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T. Spalvins
Lewis Research Center
Cleveland, Ohio

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SPUTTERING AND ION PLATING FOR AEROSPACE APPLICATIONS

by T. Spalvins

National Aeronautics and Space Admininstration
Lewis Research Center
Cleveland, Ohio 44135

SUMMARY

Sputtering and ion plating technologies are reviewed in terms of their potential and present uses in the aerospace industry. Sputtering offers great universality and flexibility is depositing any material or in the synthesis of new ones. The sputter deposition process has two areas of interest: thin film and fabrication technology. Thin film sputtering technology is primarily used for aerospace mechanical components to reduce friction, wear, erosion, corrosion, high temperature oxidation, diffusion and fatigue, and also to sputter-construct temperature and strain sensors for aircraft engines. Sputter fabrication is used in intricate aircraft component manufacturing. Ion plating applications are discussed in terms of the high energy evaporant flux and the high throwing power. Excellent adherence and 3-dimensional coverage are the primary attributes of this technology.

INTRODUCTION

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The effectiveness and durability of spacecraft engines and structures are heavily related to surface phenomena such as friction, wear, erosion, corrosion, high temperature oxidation, diffusion and fatigue. A spacecraft literally consists of thousands of components which when in motion come in mechanical contact and are exposed to friction, wear and in many instances hostile environmental conditions.

Over the past two decades a variety of vacuum deposition and surface treatment techniques have emerged as a result of the demanding requirements to protect and increase the functional capabilities of mechanical components for aerospace applications. It is important to distinguish between the two most recent and widely discussed surface modification processes: (1) vacuum deposition techniques and (2) vacuum surface treatment techniques. The former such as physical and chemical vapor deposition, sputtering and ion plating are widely used for aerospace applications, while the latter are still extensively investigated and tested in laboratories and experimental stations.

The surface treatment techniques such as ion implantation and laser beam irradiation are not coating techniques. For instance, in ion implantation the atoms implanted are embedded below the surface and do not generate a buildup or a covering film. As a result there is no change in the dimensions of the components. Since ion plating is one of the techniques described in this paper, it is useful to distinguish between ion plating and ion implantation, despite the similarities in their names.

A particularly noticeable trend in the sputtering and ion plating technology is toward energizing the metal vapor flux (refs. 1 to 4). Attempts are made to increase the ionization efficiency and ion energies of the evaporant flux, since this generally leads to improved coating properties.

The objective of this paper is to describe the potentials of sputtering and ion plating as they apply to aerospace and illustrate with specific applications the performance of sputtered and ion plated films.

SPUTTERING POTENTIAL

From an industrial point of view, the following unique sputtering features are an integral part of the process: versatility in material deposition (virtually any material can be deposited), momentum transfer (impact evaporation), sputter-etching (cleaning), precise controls (stoichiometry, uniformity, thickness) and high flexibility in selecting sputtering modes and configurations. In addition, during the sputtering process there is no adsorption of hydrogen and hydrogen embrittlement on high strength steel surfaces such as is experienced with such deposition techniques as electroplating.

Sputtering targets may be classified as follows: elemental, multielement, multielement compound or mixture, composite and layer type targets. Powders of different materials can be mixed in any ratio and hot pressed into a sputtering target of any size and shape. Alternatively, the composite targets can be constructed of materials of different segments or in layer type structures as shown in Fig. 1. As a result one can tailor or synthesize new coatings with any chemical combination and form graded compositions, laminated and dispersion strengthened structures.

On the basis of sputtering rate considerations two distinct areas of application can be distinguished (1) thin film technology and (2) fabrication technology.

THIN FILM TECHNOLOGY

In the last 10 years, sputter deposition has rapidly spread not only into the aerospace and aircraft industries but into practically any industrial area which require films that are difficult or impossible to apply by the other deposition techniques. With the increased industrial demand of sputter-deposition, the trend is toward full automation, where the component to be coated is accepted at one end of the sputtering equipment and the coated product emerges at the other end. Also, as pollution controls become more demanding and more stringently enforced, the sputtering technique offers an excellent alternative, since this process does not produce any effluents.

