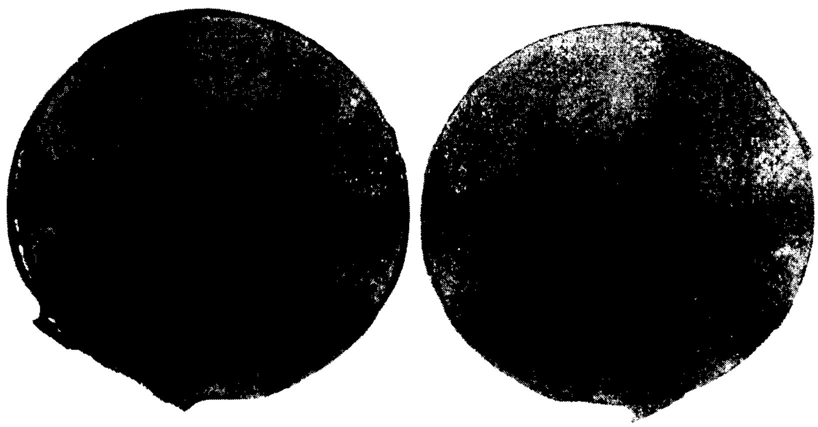
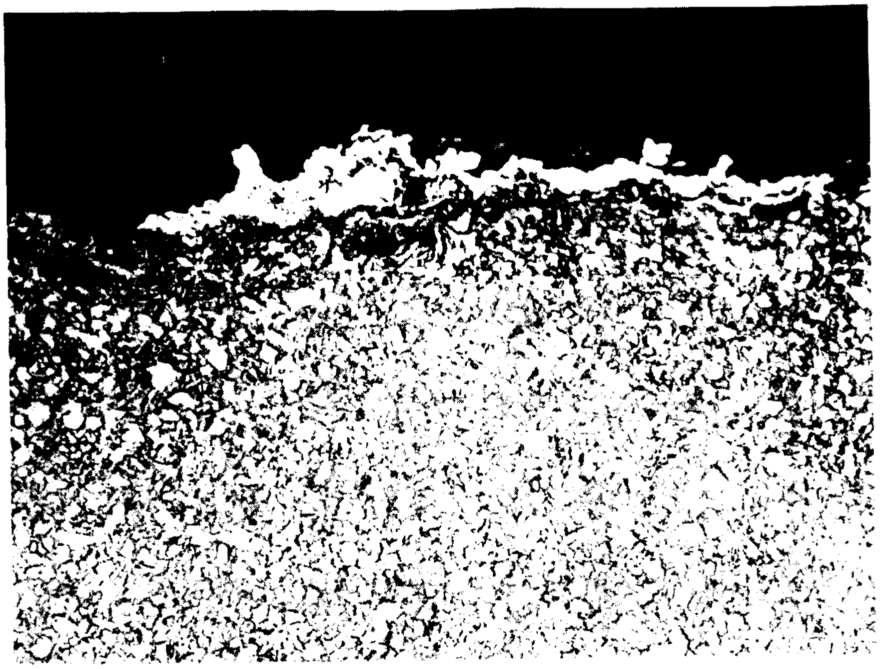
FIGURE 52. SPECIMEN INT-7. ENLARGEMENT OF AREA OF FIGURE 51. ELECTROLESS NICKEL PLATED. $FeCl_3$ ETCHANT.



31012 2X

FIGURE 53. AFTER BOND TESTING, SPECIMEN NO. INT-3 WITH FG T-800 SPRAY DEPOSITED TRIBALLOY ON TYPE 718 INCONEL SUBSTRATE. EXAMPLE OF A HIGHER BOND STRENGTH SPECIMEN, SHOWING AREAS OF PULLED AWAY DEPOSIT.



31031 200X

FIGURE 54. SPECIMEN INT-3. CROSS SECTION SHOWING AN AREA WITH SOME REMAINING ADHERENT FG T-800 DEPOSIT. ELECTROLESS NICKEL PLATED. $FeCl_3$ ETCHANT.

31032 500X

FIGURE 55. SPECIMEN INT-3. CROSS SECTION WHERE THE DEPOSIT HAS MOSTLY PULLED AWAY EXCEPT FOR VALLEYS IN THE PRE-SPRAY GRITTED SURFACE. ELECTROLESS NICKEL PLATED. $FeCl_3$ ETCHANT.

# ESTABLISH BALANCING METHODOLOGY AND DEVELOPMENT RECOMMENDATIONS

Based upon the success of the screening tests of the selected spray process and material combinations, this portion of the report will identify and define a cost-effective, time efficient, automated, state-of-the-art balancing methodology of thermal spray weight addition using the FARE process selected. The defined method should match the capabilities and characteristics of weight addition technology to existing and future needs in Army engine overhaul. The major goal is to exploit this automated technique to produce an improvement in balancing productivity, reliability, quality, consistency, and cost.

The factors weighing upon the selection of the thermal spray process and materials made under **Definition of Requirements and Selection of Process and Materials Specifications** have a direct effect upon the balancing methods available for evaluation under this task. Primarily, the FARE process was selected because it is a pulsed spray process which is more adaptable to automated balancing than a continuous process because it eliminates the need for shadow masking, rotating windows, or timed shutters. The disadvantages of these devices are:

(1) These are complicated extra mechanical devices to be developed, controlled, and maintained.

(2) Their presence makes gun positioning and access to the part more difficult.

(3) Spray material will build up on the shield or shutter and unbalance it or render it inoperable.

Incremental, automatic weight correction of a rotor by thermal spraying during rotation allows redefinition and reoptimization of the process of balancing. Thermal spray balancing allows new, more effective weight correction strategies to be developed within the framework of classical vibration measurement and state-of-the-art balancing machines. Balancing consists of vibration measurement, correction inference, and physical correction. The automation replaces two or three costly manual cycles with a larger number of much less costly cycles of vibration measurement, vibration *change* measurement, correction inference, and physical correction. The use of vibration as well as vibration change to guide the process constitutes continuous calibration of the machine for each part and advances the state of the art beyond classical balancing machines which are calibrated with a known weight periodically. Thermal spray automated balancing should be adaptable to both high- and low-speed balancing algorithms. Current methods for balancing of aircraft gas turbine rotors should be enhanced by the use of thermal spray weight addition in place of weight removal by grinding.

The primary concerns for thermal spray weight addition are related to what materials can be placed by spraying, and their ability to stay in place and not cause increased degradation of the rotor or components by factors such as fatigue, corrosion, or thermal effects.

## AUTOMATED THERMAL SPRAY BALANCING METHODOLOGY

This document describes the method of implementing automated thermal spray balancing using the FARE gun. Where possible, we give our selected approach, followed by the reasons for the selection over alternatives. Following this section describing the proposed methodology for automated balancing, there is a section that describes the recommendations for development. Where development and tests are needed, these are identified.

The *Spray Automated Balancing Of Rotors* (SABOR) technique is described in the following discussion and illustrated in Figure 56.

## General Concept of SABOR

The part or assembly will be rotated in a balancing machine to a selected initial speed. As is normal in a balancing machine, vibration response to unbalance (magnitude and phase angle) will be measured on the two bearings of the machine. A microcomputer will use prestored knowledge of the part, calibration of the machine, and calibration of the gun to determine, for each balance plane, when in the revolution to fire the gun (timing delay), and how many times to fire it. A required speed change may also be determined. The gun's control system will be directed to control speed and firing appropriately.

After the calculated number of shots has been fired, under control of the gun's electronics, for one or both planes, the new level of vibration will be measured. Based upon this new level of vibration, the change in vibration, and prestored knowledge, an updated time delay and number of shots will be determined. The rotor speed may again be adjusted to optimize the process.

The cycle of checking vibration and firing will be repeated until the part is in tolerance. The delay required for calculation will of course be momentary, so, as long as a single gun is firing at a single plane, the process will proceed rapidly. The handling of two planes requires either two guns or automatic position control of a single gun. The optimum cycle for most effective balancing remains to be determined, and the algorithmic parameters will be discussed subsequently.

In the following sections we discuss in more detail:

- Computer automated control
- Operating the FARE gun
- Balancing machine selection
- Balancing speed selection
- Timing control
- Weight effectiveness
- Balancing control algorithms
- Materials
- High-speed balancing
- Two-plane balancing
- Loading and unloading automation
- Manpower
- Safety.

In each case, envisioned methods are presented and development needs are identified.

### Computers

#### *Preferred Approach*

The SABOR system should incorporate several microprocessors to perform the various automated functions and data base handling. These various controllers would have to exchange data to allow the system to operate in closed loop. The SABOR system would consist of three or four separate computers -- one for each major component and one master controller. They would include:

- Balancing machine computer (optional)
- FARE gun controller
- FARE gun position controller
- Master controller

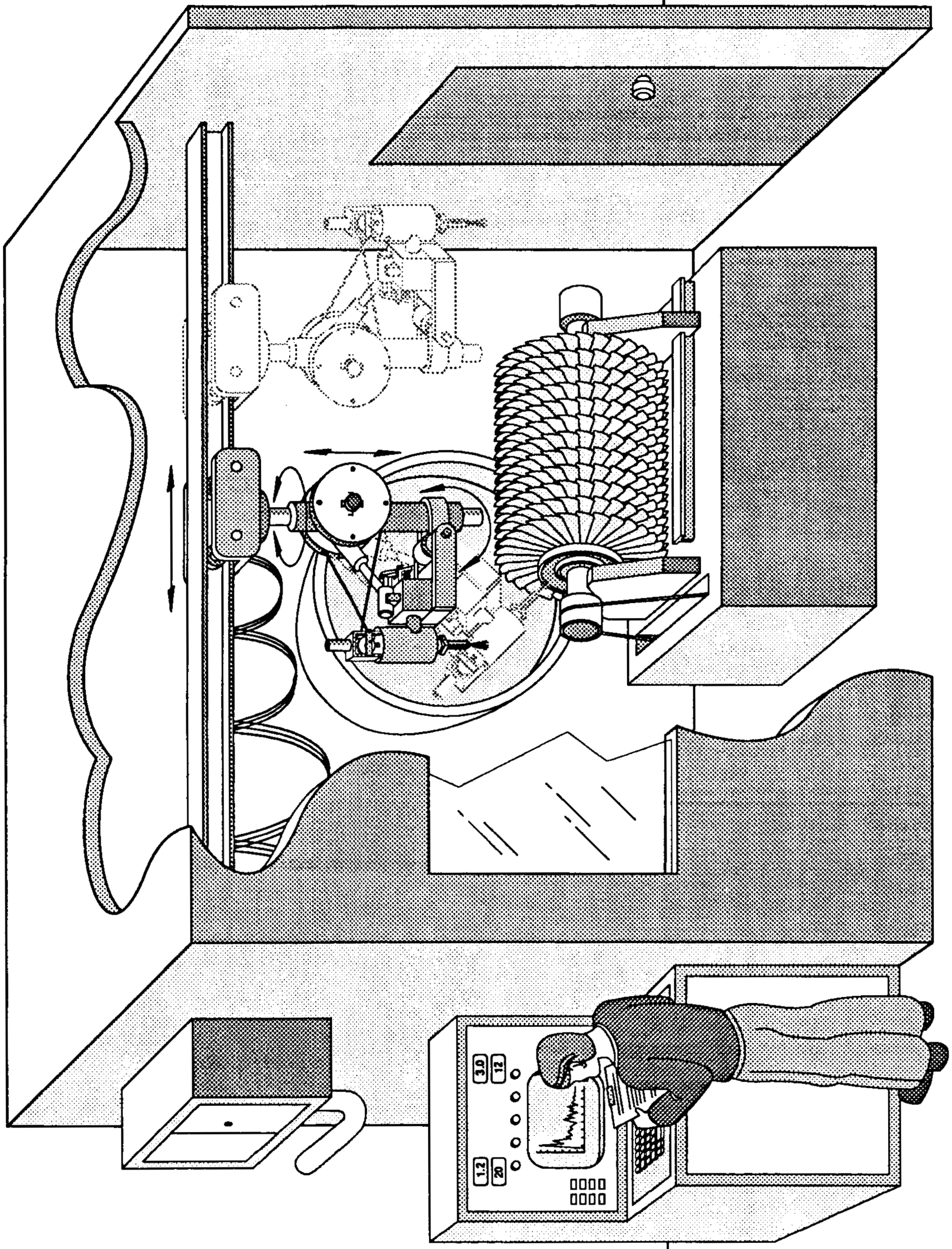


Figure 56 - Concept of Spray Automated Balancing of Rotors (SABOR)

### *Rationale and Discussion*

The balancing machine functions of reading the speed of the rotor; saving, recalling, and using the setup and sensitivity data for the part; digitizing the vibration signal; and calculating the correction weight for each balance plane will be performed by the standard balancing machine computer, or alternatively, by the master controller. The balancing machine computer will also control display and printout of the required weight corrections on standard displays and printer documents.

The FARE gun controller will contain the software necessary to time and actuate the firing of the gun to deposit spray at the right angle on the rotor. It must either sense the speed and vibration of the rotor or receive that information from the balancing machine computer. The gun controller must also receive a once per revolution pulse from the rotor in order to time the firing. Another function of the FARE gun computer will be to control the number of shots fired.

The balancing system will also utilize a computer to control a mechanical system that will position the FARE gun for metal application on the right plane and spray angle. It will necessarily receive data from the master controller for proper interaction in a closed loop automated balancing operation.

The master controller will interact with the other computer/controllers to close the control loop between them. It will receive data from the balancing machine sensors or its computer. This data will generally consist of speed, vibration amplitude, and phase information for two planes. The master controller will apply appropriate algorithms (a variety of approaches exist) to choose weight application angle and number of shots to apply in order to reduce vibration to an acceptable level. The master controller will also transfer information to the gun position controller to properly orient the gun according to the part being balanced and the plane being corrected.

Multiple distributed computing functions provide some measure of flexibility and reliability. There would be some overlap of capability from one controller to another; this would provide programmers with software flexibility. The distribution of functions among several controllers provides a degree of reliability such that the system may be able to operate in an open loop mode in case of a controller malfunction. Further, the modularity of the system provides quicker and less expensive repair or component replacement.

The automated balancing system, having the advantage of computer control, will be further enhanced by the construction and maintenance of a local data base system for recording the status and quality of each engine that is produced or overhauled. Considerable data and software could be saved on a hard disk attached to the master controller. Depending upon overall plant automation and data base management systems, the automated balancing system could be made to supply data to a plant-wide data base system for complete tracking of engines.

## Operating the FARE Gun

### *Preferred Approach*

The FARE gun will be used to apply shots of molten metal onto the target balancing plane, timed to adhere at the proper phase location to reduce the unbalance and measured vibration. Timing of the gun will be performed by a computer which is not presently a part of the unit. The rotor target area must be cleaned and roughened by grit blasting.

Certain operating and maintenance procedures are necessary elements of proper Fare gun operation. The gun requires utilities and supplies, most of which are commonly available.

*Rationale and Discussion*

The FARE gun is a combustion thermal spray process which deposits molten metal powder at high velocity and high temperature onto metal surfaces which have been properly cleaned and roughened. The process requires the following supplies and utilities:

- Propane - 760 KPa (110 psi)
- Air - 760 KPa (110 psi)
- Nitrogen - 5.5 MPa (800 psi)
- 115 volt 60 cycle power
- Cooling water - 4 l/min, 135-270 KPa (1 gpm, 20-40 psi)
- Drain
- Tapes of encapsulated powder
- Cooling air, carbon dioxide, or inert gas (optional).

Certain characteristic parameters are important to the operation of the gun for automated balancing: the standoff distance between the gun nozzle and the workpiece, the total delay of the gun from the time the fire pulse is initiated until the material is deposited on the workpiece, and the elapsed time between the deposition onto the target of the first and last particles of spray. The optimum standoff distance is known to be between 1 and 5 cm.(0.5 and 2 inches), but the total gun delay will have to be determined by testing. Current estimates are that the FARE gun can spray the majority of the material onto the target during a period of about 2 milliseconds and that the total gun delay is on the order of 0.25 seconds.

Maintenance of the SABOR system and the FARE gun and its enclosure should be considered in the program implementation. Included in the maintenance program are the upkeep of the hardware and control of the operating parameters.

In order to maintain clean film deposits without carbon contamination, it is necessary to clean the combustion chamber of the gun periodically, as carbon builds up on the internal walls of this chamber and eventually flakes off. Control of impurities in the fuel, such as butane or oil, will reduce the frequency of this maintenance need. Daily or weekly maintenance should include cleaning the booth enclosure of residue powder.

Spare parts helpful to keep the system available with minimum downtime include a spare combustion chamber with internal nozzles, a valve block, gaskets, seats for the powder injector, spare tubing connectors, and a backup controller board.

Optimum combustion requires the pressures of the air and fuel gas to be closely controlled. In cool weather, this usually requires a fuel gas heater to achieve the necessary pressure from most supply bottles. Both fuel and air should be clean and dry.

Proper adhesion of sprayed film requires that the target surface be cleaned and roughened. The recommended procedure is by grit blasting, a process similar to sand blasting. The grit material is a coarse, granular silicon carbide or alumina material which leaves a rough, angular surface to facilitate the mechanical bonding of the spray film. Surfaces adjacent to the target area which should not receive the surface treatment must be masked, with tape, for instance.

## Balancing Machine Selection

### *Preferred Approach*

The preferred balancing machine will be a hard bearing machine with conventional velocity sensors for vibration measurement on each bearing. The balancing machine will have modern electronics for control and signal conditioning. Data acquisition, signal processing, setup and tolerance information would best be handled digitally.

The rotor bearing interface will preferably be teflon coated Vee-blocks. The drive will be a conventional friction belt drive, provided tests of controllability and accuracy meet requirements spelled out in a later paragraph.

### *Rationale and Discussion*

A hard bearing machine is preferred because its settling time after a weight addition shot will be minimized. A soft bearing machine can be expected to undergo a transient response after each shot which will decay over five or more cycles of the low natural frequency typical of soft bearing machines. Accepting this settling delay, a soft bearing machine could be applied to SABOR.

The choice of velocity sensors is arbitrary, but falls in line with the most common conventional practice. If the balancing machine selected were to use accelerometers, or load cells, this would be acceptable. The important requirement is a consistent, accurate, measure of vibration response to unbalance loading.

Modern electronics is preferred for stability, reliability, maintainability, and compatibility. Even if the initial choice of balancing machine is one which is in existence, its electronics should be brought up to a level compatible with current digital processors.

The selection of teflon coated Vee-blocks for rotor bearing support are preferred over more commonly used rollers or engine type bearings, because the rollers will tend to be vulnerable to any infiltration of the powder overspray from the gun. Vee-block supports should not suffer in this way.

The choice of a friction belt drive is one of considerable convenience and avoids a development problem. Such belt drives are quite widely used in balancing machines; they are readily slipped over the shaft of the assembly to be balanced, and can accommodate different diameters without difficulty and without alignment problems. A direct drive, using a splined quill or other such flexible coupling is an alternative approach, but for small, lightweight components, introduces several additional considerations, including alignment, transmitted torque, drive vibrations, and interfacing problems. The critical question to be assessed with respect to friction belt drives is controllability and accuracy of speed required by the automated balancing process. Tests in a control loop with speed feedback from a rotor to the drive motor will be required to assess this.

In spray balancing, it will be necessary to protect the balancing machine against damage to its bearings or sensors from undeposited metal powder. Dust shields or filters will be needed in areas such as the drive motors and vibration pick-ups.

## Balancing Speed Selection

### *Preferred Approach*

Selection of the appropriate speed under this methodology will be based upon algorithms in which the balance tolerance is reduced in a step-wise procedure and the necessary balancing machine speed is incrementally increased. The preferred balancing speed should be maintained within the range of acceptable speeds for current technology balancing machines.

### *Rationale and Discussion*

Speeds appropriate for low-speed balancing machines range from about 600 rpm for larger parts to 3000 rpm for the smaller ones. Balancing speed selection is based upon producing enough vibration due to unbalance to be sensed and used for correction weight calculation. The smaller the acceptable balance tolerance, the smaller the minimum correction weights must be and the higher the balance speed must be.

A coarse balance correction could first be performed at relatively low speed; when the target tolerance is achieved, the speed would be increased to magnify the vibration and an improved tolerance goal set and approached by smaller correction shots.

## Timing Control

### *Preferred Approach*

Under a fully automated SABOR system, feedback computer control of the drive speed would set the right speed (or speeds) and maintain the speed variations within a sufficiently tight range to control the scatter of sprayed film. The speed would be set automatically by computer, based upon identification of the part to be balanced, thus eliminating potential operator errors and facilitating the balancing of groups of different types of parts in sequence with minimum machine changeover.

### *Rationale and Discussion*

There are two distinct measures of deposit accuracy; one is the error in the average location of the material on the disk, and the other is the elapsed time between the arrival of the first and last particles on the disk. Both of these are dependent upon the accuracy of the rotor speed. These time delay parameters will have to be determined experimentally.

The angle variation in spray deposition location ($\Delta\theta$, expressed in degrees) caused by disk speed variation (N, rpm) can be expressed mathematically as

$$\Delta\theta = 6\int_0^{T_D} (N - N_{OPT})\, dt$$

where N is the actual speed of the disk, which varies with time, $N_{OPT}$ is the desired speed, upon which the balancing calculations are based, and $T_D$ is the total gun time delay. This expression is a general one which reflects the fact that speed will tend to vary up and down on a continuous basis within some limits of controllability.

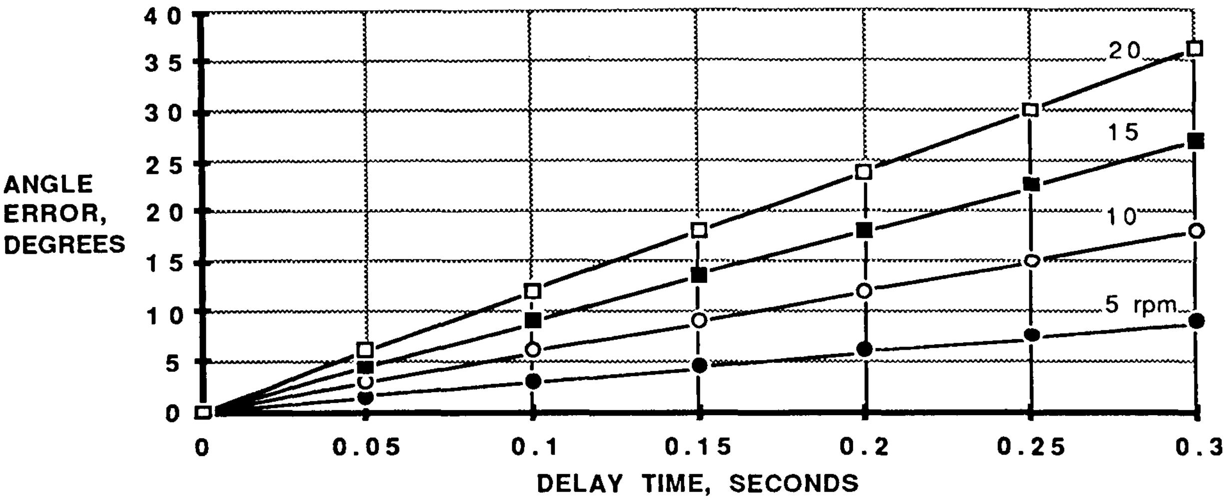
To assess the significance of speed variability, a more manageable expression is

$$\Delta\theta = 6T_D\Delta N$$

where $\Delta N$ is an average speed error, in rpm. In general, the angular error increases with time delay and with speed error. Figure 57 plots this angular discrepancy as a function of $T_D$ and $\Delta N$.

FIGURE 57

SPRAY DEPOSITION ANGLE ERROR VS GUN DELAY
AS A FUNCTION OF SPEED DEVIATION




With an automated balancing process, capable of adjustment and adaptation based on results, some significant error in angle location of a particular shot is tolerable. A target error of less than 7.5 degrees would be very satisfactory and 30 degrees is probably tolerable. Based on present estimates of a 0.25 second time delay, a speed error of 5 rpm will achieve a 7.5 degree location error. Five rpm should be readily achievable with a control system. The effect of belt slippage needs to be assessed.

For the range of typical balancing machine speeds the FARE gun should deposit spray over acceptably small angles. At 3000 rpm, the 2 millisecond deposition time would spread the film over 35 degrees of angle. At 600 rpm, the spread of the material would be only 7 degrees.

To assess the significance of the angular spread of a deposit, the concept of weight effectiveness has been developed as discussed below.

## Correction Weight Effectiveness

### *Preferred Approach*

It is proposed that weight correction effectiveness be used as one measure of performance in automated weight addition. This quantity is defined as the ratio or percentage of the vector mass to the total mass applied.

### *Rationale and Discussion*

When material is applied for unbalance compensation, the calculated vector requires the entire force (mass) to be applied at a point on the radial indicated by the calculated angle. Whenever the mass is spread in an arc on either side of the indicated radial, the distributed mass adds to the central radial as a function of the cosine of the angle of deviation from the radial. Thus, the wider the arc over which the material is spread, the more mass must be applied to achieve the necessary vector quantity. The relationship between required mass and distributed mass can be called "effectiveness" and expressed as

$$\eta = \frac{60 \sin\left(\frac{\pi}{60} N \Delta T\right)}{\pi N \Delta T}$$

This expression is derived in Appendix F.

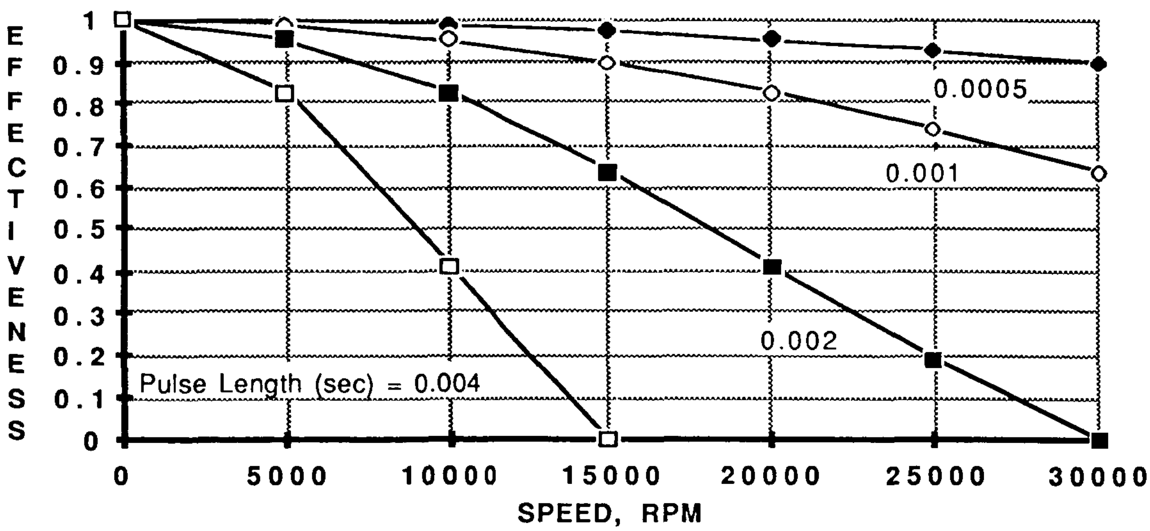
For example, all of the mass applied exactly on the vector radial would be 100 percent effective, while mass distributed 360 degrees around the disk would be zero percent effective because it achieves no vector effect. Other useful examples are:

| Angle | Effectiveness |
|---|---|
| 45° | 97.5% |
| 90° | 90.% |
| 180° | 64.% |

Figure 58 plots effectiveness against speed for different pulse times, $\Delta T$.

FIGURE 58

BALANCE EFFECTIVENESS AS A FUNCTION OF SPEED AND PULSE LENGTH



If we set 75 percent effectiveness as a nominal target, and use a pulse time of 2 milliseconds, Figure 58 shows that we should be able to balance efficiently at speeds up to 12,000 rpm. This far exceeds the requirements for low-speed balancing. This needs verifying by test.

## Balancing Algorithms

### *Preferred Approach*

The term balancing algorithm refers to the logic, mathematics, and procedure used to perform balancing. It includes the selection of balancing speed; the number of shots to be fired in succession; the phase angle and delay at which they are to be fired; how these parameters are related to vibration amplitude and phase measurements; how these properties must be changed during the balancing process; and how to determine when the part is in tolerance. Optimum algorithms will have to be developed for different parts and assemblies.

### *Rationale and Discussion*

The automated weight change aspect, wherein the weight is changed quickly in small increments, makes it possible to develop new balancing algorithms incorporating the change of the influence coefficients with correction weight increase (essentially calibration on line). This technique can also reduce the unbalance tolerance in successive steps. Increasing rotor speed increases the sensitivity to residual unbalance and spraying smaller amounts of weight with each shot allows smaller corrections to be made to achieve lower tolerances.

The SABOR system could be programmed for several different balancing algorithms to accommodate different operating modes needed.

- A mode for the generation of influence coefficients. This mode is applicable to balancing new parts where the influence data is not known, or for balancing difficult parts where the influence may be nonlinear. In this mode, a number of shots would be fired, the change in response measured, and an influence coefficient calculated and saved. For every sequence of firing, a new set of influence coefficients would be calculated and either used as updated influence for nonlinear rotors, or averaged with previous data to minimize the effects of inconsistent data samples. Initial balance corrections at relatively low speed would satisfy coarse unbalance criteria. Finer tolerances would then be achieved by increasing the rotor speed to increase the vibration amplitude. Very small unbalance tolerances could be achieved by spraying smaller shots of metal. It appears that this effect can be achieved simply by spinning the target disk at higher speed. Preliminary test data obtained under SwRI internal funding indicates that less FARE gun sprayed material adheres as the speed is increased.

- A mode for production of many parts wherein the influence coefficient and balancing speed are known. The needed correction weight is calculated from the measured initial response and the influence coefficients saved in memory. The weight is fired on the disk in as quick and efficient a manner as possible.

- A manual or operator interaction mode for special or occasional situations. Such cases might include quality assurance tests, development of optimum speed specifications, or cases where the operator wants to specify the number of shots to be applied or the position to which they should be applied.

- A mode for robotic or automatic positioner learning for new parts wherein the gun is manually positioned one step at a time and the computer reads and saves the sequence of steps for automatic repetition in the other modes.

Figure 59 shows in very general terms how the logic and flow of a typical balancing algorithm would be organized. The approach is to measure vibration and speed initially; to decide, based on available data for this part, at what speed to apply the weight, how many shots to fire, and at what angle in each plane; to set the machine speed and command the gun(s) to fire accordingly; to repeat the measurement after a limited, but significant number of shots have been fired; and to update the sensitivity information, number of shots, angle and speed commands based on the results. This process would be repeated at high repetition rates until the part is in tolerance.