In the aerospace and aircraft industries sputtering technology, because of its flexibility, is constantly finding uses in new problem areas. The technique has essentially no limitations imposed in terms of coating applications. Development and performance of thin sputtered films is illustrated below with typical applications.

Tribological coatings. - In order to prevent tribological failures of interacting component surfaces in sliding, rotating, rolling or oscillating motion, friction and wear has to be minimized and proper lubrication maintained. For instance, a spacecraft designed for planetary exploration consists of many moving mechanical components such as bearings, gears, splines, etc. which must maintain a high precisional motion. To meet the severe environmental conditions, conventional oil and grease lubricants can not be used, instead a solid film lubricant must be selected. Sputtered solid film lubricants have been used for example on ball bearings for solar array drives, despin and pointing mechanisms for antennas, gyroscopes and accelerometers. Also the Minuteman and Intercontinental missile programs have used sputter coated ball bearings.

Tribological coatings, depending on their chemical, physical and mechanical properties are divided into two groups: the soft, low shear strength films such as (MoS_2, WS_2, Au, Ag, Pb, PTFE, etc.) which reduce and provide frictional control, and the hard wear resistant refractory compound films such as (carbides, nitrides, silicides, etc.). All of the aforementioned tribological materials have been deposited by sputtering (refs. 5 to 7). Sputtered MoS_2 films are particularly indispensable for applications where extremely thin films (<2000 Å) are required for tribological control in high precision bearings where tolerances are close, reliability requirements are high and the minimization of wear debris formation is critical. MoS_2 films are directly sputtered onto bearing components (races, cage and balls) as shown in Fig. 2. The sputtered MoS_2 films are very adherent to highly polished metallic surfaces. Due to the strong adherence, extremely thin films (2000 Å) are more effective than thicker films applied by other techniques as shown in Fig. 3.

In the application of the hard refractory compound films, sputtering is essentially the only reliable direct technique (without using binders) for the deposition of these compounds. Significant improvement in bearing life has been obtained with angular contact stainless steel bearings using coatings applied by this technique (ref. 8).

High temperature protective coatings. - The primary function of these coatings is to protect the surfaces from hot corrosion, high temperature oxidation, diffusion and fatigue. To extend the durability of aircraft mechanical components such as blades and vanes of a gas turbine engine in a high temperature hostile environment, a new class of coatings known as MCrAlY have been developed (ref. 9). The coating composition of this complex alloy can be tailored for the best compatibility with the turbine blade material in terms of "M" which can be Ni, Co, NiCo, Ta, Hf, etc. These complex compositions are very difficult to deposit by other deposition techniques in stoichiometric proportions. Sputtering is basically the proper technique to deposit these alloy coatings, because of its simplicity, accuracy and high flexibility in achieving the desired compositional and structural properties. A sputtered turbine blade as shown in Fig. 4 offers an increased resistance to oxidation, hot corrosion and fatigue.

Thin film sensors. - Thin film surface temperature sensors (ref. 10) and thin film strain gages (ref. 11) have been developed by sputtering techniques directly on the components being tested. Thin film temperature sensors or thermocouples for instance have been formed by sputtering on turbine blades and vanes for the purpose to measure and control the temperature up to 980° C, under actual engine operating conditions. Prior to this new development optical pyrometers and embedded thermocouples were used to measure the actual operating temperatures. The structure of a simplistic thin film thermocouple in cross section is shown in Fig. 5(a). It essentially consists of multiple layers of sputtered protective (MCrAlY), an insulating layer (Al_2O_3, SiO_2), and a metallic thermocouple material (Pt, Pt-Rh).

The sputtered thin film strain gages have a similar structure as shown in Fig. 5(b). The strain gage has to withstand cyclic strain, vibrations and maintain operational stability from room temperature to 200° C. Sputtered strain gages in actual use on mechanical components are shown in Fig. 6.