## Materials

### *Preferred Approach*

The FARE gun sprays encapsulated powder onto a metal substrate. The powder can be a metal or a ceramic. For use in flight hardware, each combination of spray material and substrate needs to be qualified for

- Bond strength
- Fatigue strength
- Thermal cycling strength
- Balancing performance.

At present, several combinations have been partially qualified and should be sufficient for process evaluation. Testing should be performed to qualify other spray material-substrate combinations. A simple test or inspection should be sought which will quickly verify that sprayed film should not degrade the strength of the substrate.

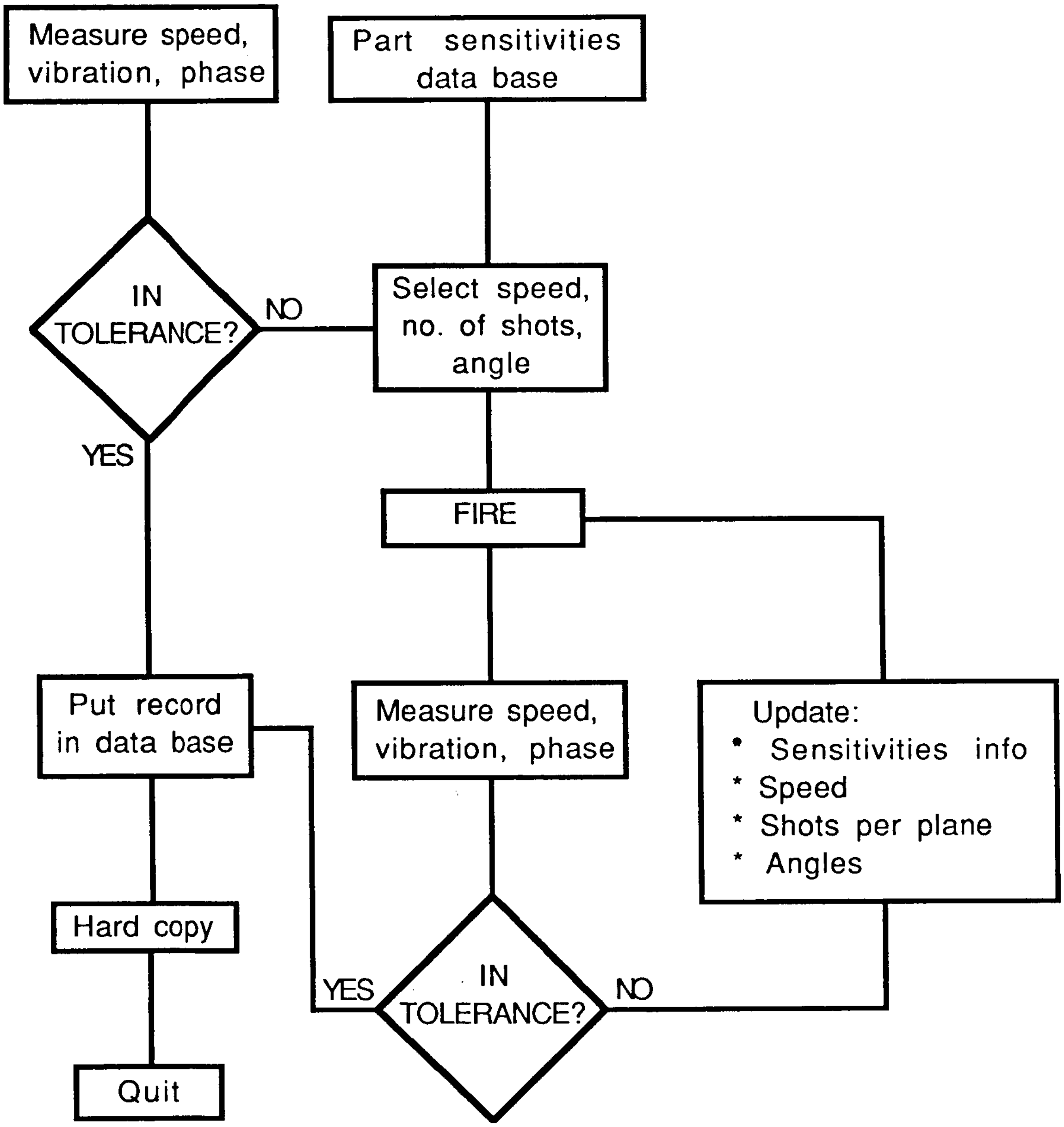
### *Rationale and Discussion*

The results of the bond and fatigue strength tests have proven acceptable for the combinations tested. Table III gives the range of bond strengths tested. Our preliminary estimates from **Definition of Requirements and Selection of Process and Materials** indicate that the highest expected centrifugal stresses are in the order of 7 MPa (1,000 psi). The fatigue results showed that the sprayed materials will have fatigue resistance characteristics similar to those for hand-ground specimens of the same base materials.

TABLE III
BOND TEST STRESS RANGES

| Substrate | Coating | Lowest (MPa) | Lowest (psi) | Highest (MPa) | Highest (psi) |
|---|---|---|---|---|---|
| 17-4 PH | Tungsten Carbide | 51.09 | 7410 | 72.97 | 10583 |
| Inconel 718 | Inconel 718 | 22.84 | 3312 | 44.58 | 6466 |
| Inconel 718 | Triballoy 800 | 26.08 | 3783 | 45.43 | 6589 |

# FIGURE 59
# TYPICAL BALANCING ALGORITHM FLOW CHART



### High-Speed Flexible Rotor Balancing

#### *Preferred Approach*

High-speed, flexible rotor balancing here implies balancing at speeds which are at, near, or above critical speeds whose mode shapes involve significant flexure of the rotor. Application of SABOR to such balancing, when needed, is a logical extension of the low-speed balancing approaches discussed elsewhere in this document. The following must be addressed for high-speed, flexible rotor balancing:

(1) The basis for balance plane selection should include the proximity of rotational speed to critical speeds, and the resultant variation in sensitivity to weight addition in different planes as a function of speed.

(2) Data acquisition speed criteria should include proximity to critical speeds, and vibration levels relative to some established safe limit. Data acquisition at more than one speed is likely to be required.

(3) Weight addition speed will desirably be the same as data acquisition speed, subject to limits imposed by reduction in correction weight effectiveness.

(4) Weight addition algorithms must include least squares minimization capability and recognition of the need to customize balancing speeds for each type of rotor because of varying resonance characteristics.

(5) Vacuum capability must be provided for bladed rotors.

#### *Rationale and Discussion*

Balance weight effectiveness, as previously discussed, tends to become unacceptable at speeds where the time over which weight is deposited exceeds half the period of revolution. Where data acquisition speeds exceed about 12,000 rpm, it will be necessary to slow the rotor to a lower speed during weight addition in the selected set of planes. Since speed selection is already envisaged as an integral part of automated balancing, even for low-speed balancing, this feature of high-speed balancing is easily executed via software control. The delay between making weight changes at one speed and reading vibration response at another increases the time and complexity to maintain closed-loop automation for high-speed balancing.

### Spray Access To Balance Planes

#### *Preferred Approach*

We see a computer controlled FARE gun positioning system as an important component for safe, efficient implementation of one- or two-plane balancing. The greatest time efficiency would be achieved with two guns positioned so that they could simultaneously apply spray material to two separate balance planes. The preferred system would mount each gun at the end of an arm that could provide translation and rotation to position the guns to apply spray accurately on the desired surfaces.

#### *Rationale and Discussion*

In order to make maximum use of one SABOR balancing machine to balance a number of different parts or assemblies, the system must be made adaptable to different weight correction locations on different parts, and for two-plane as well as one-plane correction. Thus, we see efficient two-plane balancing as using two FARE guns with three or four degree of freedom positioners.

The FARE gun positioners will be interfaced with the SABOR master computer so that when the part to be balanced is identified (by the operator or by sensors) for setup, the controller could position the FARE gun nozzles in the proper places so that material could be applied simultaneously to the designated balance planes. Such automated and pre-programmed positioning would reduce the needs for operator knowledge and interaction. Automatic positioning would be quick and accurate and could reduce the potential for variations due to operator judgement or lack of knowledge. Robotic control of the FARE gun would essentially remove the need for the operator to be in the safety enclosure during balancing of the component.

There are several intermediate term or alternative gun positioning schemes which could be implemented according to the application and need, or simply to reduce cost:

- A FARE gun on the end of a centrally mounted robotic arm could be programmed to interact with two or more balancing machines alternately. Spraying could be performed on the rotor in one balancing machine while the second machine is unloading the finished part and positioning a new one.
- Manual positioning of the FARE gun for infrequent changes of parts or balance planes.
- Floor or overhead rail mounting of one or two guns that would be positioned to sequentially or simultaneously, as appropriate, fire correction weight onto each balance plane.

The FARE gun nozzle access to certain types of parts has two considerations which will require careful engineering design: (1) applying the spray in a narrow enough stream so that there is no overspray to other surfaces to the sides of the intended path on the disk, and (2) positioning the nozzle so that the spray can be directed at the desired target area on the part and with an acceptable standoff distance and angle. On the majority of parts, direct line of sight access is available, either radially or axially to the part or assembly. Drive shafts, and most individual wheels, or gears are obviously accessible. For a few parts or assemblies where the balance correction location is inside of a curvic coupling or other mating surface, or between two closely spaced parts, special measures may need to be developed to spray balance these parts. Examples identified during our survey are the T-700 blisk which only has line of sight access from the diametrically opposite side, but around the sides of the arbor shaft, and the T-53 power turbine assembly where one balance plane is between the two wheels and presently disassembly is required to make corrections.

## Loading and Unloading Automation

### *Preferred Approach*

Automatic loading and unloading of the balancing machine would significantly increase its production rate and reduce the frequency at which the operator would need to enter the safety enclosure. We envision loading/unloading automation as a future enhancement to the basic SABOR plan.

### *Rationale and Discussion*

In high production environments, the throughput of the automated balancing system and operator safety would be enhanced by the ability to quickly load the component into the balancing machine, verify its identity, and then unload it upon completion of balancing. Additional robotic or assembly-line type mechanisms could perform these functions. This would leave the assembly of shaftless components on rotating arbors, if necessary, as the only manual function in the preparation for balancing.

### Manpower

#### *Preferred Approach*

The SABOR balancing system will change the manpower skill requirements for balancing in the typical production environment. It will require skills to operate the FARE gun and SABOR system, with less emphasis on knowledge of balancing technology. It will also require a technical support person knowledgeable about FARE gun operation and SABOR system automation.

#### *Rationale and Discussion*

The SABOR automated balancing system does not remove the need for an operator by the fact that it is an automated process. It does, however, change the knowledge and skills that the operator must have. The operator would rely less on knowledge of balancing; his functions will rather be in support of balancing, for example masking and grit-blasting of parts. He will have to have some knowledge of FARE gun operation, setup, and maintenance. Due to the flexibility of the SABOR machines to quickly and efficiently balance a variety of rotors with minimal changeover time, labor productivity should be greatly increased.

This more sophisticated system will require some plant support person knowledgeable about software and hardware troubleshooting and maintenance. One such skilled person could support several SABOR machines on a part-time basis or a number of automation systems throughout a plant.

### Safety Considerations

#### *Preferred Approach*

The SABOR system must be operated in a sound deadening enclosure with an air exchange ventilation system. The supervising operator should be stationed at a control panel outside the booth where he can maintain control from a safe environment.

#### *Rationale and Discussion*

The proposed automated balancing system must be operated within a controlled environment for several safety reasons:

- High noise level
- Combustion gases and products of combustion
- Airborne metal powder
- The potential for flying particles or rotor pieces.

The standard enclosure is a sound deadening booth with an air exhaust fan which draws air through the booth via sound insulated entrance and exit paths. These should be located so as to provide maximum air exchange. The purpose of the exhaust system is to prevent the buildup of propane gas and to remove the gases created after combustion. In addition, the metal powder does not all melt and adhere to the target surface. Some of the unmelted powder becomes airborne after firing and should be removed from the booth.

If an operator is temporarily located within the FARE gun booth, he should be protected by ear and eye protection; longer term exposure would require inhalation filters. The need for an operator stationed within the booth under normal operating conditions will be avoided by the use of automated positioners and a remote control terminal.

The absence of an operator inside the booth removes the need for safety shielding around the balancing machine rotor. Some interlock controls may still be desirable to prevent operator disregard for safety.

## RECOMMENDATIONS FOR DEVELOPMENT

Several areas requiring additional development are alluded to in the discussion above. They are discussed in greater detail in this section.

- Spray Material Specification and Test Needs
- FARE Gun Enhancement and Characterization
- Balancing Machine Speed Control
- Algorithm Development
- Engine Component Review
- Surface Preparation
- Applications Evaluation
- Balancing Demonstrations
- Gun Positioner.

Potential plans or alternatives are suggested and, in most cases, the best solution will be the result of a focussed investigation or test.

In some cases, the identified area of need is related to adapting SABOR to balancing of parts in a means compatible with present weight correction techniques. In the shorter term, the balancing system must be adapted to the present hardware; for future engines, the hardware should be designed to take maximum advantage of SABOR balancing and to avoid some of the problems identified.

### Spray Material Specification and Test Needs

Additional work is needed to investigate the acceptable combinations of substrate and spray materials for use in spray balancing of aircraft engine components. The investigations performed herein indicate that there are a number of likely combinations. There are material properties and powder characteristics which affect the quality of the film that is laid down, the percentage of the material that bonds, the compatibility of the film with the substrate, and density of the material for balancing efficiency.

Some investigation into the specifications for powder to be sprayed by the FARE process is needed. Grain size seems to be particularly important and may also be related to the melting temperature of the alloy powder.

The available experience base of materials presently used as both substrates and sprays is a valid starting point for acceptable combinations, but the experience of applying the materials by FARE gun with the primary interest in balancing, rather than other traditional applications, is important. It would be desirable to develop a small scale test, or at least a microscopic examination, to quickly qualify the validity of certain material combinations and avoid the need for extensive fatigue and bond strength tests.

The calculated stress condition which is most likely to cause debonding of the substrate and film is the differential thermal growth between the two materials. If the thermal growth rates are different, the relative growth causes a significant stress at the bond line. This factor should be further investigated for material combinations likely to be used in aircraft turbine engine balancing. They should be thermally cycled to determine the severity of this problem for each material combination and temperature range.

## FARE Gun Enhancement and Characterization

There is a need to verify by testing a few of the critical timing and operating parameters of the FARE gun. The total gun delay and the spray deposition time are important parameters related to the balancing function that have not been previously identified. Also, tests should identify the range of acceptable incidence angles between the barrel and the target, and the effect of rotor speed on this angle. The speed effect on deposit efficiency needs to be characterized in order to define the ability to balance at higher speeds. There is data to indicate that material being sprayed is a factor influencing this efficiency.

### FARE Gun Electronics Enhancement

The level of technology of the FARE gun could be updated to improve its compatibility with computer interfacing and to speed up its actuation. Even though the total firing delay time for the gun is not defined, it appears that the delay could be decreased by redesign of the electrical trigger and perhaps the mechanical actuation of the gun. The push button and relay actuation circuitry needs to be converted to digital circuitry which can be directly controlled by computer signals.

### FARE Gun Access and Accuracy Improvements

Some development work should be done to improve the access of the spray nozzle to balance locations which cannot be sprayed from a direct, perpendicular line of sight between the nozzle and the balancing surface. This solution can be approached from several directions. They are listed in a logical implementation order:

(1) Applying the spray in a narrow enough stream so that there is no overspray to other surfaces to the sides of the intended path on the disk. An expedient solution would be to use stationary side masking of the flame or the surface to be sprayed. The diameter of the spray deposit put down by the FARE gun is about 1 cm. (7/16 in.) or larger. The diameter can be controlled to a certain extent by varying the standoff distance between the nozzle and target. Changing the standoff distance is not an independent parameter, however. The quality of the deposit can also be affected by too large a standoff distance.

(2) Many access problems are related to interference of the tooling or arbors that support the parts or assemblies for mounting on the balancing machine. It could be relatively easy to redesign some of these devices so that they have spider or cage shaped arbors which the FARE gun could fire metal between. In other cases, the solution would be to simply shape the tooling so that there would be less interference with the gun position needs.

(3) Many of the tight spray locations could be avoided by redesign of the balance correction surfaces. The need for sacrificial material could be avoided and available flat surfaces not now used for metal removal could be conveniently sprayed for metal film addition.

(4) Development of a narrower nozzle for the FARE gun would make it possible to achieve deposition onto smaller bands on a disk without the manual task of masking. The problem may not be as simple as putting a smaller orifice in front of the present nozzle; the combustion chamber timing and flame velocity are based upon the relationship between the combustion chamber volume and the backpressure created by the nozzle diameter. It should

be possible to design a FARE gun with a small nozzle for application in narrow paths. SwRI has the technical skills and design information to make the necessary changes for a volume production modification.

(5) Development is needed for positioning the gun nozzle so that the spray can be directed at the desired target area on the part and with an acceptable standoff distance and angle. It is uncertain whether curved nozzles could be designed to apply the metal film at a perpendicular angle to the disk surface. This possible line of development could be pursued, if the capability is greatly needed. A simpler investigation could determine the limits upon the spray angle of incidence to still achieve acceptable deposition and bond characteristics.

(6) A desirable long-range objective would be to design rotor parts to be balanced using SABOR. For future engines, the parts could be designed without sacrificial metal, but with accessible locations to be sprayed.

**FARE Gun Weight and Size Enhancements**

In order to implement robotic control and placement of the FARE gun for SABOR balancing, the configuration of the gun should be streamlined and its weight minimized so that it can be supported by an automatic positioner or robotic arm. Primarily, the powder feed mechanism could be relocated so that most of the tape supply and guides are not at the end of the extended arm. The carburetion chamber could be configured to be a structural part of the robot, as it is a structural part of the present support arm. If practical, the valving mechanism should be designed to occupy less space and be lighter.

## Balancing Machine Speed Control

A balancing machine with closed loop computer controlled speed should be investigated for the accuracy of speed control, and the ability of the computer to change to new speeds. It should be used to determine the acceptability of a belt drive and teflon Vee-block bearings for SABOR application.

## Algorithm Development

Balancing algorithms applicable to the needs of SABOR users will need to be developed. Once a demonstration SABOR system has been constructed, several modes of balancing can be performed, manually or automatically, to identify efficient and accurate algorithms, as suggested previously in this report. The ease of changing algorithms by running a different program makes variety in algorithms an asset.

## Engine Component Review

A review of the parts to be balanced by SABOR would provide needed information on the size, balancing speed, plane access, mounting needs, balance tolerance, average correction weight, and other parameters needed for planning and designing an appropriate SABOR system. This review should apply to all engine and transmission parts in the Army helicopter inventory that are to be applied to automated balancing.

## Surface Preparation

The need for grit-blasting to surface prepare the components to be balanced may be questioned in some applications. Grit-blasting definitely roughens the surface to be sprayed, even in the portion of the arc where no balancing spray material is to be applied. Our survey indicated that this was not a problem with manufacturers. If certain parts, for which grit blasting in the balancing area is undesirable, are otherwise considered candidates for SABOR balancing, other types of surface preparation methodologies should be investigated. Possibilities include chemical etching or cleaning, or other mechanical roughening processes.

## Applications Evaluation

The spray automated balancing system should be given an applications evaluation. The needs of specific interested users should be evaluated and the system designed with the expressed needs addressed. Important considerations are desired rate of production, variety of components to be balanced in one machine, mode of operation as relates to balancing algorithms used, manpower and automation requirements, safety considerations, and level of balancing quality desired.

## Balancing Demonstrations

The concept of spray balancing needs to be demonstrated using a balancing machine, FARE gun, and computer control system. Initial demonstrations of the system should be single-plane balancing to show the ability to accurately deposit material on a balancing machine rotor under computer control. This demonstration would primarily prove the timing and control aspects of spray automated balancing.

Following the single-plane balancing demonstration, a two-plane demonstration should be performed. This plan would test the feasibility of spraying using a single gun with position control, or dual guns which move only when the type of part is changed. Under this demonstration, the range of parts that can feasibly be balanced by SABOR should be investigated.

Both of the balancing demonstration programs would be useful in developing and testing the various balancing algorithms discussed previously.

### Demonstration on Engine and Transmission Hardware

In algorithm development and in demonstration tests for one-plane and two-plane balancing, the parts to be balanced should be disks and demonstration rotors designed for effective performance of these evaluations under controlled conditions. The sizes and configurations should be representative, but the parts should be expendable. When confidence has been gained in the gun and in the algorithms, and when the inevitable development problems have been overcome, the time will come for demonstrations on representative hardware from engine and transmission shafting. Two possible examples should probably be a shaft, where balance material can be applied to an outside surface, and a wheel where balance material can be applied axially. Parts of increasing complexity should be attempted following these relatively straightforward demonstrations.

## Gun Positioner

The FARE gun positioning mechanism must be designed and developed. This redesign of the FARE gun configuration would allow the combustion chamber and tape injection system to be separated from the other portions of the gun and mounted on a remote controlled positioner. As discussed previously, the preferred design would have two gun positioners for maximum efficiency for two-plane balancing. For lower production rate environments, a single gun could be sequentially positioned and fired to perform two-plane balancing.

# CONCLUSIONS

We have surveyed the state of the art of balancing at five turbine engine manufacturers, one helicopter airframe manufacturer, and two military overhaul facilities; we have conceived and described an automated balancing methodology using the FARE thermal spray process to apply molten metal film onto a spinning disk for unbalance correction; and we have performed fatigue and bond strength screening tests on three material-spray combinations to verify adequate adhesion and minimal fatigue life degradation for the selected process. Based upon the findings identified in each of these investigations, we have drawn a number of conclusions.

## BALANCING STATE OF THE ART

Commercially available computerized balancing equipment can significantly improve the reliability, quality, and documentation, and minimize the time and cost necessary to perform production or overhaul balancing.

The aircraft engine manufacturing and overhaul industry sees no need for high-speed balancing of production components, either presently or in the foreseeable future. Engines are designed for low-speed balancing and are assembled with tight tolerances.

Throughout the manufacturing plants surveyed we found that balancing was a specialty function, normally performed in centralized shops. These facilities were manned by well-trained specialists who took pride in their skills and products. The personnel benefited by having a high degree of specialized knowledge and equipment to perform their jobs, and the companies benefited by increased quality and quantity of production. We think similar benefits could be gained through implementation of this method at the Army overhaul facility.

Additional automation techniques are needed for Army overhaul facilities to make it possible for the weight change process to be controlled by a balancing computer in a closed-loop operation.

Laser balancing is viewed with concern by manufacturers for application to flight propulsion hardware. Alternatives to the laser are needed to achieve manufacturer acceptance to automated balancing for use in manufacturing or overhaul.

Thermal spray balancing was viewed with cautious optimism when we suggested the concept for use on flight propulsion hardware. The main acceptance criterion was identified as proof that the sprayed material would stay in place.

## SPRAY AUTOMATED BALANCING

The FARE thermal spray process has clear advantages for use in spray automated balancing. As a pulsed process, it can be easily timed to apply spray at the right location on a spinning disk. It can spray a variety of materials and produces good bond strengths.

Unbalance correction by weight addition has further potential advantages for reduction of weight and reduction of parts lost due to insufficient material for removal.

There is need for applications engineering to make spray automated balancing adaptable to all engine and drive components. The more difficult configurations are where direct, perpendicular, line-of-sight access cannot be achieved between the spray nozzle and the balance correction surface, where the spray target strip is very narrow, and where the correction surface is accessible only by disassembly.

## BOND AND FATIGUE TESTS

For the material combinations tested, bond strengths of sprays applied by the FARE gun are acceptable for the levels of stress expected in the aircraft propulsion hardware operating environment. Analysis indicates that the maximum expected operational stresses acting to debond the spray material are on the order of 7 MPa (1,000 psi). Tungsten carbide sprayed on 17-4 PH stainless had an average bond strength of 62 MPa (8900 psi) and an endurance fatigue limit better than that for hand-ground specimens of 17-4 PH. The average bond strength of Inconel 718 powder sprayed on Inconel 718 was 35 MPa (5100 psi) with a fatigue endurance limit equivalent to hand-ground specimens of the same material. Bond strength tests of Triballoy 800 sprayed on Inconel 718 averaged 34 MPa (5000 psi) with a fatigue endurance value somewhat lower than the comparable value for hand-ground Inconel specimens.

Metallographic inspection of unstressed FARE gun sprayed specimens showed good adhesion characteristics of low coating porosity and an intimate bond line between the coating and substrate. The spray material, applied in built-up layers over short time intervals, produces a homogeneous coating.

Microscopic inspection of fatigue cracks in the sprayed coupons revealed that cracks in the spray material did not directly propagate into the substrate material.

One film-substrate combination acceptable for spray automated balancing application in each of the "hot" and "cold" sections of gas turbines has been identified. In the compressor section, tungsten carbide can be sprayed on 17-4 PH stainless steel, and in the turbine section, Inconel 718 powder can be sprayed on Inconel 718 with good results.

# APPENDIX A

# SPRAY FILM - SUBSTRATE STRESSES

## I. SPRAY PULSE LENGTH CALCULATION

$$T = \frac{\theta}{\omega}$$

Where: $\theta$ = angle covered by the spray
$\omega$ = rotational speed of target
$T$ = time or pulse length limit

Example – To apply a film over no more than 180° of arc ($\pi$ radians) at 3000 rpm, 50 Hz, the maximum pulse length is:

$$T = (\pi \text{ rad}) \left(\frac{\text{sec}}{50 \text{ cyc}}\right) \left(\frac{\text{cyc}}{2\pi \text{ rad}}\right) = 0.010 \text{ sec}$$

## II. ANGULAR EXTENT OF SPRAYED STRIP

$$dU = R\rho W \, t \, d\theta \, R \cos\theta$$

Where: $\theta$ = angular extent
$U$ = unbalance
$R$ = radius to film
$W$ = width of film
$t$ = thickness of film
$\rho$ = density of film applied

$$U = R^2 \rho W t \int_{-\frac{\theta}{2}}^{\frac{\theta}{2}} \cos\theta \, d\theta$$

$$U = 2R^2 \rho W t \sin\left(\frac{\theta}{2}\right)$$

$$\theta = 2 \sin^{-1}\left[\frac{U}{2R^2 \rho W t}\right]$$

Centrifugal Force Applied to Sprayed Film

$$F_{orce} = MR\omega^2$$

| | | | |
|---|---|---|---|
| Where: | M | = | eccentric mass |
| | R | = | radius of mass |
| | $\omega$ | = | rotational speed in radian/sec |
| and | U | = | Mr |

Stress on Sprayed Film

$$\sigma = \frac{F}{A} = \frac{MR\omega^2}{LW} = \frac{U\omega^2}{LW}$$

See Table *"Turbine Balance Survey"* for example data.

## III. STRESS CREATED BY ENGINE ACCELERATION TO SPEED

$$\alpha \text{ (rotational acceleration)} = \frac{\Delta\omega}{\Delta t}$$

$$a = \alpha r = \frac{r\Delta\omega}{\Delta t}$$

$$F = ma = mr\frac{\Delta\omega}{\Delta t}$$

$$\sigma = \frac{F}{A} = \frac{mr}{A}\frac{\Delta\omega}{\Delta t}$$

Example T-63

for: mr = 2 gm-in (high unbalance)
r = 2 in
m = 1 gram

$$\Delta\omega = 12000\text{ rpm} = \left(\frac{12000\text{ rev}}{\text{min}}\right)\left(\frac{\text{min}}{60\text{ sec}}\right)\left(\frac{2\pi\text{ rad}}{\text{rev}}\right) = 1256\text{ rad/sec}$$

idle to max speed

$\Delta t$ = 6 seconds – per industry survey, typical for Allison engine
6-8 seconds idle to max speed
6-8 seconds fire to idle
1 gram 10 mils thick has area of 0.779 in$^2$

$$\sigma = \left(\frac{(2\text{ gm-in})\text{ lbs}}{453.6\text{ gm}}\right)\left(\frac{1}{0.779\text{ in}^2}\right)\left(\frac{1256\text{ rad/sec}}{6\text{ sec}}\right)\left(\frac{\text{sec}^2}{386.4\text{ in}}\right) = 0.0031\text{ psi}$$

No reasonable variation of these parameters can make this stress a concern.

## IV. STRESS CREATED BY A DIFFERENCE IN THERMAL GROWTH BETWEEN A SPRAYED FILM AND ITS SUBSTRATE

$$\text{STRAIN} = \varepsilon = \frac{\Delta L}{L} = (\alpha_1 - \alpha_2)\,\Delta T$$

$$\varepsilon = \Delta\alpha\Delta T$$

$$E = \frac{\sigma}{\varepsilon}$$

$$\sigma = E\Delta\alpha\Delta T$$

Where:

| | | |
|---|---|---|
| $L$ | = | length of film |
| $\Delta L$ | = | change in length due to change in temperature |
| $\Delta\alpha$ | = | difference in thermal expansion coefficient between film and substrate |
| $\Delta T$ | = | change in temperature |
| $E$ | = | modulus of elasticity of film |
| $\sigma$ | = | stress in film |

For example: If pure Tungsten were sprayed on Inconel 718

| | | | | |
|---|---|---|---|---|
| $\alpha_1$ | – | Inconel | = | $8.0 \times 10^{-6}$ in/in/°F @ 1000°F |
| $\alpha_2$ | – | Tungsten | = | $8.83 \times 10^{-6}$ in/in/°F @ 1000°F |
| $\Delta T$ | = | 1500°F | | |
| $E$ | – | Tungsten | = | $50 \times 10^6$ psi |
| $\sigma$ | = | $(50 \times 10^6)(.83 \times 10^{-6})(1500°)$ = 62,250 psi | | |

| | | | | | |
|---|---|---|---|---|---|
| **T-700 Centrifugal Stage** | | | | | |
| Film thickness - in. (vary) | 0.006 | 0.010 | 0.020 | 0.050 | 0.100 |
| Strip width - in. (est.) | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| Speed - RPM (input) | 44,700 | 44,700 | 44,700 | 44,700 | 44,700 |
| Radius - in. (input) | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 |
| Angular extent - degrees | 153.69 | 71.50 | 33.97 | 13.42 | 6.70 |
| Unbalance - gm-in (input) | 12.00 | 12.00 | 12.00 | 12.00 | 12.00 |
| Area - in^2 | 5.36 | 2.50 | 1.19 | 0.47 | 0.23 |
| Force - lbs. | 1,500.17 | 1,500.17 | 1,500.17 | 1,500.17 | 1,500.17 |
| Mass - grams | 4.13 | 3.20 | 3.04 | 3.01 | 3.00 |
| Stress - psi | 280 | 601 | 1,265 | 3,202 | 6,416 |
| | | | | | |
| | | | | | |
| **T-700 Pow. Turb. Shaft** | | | | | |
| Film thickness - in. (vary) | 0.005 | 0.013 | 0.020 | 0.050 | 0.100 |
| Strip width - in. (est.) | 1.30 | 0.50 | 0.50 | 0.50 | 0.50 |
| Speed - RPM (input) | 21,000 | 21,000 | 21,000 | 21,000 | 21,000 |
| Radius - in. (input) | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 |
| Angular extent - degrees | 174.21 | 174.21 | 80.96 | 30.10 | 14.92 |
| Unbalance - gm-in (input) | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 |
| Area - in^2 | 2.37 | 0.91 | 0.42 | 0.16 | 0.08 |
| Force - lbs. | 16.56 | 16.56 | 16.56 | 16.56 | 16.56 |
| Mass - grams | 1.52 | 1.52 | 1.09 | 1.01 | 1.00 |
| Stress - psi | 7 | 18 | 39 | 105 | 212 |
| | | | | | |
| | | | | | |
| **T-700 Pow. Turbine** | | | | | |
| Film thickness - in. (vary) | 0.005 | 0.010 | 0.020 | 0.050 | 0.100 |
| Strip width - in. (est.) | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| Speed - RPM (input) | 21,000 | 21,000 | 21,000 | 21,000 | 21,000 |
| Radius - in. (input) | 5.50 | 5.50 | 5.50 | 5.50 | 5.50 |
| Angular extent - degrees | 11.82 | 5.90 | 2.95 | 1.18 | 0.59 |
| Unbalance - gm-in (input) | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| Area - in^2 | 0.57 | 0.28 | 0.14 | 0.06 | 0.03 |
| Force - lbs. | 55.18 | 55.18 | 55.18 | 55.18 | 55.18 |
| Mass - grams | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 |
| Stress - psi | 97 | 195 | 390 | 974 | 1,948 |
| | | | | | |
| | | | | | |

# TURBINE BALANCE SURVEY

| | | | | | |
|---|---|---|---|---|---|
| **T-55 Gas Generator** | | | | | |
| Film thickness - in. (vary) | 0.005 | 0.010 | 0.020 | 0.050 | 0.100 |
| Strip width - in. (est.) | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| Speed - RPM (input) | 18,720 | 18,720 | 18,720 | 18,720 | 18,720 |
| Radius - in. (input) | 7.00 | 7.00 | 7.00 | 7.00 | 7.00 |
| Angular extent - degrees | 145.06 | 56.97 | 27.59 | 10.95 | 5.47 |
| Unbalance - gm-in (input) | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 |
| Area - in^2 | 8.86 | 3.48 | 1.69 | 0.67 | 0.33 |
| Force - lbs. | 657.78 | 657.78 | 657.78 | 657.78 | 657.78 |
| Mass - grams | 5.69 | 4.47 | 4.33 | 4.29 | 4.29 |
| Stress - psi | 74 | 189 | 390 | 984 | 1,969 |
| | | | | | |
| | | | | | |
| **T-55 Power Turbine** | | | | | |
| Film thickness - in. (vary) | 0.005 | 0.012 | 0.020 | 0.050 | 0.100 |
| Strip width - in. (est.) | 1.16 | 0.50 | 0.50 | 0.50 | 0.50 |
| Speed - RPM (input) | 15,333 | 15,333 | 15,333 | 15,333 | 15,333 |
| Radius - in. (input) | 4.50 | 4.50 | 4.50 | 4.50 | 4.50 |
| Angular extent - degrees | 168.42 | 148.20 | 70.49 | 26.69 | 13.25 |
| Unbalance - gm-in (input) | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 |
| Area - in^2 | 15.34 | 5.82 | 2.77 | 1.05 | 0.52 |
| Force - lbs. | 441.29 | 441.29 | 441.29 | 441.29 | 441.29 |
| Mass - grams | 9.85 | 8.96 | 7.11 | 6.73 | 6.68 |
| Stress - psi | 29 | 76 | 159 | 421 | 848 |
| | | | | | |
| | | | | | |
| **T-53 Gas Generator** | | | | | |
| Film thickness - in. (vary) | 0.005 | 0.010 | 0.020 | 0.050 | 0.100 |
| Strip width - in. (est.) | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| Speed - RPM (input) | 25,150 | 25,150 | 25,150 | 25,150 | 25,150 |
| Radius - in. (input) | 7.00 | 7.00 | 7.00 | 7.00 | 7.00 |
| Angular extent - degrees | 145.06 | 56.97 | 27.59 | 10.95 | 5.47 |
| Unbalance - gm-in (input) | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 |
| Area - in^2 | 8.86 | 3.48 | 1.69 | 0.67 | 0.33 |
| Force - lbs. | 1,187.25 | 1,187.25 | 1,187.25 | 1,187.25 | 1,187.25 |
| Mass - grams | 5.69 | 4.47 | 4.33 | 4.29 | 4.29 |
| Stress - psi | 134 | 341 | 704 | 1,775 | 3,555 |
| | | | | | |
| | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| **T-53 Power Turbine** | | | | | |
| Film thickness - in. (vary) | 0.005 | 0.012 | 0.020 | 0.050 | 0.100 |
| Strip width - in. (est.) | 1.16 | 0.50 | 0.50 | 0.50 | 0.50 |
| Speed - RPM (input) | 21,510 | 21,510 | 21,510 | 21,510 | 21,510 |
| Radius - in. (input) | 4.50 | 4.50 | 4.50 | 4.50 | 4.50 |
| Angular extent - degrees | 168.42 | 148.20 | 70.49 | 26.69 | 13.25 |
| Unbalance - gm-in (input) | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 |
| Area - in^2 | 15.34 | 5.82 | 2.77 | 1.05 | 0.52 |
| Force - lbs. | 868.46 | 868.46 | 868.46 | 868.46 | 868.46 |
| Mass - grams | 9.85 | 8.96 | 7.11 | 6.73 | 6.68 |
| Stress - psi | 57 | 149 | 314 | 829 | 1,669 |
| | | | | | |
| | | | | | |
| **T-63 Gas Generator** | | | | | |
| Film thickness - in. (vary) | 0.005 | 0.010 | 0.020 | 0.050 | 0.100 |
| Strip width - in. (est.) | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| Speed - RPM (input) | 53,500 | 53,500 | 53,500 | 53,500 | 53,500 |
| Radius - in. (input) | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| Angular extent - degrees | 52.42 | 25.52 | 12.68 | 5.06 | 2.53 |
| Unbalance - gm-in (input) | 1.13 | 1.13 | 1.13 | 1.13 | 1.13 |
| Area - in^2 | 0.91 | 0.45 | 0.22 | 0.09 | 0.04 |
| Force - lbs. | 203.08 | 203.08 | 203.08 | 203.08 | 203.08 |
| Mass - grams | 0.59 | 0.57 | 0.57 | 0.57 | 0.57 |
| Stress - psi | 222 | 456 | 918 | 2,298 | 4,597 |
| | | | | | |
| | | | | | |
| **Typical Drive Shaft** | | | | | |
| Film thickness - in. (vary) | 0.005 | 0.013 | 0.020 | 0.050 | 0.100 |
| Strip width - in. (est.) | 2.60 | 1.00 | 1.00 | 1.00 | 1.00 |
| Speed - RPM (avg. - input) | 8,000 | 8,000 | 8,000 | 8,000 | 8,000 |
| Radius - in. (est.) | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Angular extent - degrees | 174.21 | 174.21 | 80.96 | 30.10 | 14.92 |
| Unbalance - gm-in (input) | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 |
| Area - in^2 | 23.72 | 9.12 | 4.24 | 1.58 | 0.78 |
| Force - lbs. | 120.13 | 120.13 | 120.13 | 120.13 | 120.13 |
| Mass - grams | 15.22 | 15.22 | 10.88 | 10.12 | 10.03 |
| Stress - psi | 5 | 13 | 28 | 76 | 154 |

# APPENDIX B

# THERMAL SPRAY PROCESSES

## Thermal Spray Processes

Thermal Spray (THSP) is a process in which a metallic or nonmetallic material is heated and then propelled in atomized form onto a substrate. The material may be initially in the form of wire, rod, or powder. It is heated to the plastic state by an oxy-fuel gas flame, by an electric or plasma arc, or by detonation of an explosive mixture. The hot material is propelled from the spray gun to the substrate by a gas jet. Most metals, cermets, oxides, and hard metallic compounds can be deposited by one or more of the process variations. Even abrasives can be sprayed by some of these techniques.

When the molten particles strike a substrate, they flatten and form thin platelets that conform to the surface. These platelets rapidly solidify and cool. Successive layers are built up to the desired thickness. The bond between the spray deposit and substrate may be mechanical, metallurgical, chemical, or a combination of these.

The density of the deposit will depend upon the material type, method of deposition, the spraying procedures, and subsequent processing. The properties of the deposit may depend upon its density, the cohesion between the deposited particles, and its adhesion to the substrate.

Thermal spraying is widely used for surfacing applications to attain or restore desired dimensions, to improve resistance to abrasion, wear, corrosion, oxidation, or a combination of these.

## Alternative Approaches

Thermal spraying can be conveniently grouped into four variations:

(1) Flame spraying (FLSP)
(2) Plasma spraying (PSP)
(3) Arc spraying (ASP)
(4) Detonation flame spraying

These variations are based on the method of heating the spray material to the molten or plastic state and the technique for propelling the atomized material to the substrate.

In flame spraying, the surfacing material is continuously fed into and melted by an oxy-fuel gas flame. The material may be initially in the form of wire, rod, or powder. Molten particles are projected onto a substrate by either an air jet or the combination gases.

In plasma spraying, the heat for melting the surfacing material is provided by a nontransferred arc. The arc is maintained between an electrode, usually tungsten, and a constricting nozzle which serves as the other electrode. An inert or reducing gas, under pressure, enters the annular space between the electrodes where it is heated to a very high temperature (above 8,300°C or 15,000°F). The hot plasma gas passes through and exits from the nozzle as a very high velocity jet. The surfacing material in powder form is injected into the hot gas jet where it is melted and projected onto the substrate.

The surfacing materials used with arc spraying are metals or alloys in wire form. Two continuously fed wires are melted by an arc operating between them. The molten metal is atomized and projected onto a substrate by a high velocity gas jet, usually air.

The detonation flame spraying method operates on principles significantly different from the other three methods. This technique repeatedly heats charges of powder and projects the molten particles onto a substrate by rapid, successive detonations of an explosive mixture of oxygen and acetylene or fuel mixture in a gun chamber. The particles leave the gun at a much higher velocity than with the other methods.

## Flame Spraying

Flame spraying is used to deposit surfacing materials in the forms of metal wires, ceramic rods, and metallic and nonmetallic powders. A wide variety of materials in these forms can be sprayed with this method.

Materials are normally deposited in multiple layers, each of which is less than 0.25 mm (0.010 in.) thick. The total thickness of a material that should be deposited will depend upon several factors including:

- Type of surfacing material and its properties
- Type and properties of the workpiece material
- Service requirements of the composite
- Post-spray treatment of the composite.

A typical flame spraying arrangement consists of the following equipment:

- A flame spray gun
- A source of surfacing material and the associated feeding equipment
- Oxygen and fuel gas supplies, pressure regulators, and flow meters
- A compressed air source and control unit, when required
- Workpiece holding device.

The gun design depends upon the type of material to be sprayed and its physical form. When automated, the gun or the workpiece, or both, are driven by mechanisms designed to produce the desired deposit configurations.

Three common fuel gases are used for flame spraying: acetylene, propane, and methylacetylene-propadiene (MPS). Acetylene in combination with oxygen produces the highest flame temperature. The distinct characteristics of an oxyacetylene flame make it rather easy to adjust the combination ratio to produce oxidizing, neutral, or reducing conditions. Since the molten particles are exposed to oxygen, an oxide film will form on them, even when a reducing gas mixture is used. The thickness of the oxide film does not appear to vary greatly with minor changes in the fuel gas-to-oxygen ratio.

A wire type gun consists essentially of two subassemblies: a drive unit which feeds the wire and a gas head which controls the flow of fuel gas, oxygen, and compressed air. The principles of operation of all wire type guns are very similar.

The wire drive unit consists of a motor and drive rolls. They may be air or electrically powered with adjustable speed controls. Speed controls may be mechanical, electromechanical, electronic, or pneumatic, depending upon the type of power.

The gas head (Figure 60) consists of valves to control the fuel gas, oxygen, and compressed air, and a gas nozzle and air cap. The wire is fed through a central orifice in the nozzle. If the wire feed rate is excessive, the wire tip will extend beyond the hot zone of the flame and it will not melt and atomize properly. This will produce very coarse deposits. If the feed is too slow, thc metal will oxidize badly, and the wire may fuse in the nozzle. The spray deposit will have a high oxide content.

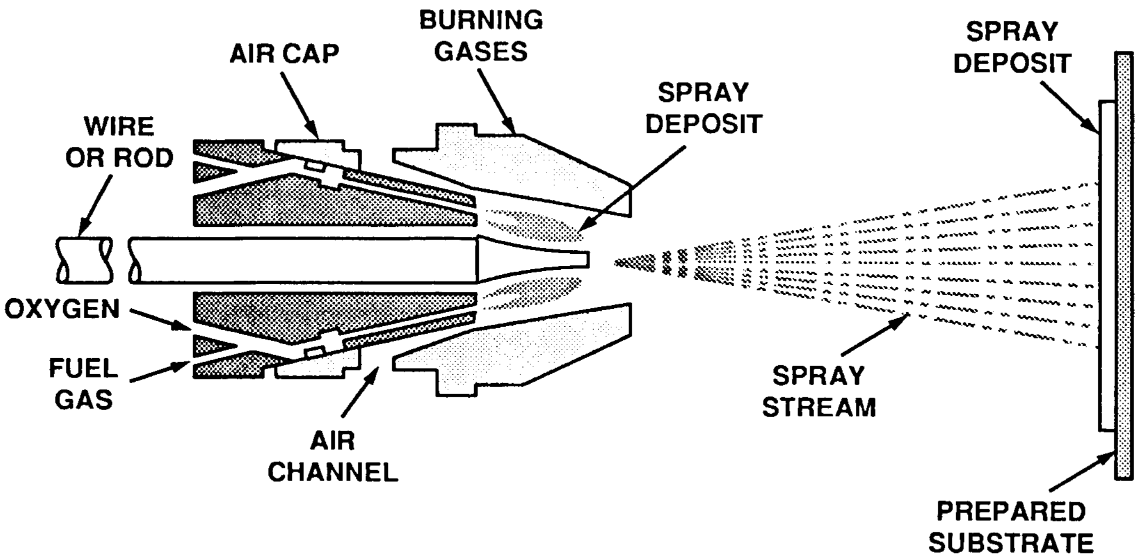



FIGURE 60. WIRE FLAME SPRAY GUN CROSS SECTION

## Powder Flame Spray

In the combustion flame spray, shown in Figure 61, the powder is fed into the chamber where it is melted in an oxyhydrogen or oxyacetylene flame at a temperature of over 2500°C (4500°F). The melted material is then projected onto the prepared base material. This process depends upon melting of the suspended particles in a gaseous medium. The temperature and size of the particles must be closely controlled. Large particles will receive insufficient heat, resulting in a weak point or area in the coating.

## Arc Spraying

Arc spraying (ASP) utilizes an arc between two wires to melt their tips. A jet of compressed gas, normally air, atomizes the molten metal and projects the particles onto a prepared substrate. A simple version of arc spraying is shown in Figure 62.

The apparatus simultaneously and continuously feeds two wires through electrical contacts at uniform speeds. The contacts also serve as guides to direct the wires toward a point of intersection.

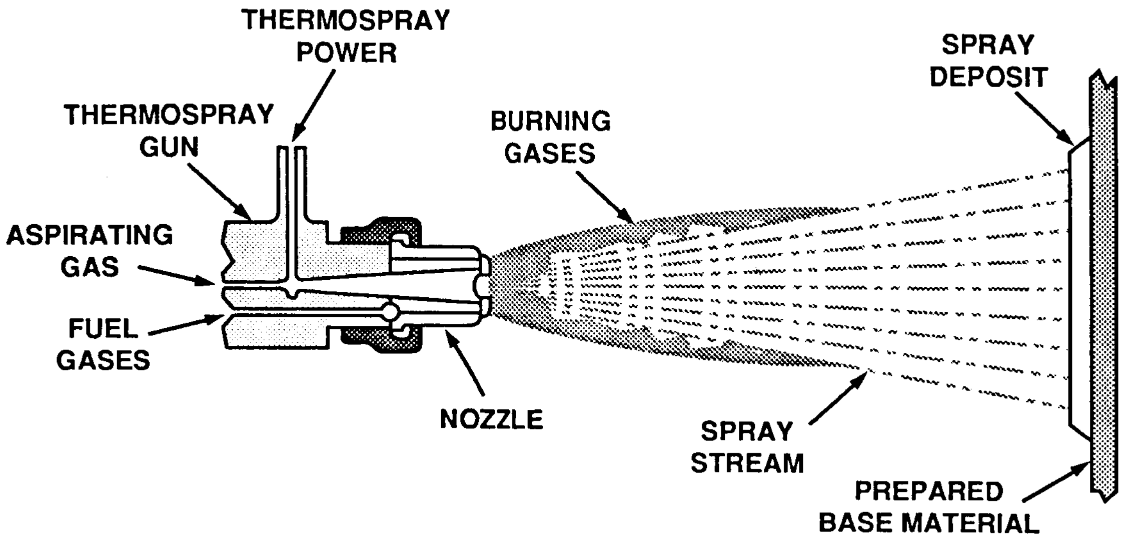



FIGURE 61. COMBUSTION FLAME SPRAY GUN

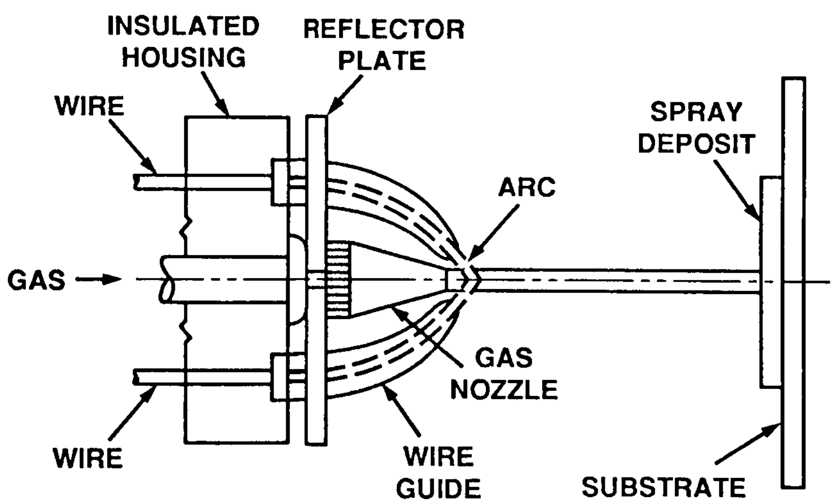



FIGURE 62. ARC SPRAYING

Direct current power is normally used for arc spraying; one wire is positive (anode) and the other is negative (cathode). The cathode wire tip is heated to a higher temperature than the anode wire tip and melts at a faster rate. Consequently, the particles atomized from the cathode wire are much smaller than those from the anode wire when the two wires are identical. When dissimilar metals are sprayed, the deposit is a heterogeneous blend of the two metals with some alloying.

The velocity of the gas as it leaves the gun nozzle can be regulated over a broad range to control the deposit characteristics. Molten metal particles are ejected from the arc at the rate of several thousand particles per second, some of which are in the superheated state. These molten particles will bond to minute protrusions of properly cleaned and roughened substrate. The resulting deposit is highly adherent to the substrate and has strong interparticle cohesive strength.

In addition to the strong bond strength, other advantages of this process over wire flame spraying are:

(1) The quantity of metal oxides in the deposit can be controlled by spray conditions.
(2) Spray rates are generally higher.
(3) It may be more economical.

Arc spraying may be more economical than other spraying methods in some cases. Energy and labor costs may be lower because of higher spray rates and deposition efficiencies available with this method. One adverse effect of the high energy state of the atomized particles is their tendency to change composition through selective oxidation or vaporization, or both. The nature of these effects is complex, but they can be minimized by judicious selection of wire composition.

The arc method is less versatile than the plasma method because only wire can be sprayed. Particle temperatures and velocities are generally lower than with plasma spraying but higher than with wire flame spraying.

## Plasma Spraying

Plasma spraying utilizes the heat of a plasma arc to melt the surfacing material. The term "plasma arc" is used to describe a family of metal working processes that use a constricted electric arc to provide high density thermal energy. Arc constriction is usually accomplished by forcing the arc plasma through a water-cooled copper orifice. The purpose of this is to control and increase the energy density of the arc stream. Plasma arc processes are employed for welding, cutting, and surfacing of metals. In plasma spraying, a nontransferred arc is constricted between an electrode and a constricting nozzle. A plasma spray unit consists of a gun, power source, gas source, spray material supply, and associated fixturing and traversing devices.

Several types of plasma spray torches are available. In each instance, the arc is generated between an electrode and a water-cooled chamber into which a plasma gas is injected. The gas picks up arc energy and exits from a nozzle in a configuration that resembles an open welding flame. A typical gun is shown in Figure 63.

An important factor in producing quality deposits is the introduction of powder at the proper point in the arc plasma and at the correct feed rate. Since the particles are in the plasma for only about $2 \times 10^{-5}$s, slight variations in the location of the feed point may significantly change the amount of heat transmitted to the powder.

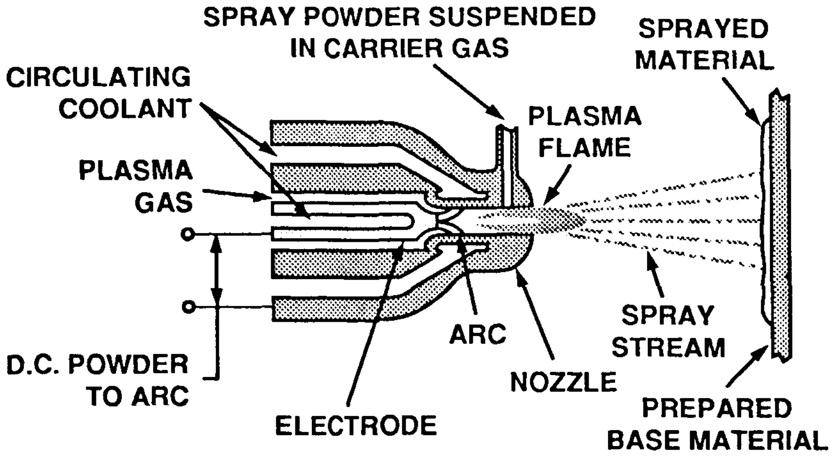



**FIGURE 63. PLASMA SPRAY GUN CROSS SECTION**

Current torch designs have power capacities of from 40 to 100 KW. Direct current of 100 to 1100 A is used at 40 to 100 V. High power is necessary when spraying with high particle velocities. Particle velocity is an important variable with respect to bond strength, deposit density, and deposit integrity.

Mechanical powder feed mechanisms are the most popular type, since they utilize the metering action of a screw or wheel to deliver powder at a constant rate to a mixing chamber. Here, the powder is introduced into the carrier gas stream.

A complete system, including the spray unit, can be operated from a console. The console provides adjustment of the plasma gas flow rates, plasma current, starting and stopping functions and, in some cases, operation of the powder feed unit. These functions are common to all plasma spray systems.

Plasma spraying can be done in a sealed chamber containing an inert gas atmosphere at or below atmospheric pressure. This technique provides improved oxidation protection for the molten particles and the substrate. The substrate can then be preheated to a higher temperature without excessive oxidation. Deposition efficiency and deposit quality are better than when spraying in air.

Four gases commonly used for plasma spraying and their important characteristics are as follows:

(1) Nitrogen is widely used because it is inexpensive, diatomic, and permits high spraying rates and deposit efficiencies. Nozzle life will be shorter than with monatomic gases, but this factor can be offset by the lower cost of the gas.

(2) Argon provides a high velocity plasma. It is used to spray materials that would be adversely affected if hydrogen or nitrogen were used. Carbides and high temperature alloys are most commonly sprayed with argon.

(3) Hydrogen may be used as a secondary gas with nitrogen or argon in amounts of 5 to 25 percent. Hydrogen addition raises the arc voltage and, thus, the power. It may be detrimental with certain metals.

(4) Helium is usually used as a secondary gas mixed with argon. It will also tend to raise the arc voltage.

It is usually necessary to use plasma spraying equipment for powders with melting points above 2800°C (5000°F). This method is well qualified for depositing refractory metals and ceramics. Plasma sprayed ceramic deposits exhibit high densities and hardnesses. High density, plasma sprayed deposits can be thinner, but may be more susceptible to cracking.

## Detonation Flame Spraying

Detonation flame spraying describes several processes, developed by different manufacturers to accomplish the same goal. The D-gun developed by Union Carbide is perhaps the best known, but because of its proprietary nature and expense, the FARE process was developed by Southwest Research Institute for American Airlines and is now marketed by the H. B. Zachry Co. of San Antonio.

### D-Gun Process

The D-gun (Figure 64) is a process in which a specially designed gun is used to detonate an oxygen and acetylene mixture. The powdered surfacing material is suspended in nitrogen and metered into the combustion gun where the oxyacetylene mixture is detonated by an electric spark several times per second. This creates a hot, high velocity gas stream that heats the powder to its plastic state and then accelerates the particles to a speed of about 800 m/s (2500 ft/s) as they leave the gun barrel. The molten particles impinge on the surface of the workpiece. Successive detonations in the gun build up the deposit to the desired thickness.

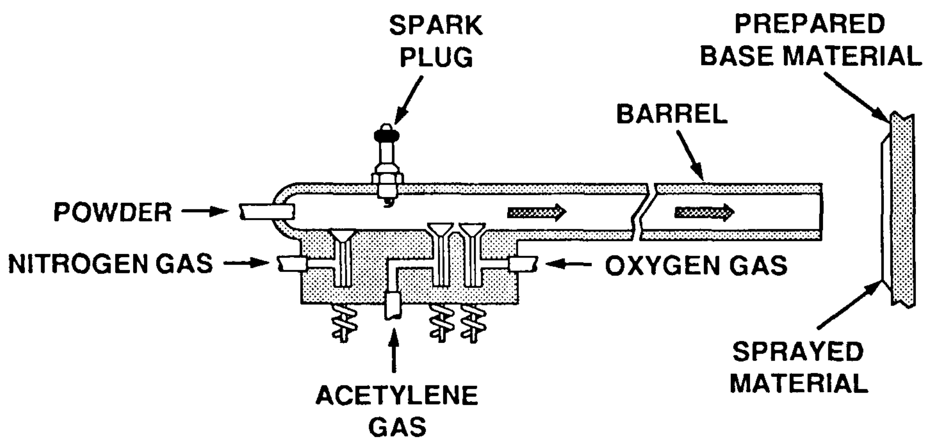



FIGURE 64. D-GUN EQUIPMENT

The high bond integrity of detonation sprayed deposits is due to the high velocity at which the particles strike the substrate. It is roughly 2.5 to 5 times faster than the velocities of particles from a plasma or powder flame spraying gun. Since kinetic energy is a function of the square of the velocity, particles from a detonation flame spray gun strike the surface with an energy at least 25 times greater than those from a flame spray gun. As a result, coatings with only 0.25 to 1 percent porosity are commonly achieved with this equipment. These include the following materials:

(1) Alumina
(2) Alumina-titania
(3) Chromium carbide with a nickel-chromium alloy binder
(4) Tungsten carbide with a cobalt binder
(5) Tungsten carbide-tungsten chromium carbide mixture with a nickel chromium alloy binder.

These are primarily wear resistant coatings for elevated temperature service. Sprays of liquid carbon dioxide are used to cool the workpiece during spraying. Consequently, metallurgical changes or warpage of the workpiece do not normally occur with this spraying method.

Since the spraying operation is a series of rapid detonations, the noise level is quite high. Spraying is normally done in a specially constructed application room to contain this noise.

### FARE Process

FARE is an acronym for **F**uel/**A**ir **R**epetitive **E**xplosion, the name associated with a hard face coating process developed by Southwest Research Institute and the H. B. Zachry Company. The FARE Process cycle consists of injecting a refractory powder into a combustion chamber in which an explosive mixture of air/propane is ignited by a spark plug. At the temperatures and pressures generated by the combustion gases, the powdered refractory particles are softened and expelled through a nozzle outlet from the chamber onto the surface to be coated, at particle impact velocities and temperatures of approximately 450 m/s (1500 fps) and 1700°C (3000°F), respectively. The cycle is repetitive, its frequency (firing rate) controllable from 1 to 5 cycles per second. Depending upon the firing rate and rate of nozzle movement relative to the surface being coated, coating material can be deposited at a rate of 1800 g/hr. (4 lb/hr.), coating an area of 130 $mm^2$/shot (0.2 sq in/shot) at a thickness of 0.025 mm (0.001 in) for each shot. The actual combustion process and coating deposition period represent only 10 percent of the total cycle time at the maximum firing rate. During the remaining 90 percent of the cycle, purge air is forced through the combustion chamber and out the nozzle, an aid in workpiece temperature control. This short combustion-coating period also minimizes the heat input to the substrate material, allowing it to remain at a sufficiently low temperature to avoid distortion and metallurgical changes. The process is operated continuously until the required coating thickness has been achieved. Coatings over one tenth of an inch thick have been achieved with the FARE process.

The FARE concept uses the powdered refractory material delivered to the injector as premeasured discrete cells encapsulated in PVC tape; this is illustrated in Figures 65 and 66. The combustion chamber and nozzle are water-cooled. The inlet valve opens for a period of 10 milliseconds, allowing the chamber to reach a charge pressure of approximately 450 KPa (65 psig). The volume of the chamber and bore of the nozzle are sized to prevent an excessive loss of mixture through the nozzle during the charging process. The combustible mixture is ignited by conventional spark plugs.

The only utilities required for this gun are a supply of propane and 760 KPa (110 psig) shop air, along with standard electrical power and cooling water.

The system, in comparison with other available means for flame spraying of hard coatings, provides superior performance in terms of hardness, bond strength, low porosity, versatility, and ease and cost of operation.

The size and deposition rate are constant once spray distance has been determined for a particular substrate material. This makes the system very adaptable to automation.

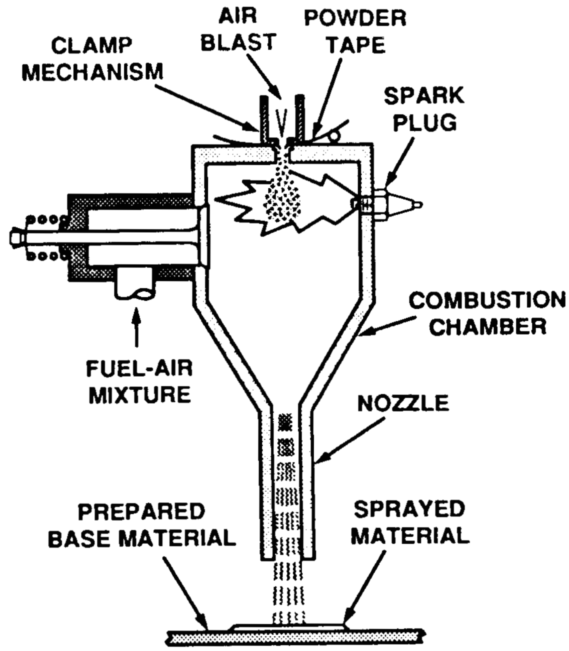



FIGURE 65. DETAIL OF FARE GUN POWDER DISPENSER SYSTEM

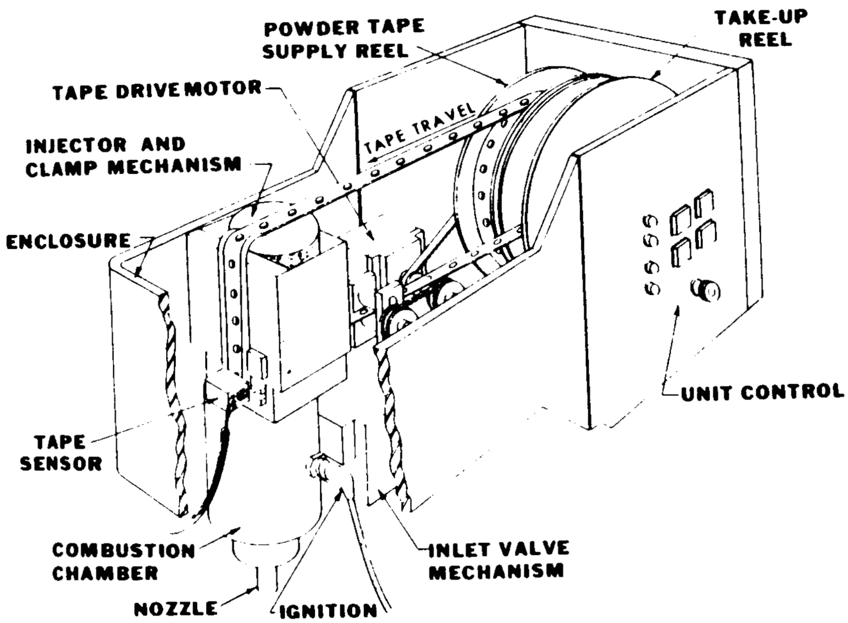



FIGURE 66. POWDER TAPE SCHEMATIC

## GATOR-GARD

The GATOR-GARD process uses a high temperature, high velocity, ionized gas to deposit metal or ceramic particles on substrate materials. The high particle velocities and their extremely short dwell time at high temperature produces dense, well bonded coatings with unique structures which can be tailored for maximum resistance to wear, erosion and impact.

The nozzle first cools the plasma gas and then introduces the powder, which is entrained in an inert gas, to the gas stream. The particles are then educted into the hot, high velocity gas stream inside the nozzle and contained long enough for uniform particle temperatures and velocities to be obtained throughout the cross-sectional area of the gas stream. The effect of cooling the gas stream prior to the introduction of the powder is seen in the retention of the original material phase structure in the as deposited coating.

The resultant coating has a uniformly low stress level when compared to other coatings of this nature, high bond strength, greater than 70 MPa (10,000 psi) and is nearly 100 percent dense. The high particle velocities obtained also reduce the particle dwell time in air, minimizing the formation of oxides and the phase transformation of time/temperature dependent materials.

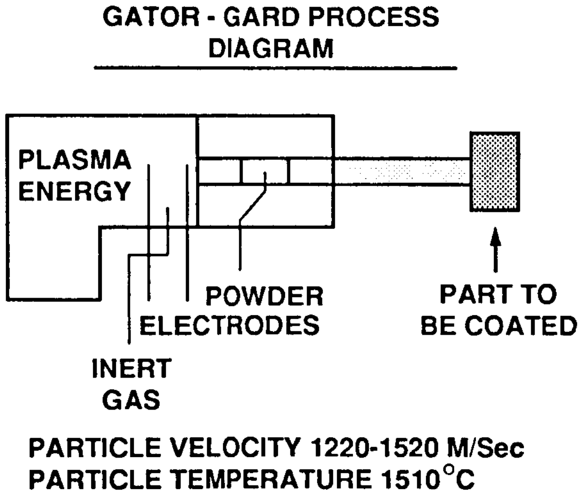



FIGURE 66. GATOR-GARD PROCESS DIAGRAM

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# APPENDIX C

## ALLOY CERTIFICATES

**CYTEMP SPECIALTY STEEL DIVISION** PAGE: 01 PRSC-111 (R6/85)

CYCLOPS CORPORATION

TITUSVILLE, PA 16354

**MATERIAL CERTIFICATION**

P.O. NUMBER 24187 MILL ORDER NO. 63246- 11/30/86

DESCRIPTION UNILOY 17-4 SOL TRT CENTERLESS GROUND AIRCRAFT QUALITY BARS TO

SPECIFICATION AMS5643L AMS2303A NAA MSO-160-003 REV D EX SONIC CAPABLE ASTM A564-85 TYPE 630 ASME SA564 TYPE 630 QQS763B CL 324 NO CENTER HOLES DELETE CLM ASTM A484-85

SIZE 1.000 RD X 11/13 FT

SHIP TO

FRY STEEL COMPANY

13325 MOLETTE STREET

SANTA FE SPRING CA90670

DATE SHIPPED 11/30/86

QTY. & WGT. 314 Bars - 10,178#

CHEMICAL COMPOSITION

| HEAT ID. | C | MN | SI | S | P | CR | NI | MO | CU |
|---|---|---|---|---|---|---|---|---|---|
| 166833 | .040 | .33 | .54 | .019 | .022 | 15.76 | 4.31 | .18 | 3.27 |
| | CBTA | | | | | | | | |
| | .29 | | | | | | | | |

FRY STEEL CO. CERTIFIES THAT THIS IS A TRUE COPY OF THE ORIGINAL MILL TEST REPORT NOW ON FILE.

RECEIVED AND INSPECTED

DEC 3 1986

BY Henry Kraft

HENRY KRAFT Q.C. MANAGER

MECHANICAL PROPERTIES

CONDITION AS SHIPPED: 1900F 30 MIN WATER

| IDENTIFICATION | HARDNESS, BHN | MAG PART F/S |
|---|---|---|
| | 331/341 | 0/0 |

CONDITION 1 CAP AFT: 900F 1 HR AIR

| IDENTIFICATION | UTS, KSI | .2% YLD, KSI | % EL | % R/A |
|---|---|---|---|---|
| | 206.8 | 185.2 | 13.6 | 52.5 |

| IDENTIFICATION | BHN | FERRITE, % |
|---|---|---|
| | 409 | <1 |

CONDITION 2 CAP AFT: 950F 4 HRS AIR

| IDENTIFICATION | UTS, KSI | .2% YLD, KSI | % EL | % R/A |
|---|---|---|---|---|
| | 182.5 | 170.2 | 13.6 | 57.2 |

REMARKS

MACRO ETCH TEST ACCEPTABLE PER ASTM E340

FREE OF HG & DETRIMENTAL LOW MELTING ALLOY CONTAMINATION

**ORIGINAL PAGE IS OF POOR QUALITY**

All testing procedures are in accordance with ASTM standards or applicable specifications.

The recording of false, fictitious or fradulent statements or entries on this document may be punished as a felony under federal statutes including Federal Law, Title 18, Chapter 47.

The above are true and correct results of tests on samples of the material. Said results meet the specification(s) applicable and are on record.

By Gary Williams

Quality Control Representative

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PAGE: 01

# CYTEMP SPECIALTY STEEL DIVISION

CYCLOPS CORPORATION
TITUSVILLE, PA 16354

## MATERIAL CERTIFICATION

MILL ORDER NO. 60067- 04/29/86

NUMBER 22824
CRIPTION DUBVAC UNITEMP 718 ANNEAL CENTERLESS GROUND TO
CIFICATION AMS5662E BSOTF15A-S13 D50T69A-S6 CAPABLE C50TF13-S6 ASTM B637-84
ASME SB637 SPS M275 RBD 170-153 REV F DELETE CLM RPT CA & MG

1.000" RD X 11/13 FT. FRY STEEL CO. CERTIFIES THAT THIS IS A TRUE COPY OF THE ORIGINAL MILL TEST REPORT NOW ON FILE.
RECEIVED AND INSPECTED

DATE SHIPPED 4/30/86
QTY. & WGT. 136 Bars - 4852#

P TO

FRY STEEL COMPANY

APR 2 2 1987

13325 MOLETTE STREET
SANTA FE SPRINGS, CALIF.

BY [signature]
HENRY KRAFT Q.C. MANAGER

### CHEMICAL COMPOSITION

| AT ID. | C | MN | SI | S | P | CR | NI | MO | CO |
|---|---|---|---|---|---|---|---|---|---|
| 6L8359K11 | .034 | .06 | .10 | .001 | .007 | 18.37 | 52.94 | 3.01 | .30 |
| | CU | AL | TI | FE | B | CBTA | CAPPM | MGPPM | |
| | .06 | .56 | 1.03 | 18.10 | .0037 | 5.36 | <5 | 12 | |

### MECHANICAL PROPERTIES

CONDITION AS SHIPPED: 1750F 1 HR WATER

| IDENTIFICATION | HARDNESS, BHN | GRAIN SIZE |
|---|---|---|
| | 217/248 | 8 & FINER |

CONDITION 1 CAP. AFT: 1325F 8 HRS COOL 100F/HR TO 1150F 8 HRS AIR

| IDENTIFICATION | UTS, KSI | .2% YLD, KSI | % EL | % R/A |
|---|---|---|---|---|
| R.T. | 206.7 | 173.8 | 17.1 | 36.5 |
| 1200 | 166.8 | 139.0 | 25.7 | 38.8 |

| IDENTIFICATION | S/R TEMP, F | S/R STRESS, KSI | S/R TIME, HRS | S/R % EL |
|---|---|---|---|---|
| COMB | 1200 | 110.0 | 66.3 | 22.3 |

| IDENTIFICATION | BHN |
|---|---|
| | 409 |

CONDITION 2 CAP AFT: 1750F 1 HR WATER+1325F 8 HRS COOL 100F/HR TO 1150F 8 HRS AI

| IDENTIFICATION | UTS, KSI | .2% YLD, KSI | % EL | % R/A |
|---|---|---|---|---|
| R.T. | 204.5 | 182.4 | 14.3 | 29.9 |
| 1200 | 167.5 | 148.5 | 21.4 | 53.7 |

| IDENTIFICATION | S/R TEMP, F | S/R STRESS, KSI | S/R TIME, HRS | S/R % EL |
|---|---|---|---|---|
| COMB | 1200 | 110.0 | 85.7 | 18.5 |

| IDENTIFICATION | BHN | GRAIN SIZE |
|---|---|---|
| | 432 | 8 & FINER |

CONDITION 3 CAP AFT: 1700F 1 HR WATER+1325F 8 HRS COOL 100F/HR TO 1150F 8 HRS AI

| IDENTIFICATION | UTS, KSI | .2% YLD, KSI | % EL | % R/A |
|---|---|---|---|---|

All testing procedures are in accordance with ASTM standards or applicable specifications.

The recording of false, fictitious or fraudulent statements or entries on this document may be punished as a felony under federal statutes including Federal Law Title 18 Chapter 47.

The above are true and correct results of tests samples of the material. Said results meet the specification(s) applicable and are on record.

By [signature]
Quality Control Representative

PAGE: 02

PRSC-111 (R6/85)

CYCLOPS CORPORATION

# CYTEMP SPECIALTY STEEL DIVISION

TITUSVILLE, PA 16354

## MATERIAL CERTIFICATION

NUMBER 22824 MILL ORDER NO. 60067- 04/29/86

DESCRIPTION DUOVAC UNITEMP 718 ANNEAL CENTERLESS GROUND TO

SPECIFICATION AMS5662E B50TF15A-S13 B50T69A-S6 CAPABLE C50TF13-S6 ASTM B637-84
ASME SB637 SPS M275 RBO 170-153 REV F DELETE CLM RPT CA & MG

SIZE 1.000" RD X 11/13 FT.

SHIP TO

FRY STEEL COMPANY

DATE SHIPPED

QTY. & WGT.

13325 MOLETTE STREET
SANTA FE SPRINGS,CALIF. 90670

MECHANICAL PROPERTIES

| | | | | |
|---|---|---|---|---|
| R.T. | 200.8 | 160.1 | 18.6 | 34.2 |
| 1200 | 165.8 | 138.5 | 25.7 | 48.5 |

| IDENTIFICATION | S/R TEMP. F | S/R STRESS.KSI | S/R TIME. HRS | S/R % EL |
|---|---|---|---|---|
| COMB | 1200 | 110.0 | 123.4 | 17.3 |

| IDENTIFICATION | BHN |
|---|---|
| | 421 |

CONDITION 4 CAP AFT: 1900F 30 MIN AIR+1400F 10 HRS COOL 100F/HR TO 1200F 10HR AIR

| IDENTIFICATION | UTS. KSI | .2% YLD. KSI | % EL | % R/A |
|---|---|---|---|---|
| | 202.3 | 172.2 | 19.3 | 40.4 |

| IDENTIFICATION | BHN | GRAIN SIZE | LAVES | BANDING |
|---|---|---|---|---|
| | 400 | 4 TO 6 | NONE | NONE |

| IDENTIFICATION | RECRYSTAL | PRECIP PHASE |
|---|---|---|
| | 100% | NONE |

REMARKS

MACRO ETCH TEST ACCEPTABLE PER ASTM A604
STRESS RUPTURE SAMPLE .160" DIA. WITH NOTCH RADIUS OF .005"
TEST SOURCE #T7767 (TITUSVILLE)
FREE OF HG & DETRIMENTAL LOW MELTING ALLOY CONTAMINATION

FRY STEEL CO. CERTIFIES THAT THIS IS A TRUE COPY OF THE ORIGINAL MILL TEST REPORT NOW ON FILE.
RECEIVED AND INSPECTED

MAY 9 1986

BY Henry Kraft
HENRY KRAFT Q.C. MANAGER

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1" RD HEAT 6L8359K11 718 PAGE 2 OF 2

All testing procedures are in accordance with ASTM standards or applicable specifications.

The recording of false, fictitious or fradulent statements or entries on this document may be punished as a felony under federal statutes including Federal Law, Title 18, Chapter 47.

The above are true and correct results of tests on samples of the material. Said results meet the specification(s) applicable and are on record.

By Kaye Williams
Quality Control Representative

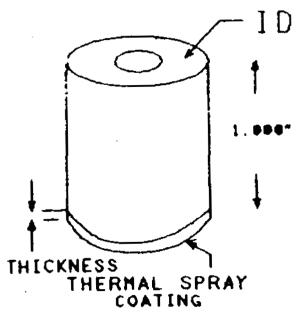
# APPENDIX D

# BOND & FATIGUE TEST SPECIMEN DATA SHEETS

## THERMAL SPRAY COATING BOND TEST SPECIMENS

TUNGSTEN CARBIDE COATING, FC 112

ON 17-4 PH STAINLESS STEEL SUBSTRATE

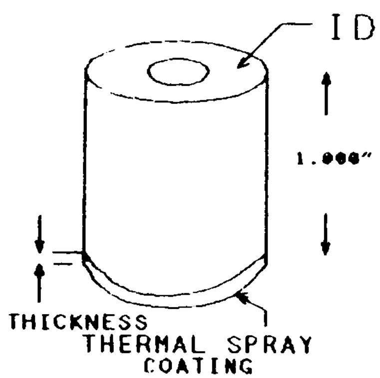



| ID SPECIMEN No. | LENGTH ORIGINAL | LENGTH FINAL | NUMBER OF SHOTS | COATING THICKNESS | LBS LOAD ULTIMATE | TENSILE STRENGTH | DATE |
|---|---|---|---|---|---|---|---|
| 17 - 2 / 12 | 1.005 | 1.0105 | 100 TAPE BROKE | 0.0055 | 5240.0 | 6671 | 9-3-87 |
| 17 - 5 / 15 | 1.003 | 1.022 | 250 | 0.013 | 4276.0 | 5444 | 9-3-87 |
| 17 - 16/ 19 | 1.0055 | 1.009 | 100 | 0.0035 | 3919.8 | 4991 | 9-15-87 |
| 17 - 18/ 22 | 1.000 | NA | 0 | NONE | 5877.7 | 7484 | 9-15-87 |
| 17 - 1 / 11+ | 1.000 | 1.010 | 150 | 0.010 | 5195.9 | 6616 | 9-15-87 |
| 17 - 3 / 13+ | 1.002 | 1.014 | 150 | 0.012 | 5819.9 | 7410 | 9-15-87 |
| 17 - 23/ 22+ | 1.000 | 1.012 | 150 | 0.012 | 6607.9 | 8413 | 9-15-87 |
| 17 - 6 / 16= | 1.000 | 1.009 | 125 | 0.009 | 8311.9 | 10583 | 9-18-87 |
| 17 - 7 / 17+ | 1.000 | 1.009 | 125 | 0.009 | 6655.9 | 8475 | 9-18-87 |
| 17 - 9 / 19+ | 1.000 | 1.009 | 125 | 0.009 | 7631.9 poor alignment | 9717 | 9-18-87 |

# THERMAL SPRAY COATING BOND TEST SPECIMENS

INCONEL 718
COATING, FG 718

INCONEL 718
SUBSTRATE



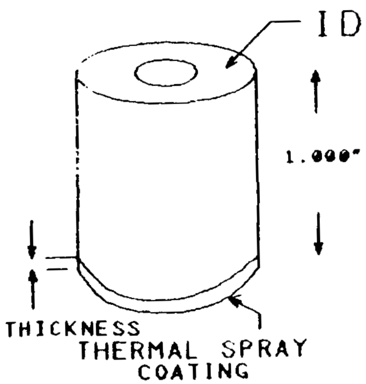

| ID SPECIMEN No. | LENGTH ORIGINAL | LENGTH FINAL | NUMBER OF SHOTS | COATING THICKNESS | LBS LOAD ULTIMATE | TENSILE STRENGTH | DATE |
|---|---|---|---|---|---|---|---|
| IN-1 / | 1.003 | 1.019 | 75 | 0.040 | – | – | – |
| IN-2 / 8 | 1.005 | 1.016 | 75 | 0.011 | 4295.4 | 5469 | 10-6-87 |
| IN-3 / 9 | 1.002 | 1.012 | 75 | 0.010 | 5078.6 | 6466 | 10-6-87 |
| IN-4 / 10 | 1.004 | 1.010 | 75 | 0.006 | 3120.7 | 3973 | 10-6-87 |
| IN-5 / 11 | 1.003 | 1.018 | 75 | 0.015 | 2601.2 | 3312 | 10-6-87 |
| IN-6 / 12 | 1.004 | 1.011 | 75 | 0.007 | 4942.7 | 6293 | 10-6-87 |
| IN-7 / 17-12 | – | – | 0 | NONE | 8191.3 | 10429 | 10-6-87 |

# THERMAL SPRAY COATING BOND TEST SPECIMENS

TRIBALLOY T-800
SPRAY POWDER

INCONEL 718
SUBSTRATE

| ID SPECIMEN No. | LENGTH ORIGINAL | LENGTH FINAL | NUMBER OF SHOTS | COATING THICKNESS | LBS LOAD ULTIMATE | TENSILE STRENGTH | DATE |
|---|---|---|---|---|---|---|---|
| INT-2/17-14 | .990 | 1.000 | 35 | .010 | 4264 | 5429 | 1-11-88 |
| INT-3/17-15 | .999 | 1.008 | 35 | .009 | 5175 | 6589 | 1-11-88 |
| INT-4/17-18 | 1.002 | 1.012 | 35 | .010 | 3432 | 4370 | 1-11-88 |
| INT-5/17-20 | 1.002 | 1.013 | 35 | .010 | 3625 | 4615 | 1-11-88 |
| INT-7/17-24 | .994 | 1.006 | 35 | .012 | 2971 | 3783 | 1-11-88 |

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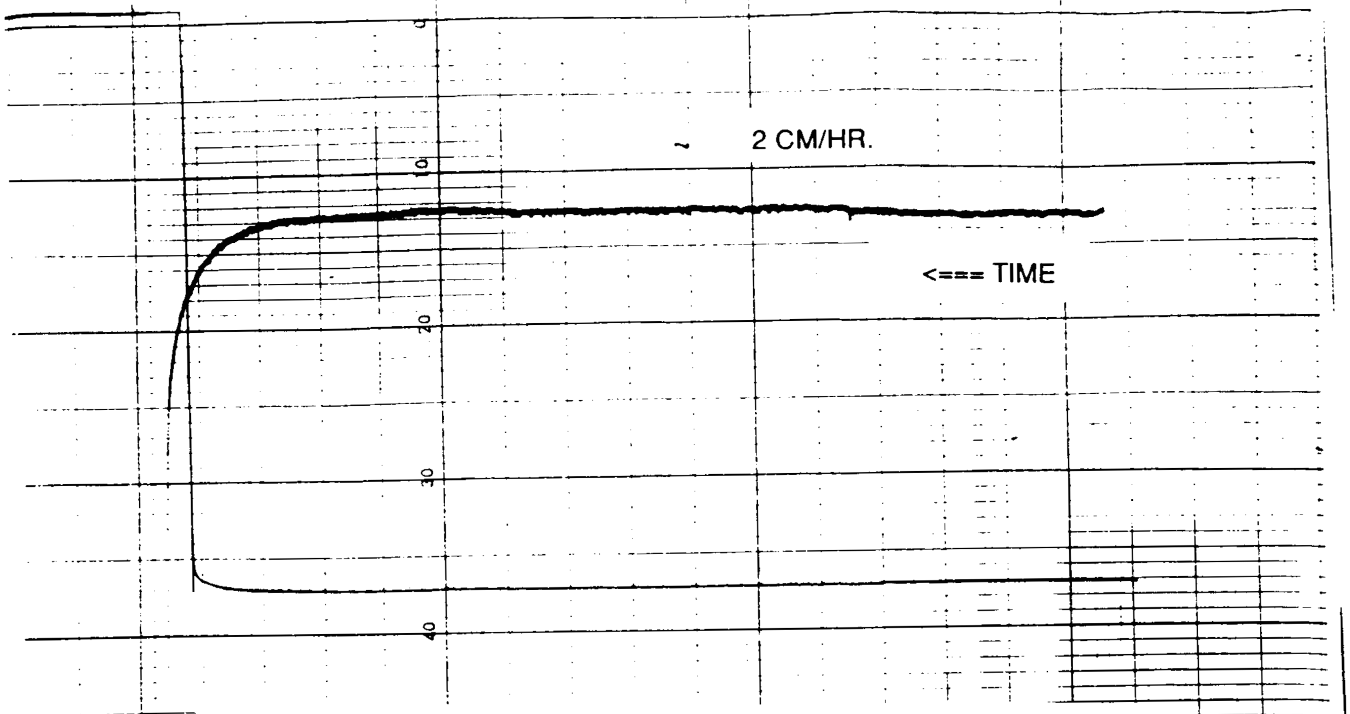
THERMAL SPRAY FATIGUE BAR DATA SUMMARY

| Specimen | No. of Shots | Thick./Shot, in. | No. Layers | Avg. Thick., in. | Surface Finish, RMS |
|---|---|---|---|---|---|
| 17-1 | 250 | 0.0001 | 10 | 0.015 | 168 |
| 17-2 | 250 | 0.0001 | 10 | 0.016 | 173 |
| 17-3 | 250 | 0.0001 | 10 | 0.015 | 186 |
| 17-4 | 250 | 0.0001 | 10 | 0.016 | 165 |
| 17-5 | 250 | 0.0001 | 10 | 0.015 | 158 |
| 17-6 | 250 | 0.0001 | 10 | 0.015 | 173 |
| 17-7 | 250 | 0.0001 | 10 | 0.016 | 183 |
| 17-8 | 250 | 0.0001 | 10 | 0.015 | 192 |
| INB-1 | 60 | 0.008 | 2 | 0.019 | 555 |
| INB-2 | 60 | 0.008 | 2 | 0.013 | 596 |
| INB-3 | 60 | 0.008 | 2 | 0.015 | 556 |
| INB-4 | 115 | 0.008 | 4 | 0.025 | 492 |
| INB-5 | 60 | 0.008 | 3 | 0.013 | 628 |
| INB-6 | 65 | 0.008 | 3 | 0.022 | 562 |
| INB-7 | 65 | 0.008 | 3 | 0.010 | 554 |
| INB-8 | 90 | 0.008 | 5 | 0.008 | 603 |
| INB-9 | 65 | 0.008 | 3 | 0.016 | |
| INB-10 | 65 | 0.008 | 3 | 0.010 | |
| INT-1 | 60 | 0.004 | 3 | 0.014 | 149 |
| INT-2 | 60 | 0.004 | 3 | 0.016 | 178 |
| INT-3 | 60 | 0.004 | 3 | 0.016 | |
| INT-4 | 60 | 0.004 | 3 | 0.016 | 153 |
| INT-5 | 60 | 0.004 | 3 | 0.016 | 144 |
| INT-6 | 60 | 0.004 | 3 | 0.016 | 186 |
| INT-7 | 60 | 0.004 | 3 | 0.017 | 167 |
| INT-8 | 60 | 0.004 | 3 | 0.015 | |

# APPENDIX E

## EXAMPLE FATIGUE TEST DEFLECTION DATA




EXAMPLE TIME VS DEFLECTION PLOT FOR FATIGUE SPECIMEN IN-T-4



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# APPENDIX F

## WEIGHT EFFECTIVENESS ANALYSIS

Consider the sprayed material to be deposited over a total angle $\Delta\beta$, such that w is the added weight per unit angle. In general, w is a continuous function of $\theta$ where $\theta$ is the angular location of the deposit. $\Delta\beta$ is considered to extend by $\Delta\beta/2$ on either side of the Y-axis.

Consider an elemental deposit angle $d\theta$ at $\theta$ from the Y axis in Figure 68.

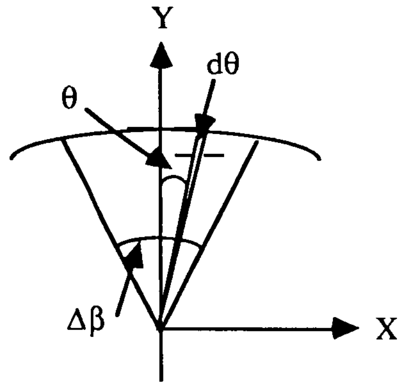


FIGURE 68

The elemental weight added is $wd\theta$ and its contribution when included in X and Y direction forces are:

X: $w \cos \theta d\theta$

Y: $w \sin \theta d\theta$

$\therefore$ the total effect of material deposited over angle $\Delta\beta$ is:

$$W_x = \int_{-\Delta\beta/2}^{\Delta\beta/2} w \sin \theta d\theta$$

$$W_y = \int_{-\Delta\beta/2}^{\Delta\beta/2} w \cos \theta d\theta$$

If w is considered constant, then

$$W_y = 2w \sin \Delta\beta/2$$

$$W_x = 0$$

The effectiveness is the effective weight added ($W_y$) divided by the total weight added

$$\therefore \text{ Effectiveness, } \eta = W_y/W = \frac{2 \sin \Delta\beta/2}{\Delta\beta}$$

If we combine the effectiveness analysis with the effects of speed (N, rpm) and deposit pulse time, $\Delta T$, we obtain:

$$\text{Effectiveness, } \eta = \frac{60 \sin (\frac{\pi}{60} N\Delta T)}{\pi N\Delta T}$$

# REFERENCES

1. Bishop, R. E. D., and Parkinson, A. G., *On the Isolation of Modes in the Balancing of Flexible Shafts,* Proceedings of the Institute of Mechanical Engineers, London, Vol. 177, p. 407, 1963.

2. DeMuth, R. S., and Zorzi, E. S., *Development of High-Speed Balancing Technology,* NASA CR165314, Jan. 1981.

3. Martin, Michael R., *Development of a Multiplane Multispeed Balancing System for Turbine Engines,* NASA Contractor Report 174750, July 1984.

4. Martin, Michael R., *Fatigue Life of Laser Cut Metals,* NASA Contractor Report 179501, Sept. 1986.

5. Parkinson, A. G., Darlow, M. S., Smalley, A. J., and Badgley, R. H., *An Introduction to a Unified Approach to Flexible Rotor Balancing,* ASME Paper No. 79-GT-161, presented at the ASME Gas Turbine Conference, Mar. 1979.

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National Aeronautics and Space Administration

# Report Documentation Page

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5. Report Date

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7. Author(s)

Anthony J. Smalley, Richard M. Baldwin, and Wilbur R. Schick

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6220 Culebra Road
P.O. Drawer 28510
San Antonio, Texas 78284

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and
NASA Lewis Research Center
Cleveland, Ohio 44135-3191

14. Sponsoring Agency Code

15. Supplementary Notes

Project Manager, David P. Fleming, Structure Division, NASA Lewis Research Center.

16. Abstract

The work performed in this document comprised two parts. In the first part, a survey was performed to assess the state of the art in rotor balancing technology as it applies to Army gas turbine engines and associated power transmission hardware. The second part evaluated thermal spray processes for balancing weight addition in an automated balancing procedure. The industry survey revealed that: 1) computerized balancing equipment is valuable to reduce errors, improve balance quality, and provide documentation; 2) low-speed balancing is used exclusively, with no foreseeable need for production high-speed balancing; 3) automated procedures are desired; and 4) thermal spray balancing is viewed with cautious optimism whereas laser balancing is viewed with concern for flight propulsion hardware. The FARE method (Fuel/Air Repetitive Explosion) was selected for experimental evaluation of bond strength and fatigue strength. Material combinations tested were tungsten carbide on stainless steel (17-4), Inconel 718 on Inconel 718, and Triballoy 800 on Inconel 718. Bond strengths were entirely adequate for use in balancing. Material combinations have been identified, for use in the hot and cold sections of an engine, with fatigue strengths equivalent to those for hand-ground materials.

| 17. Key Words (Suggested by Author(s)) | 18. Distribution Statement |
|---|---|
| Gas turbine balancing; Shaft balancing; Automated balancing; Thermal spray weight addition; Fatigue life | Unclassified – Unlimited<br>Subject Category 09 |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No of pages | 22. Price* |
|---|---|---|---|
| Unclassified | Unclassified | 122 | A06 |

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