FABRICATION TECHNOLOGY

With the development of high-rate sputter deposition (up to 250 μm/hr), a new sputter-manufacturing technology has emerged. This new technology is already being used to improve the performance of regeneratively cooled thrust chambers of rocket engines. Very intricate inner and outer cylindrical structures with coolant passages for thrust chambers are being manufactured and tested. The integral coolant passage fabrication consists of a copper cylinder with machined grooves which are filled with an easily removable low melting filler material and finally sputter-deposited with an outer layer. A typical inner layer with machined coolant passages and a completed chamber section with sputtered outer layer is shown in cross section in Fig. 7.

ION PLATING

Characteristics and Potentials

Ion plating is another vacuum deposition technique which combines some of the unique advantages of electroplating, vapor deposition and sputtering. The basic ion plating system consists of a dc-diode configuration with an evaporation source (ref. 12). The ion plating process is more energetic than sputtering, since the process uses a high substrate bias of several thousand volts to accelerate the positively ionized evaporant atoms into the substate. The ions and energetic neutrals may have a distribution of energies from thermal up to the voltage applied to the discharge.

The two important features of the process are: (1) the flux of high energy ions and neutrals which forms an exceptionally strong adherence between the film and the substrate and (2) the high throwing power which allows one to coat uniformly 3-dimensional complex surfaces. These two features have generated new potentials in coating utilization.

The excellent film adherence is generally attributed to the formation of a graded interfacial region, even where the film and substrate materials are mutually incompatible. Strongly, adherent, fully dense (pore free) and uniformly-continuous films can be obtained at lower nominal thickness using this technique. The graded interface formed not only provides excellent adherence, but also improves the mechanical properties, such as yield strength, tensile strength and fatigue life of the components, as shown in Figs. 8 and 9.

APPLICATIONS AND PERFORMANCE

The applications of ion plated films originate from the two unique features: the excellent adherence and the high throwing power.

Most ion plated films in aerospace are used for tribological applications (friction, wear, lubrication) and as protective films to increase corrosion resistance, fatigue limit and creep resistance. Soft, metallic films (Ag, Au, Pb) have been used very successfully as lubricants for spaceborn bearings. These ion plated lubricating thin films 2000 Å thick are very effective in increasing the endurance life, reducing the coefficient of friction and eliminating instant or catastrophic failures.

The high throwing power and the strong adherence is widely used to coat 3-dimensional complex mechanical surfaces, such as internal surfaces of tubes, ball bearings, screws and threads without specimen rotation as shown in Fig. 10. Large scale automated ion plating facilities are in operation in the aircraft industry to protect the surfaces from oxidation, corrosion and fatigue failures. A production facility is in operation to ion plate aluminum on steel and titanium aircraft fasteners without hydrogen embrittlement.

Also large aircraft components such as the main landing gear cylinders for the F-15 aircraft, piston axle assemblies for the F-4 aircraft and stator vane assemblies and bulkheads are ion plated with a protective aluminum coating (ref. 13). An ion plated landing gear cylinder is shown in Fig. 11 and a piston axle assembly is shown in Fig. 12.

Other ion plating aircraft applications include strike coats to surfaces which would be otherwise very difficult or impossible to electroplate, can now be electroplated over the ion plated film. Ion plating of metal surfaces to facilitate joining by conventional soldering and brazing techniques; and because of the high throwing power, porous components can be sealed for vacuum and hydraulic applications.

CONCLUSIONS

The potential and applications of sputtering and ion plating in the aerospace and aircraft industry has been reviewed with the following conclusions:

1. Sputtering offers great universality and flexibility for depositing any material without restrictions on composition, and to synthesize new material compositions.
2. Sputtered thin films are primarily used to prevent tribological failures, resist oxidation, corrosion and diffusion and develop thin film temperature and strain sensors.
3. Sputter fabrication technology has been developed for manufacturing intricate mechanical components.
4. Ion plated films have two distinct advantages: excellent adherence which has strengthening effects on mechanical properties, and 3-dimensional coverage of complex surfaces.

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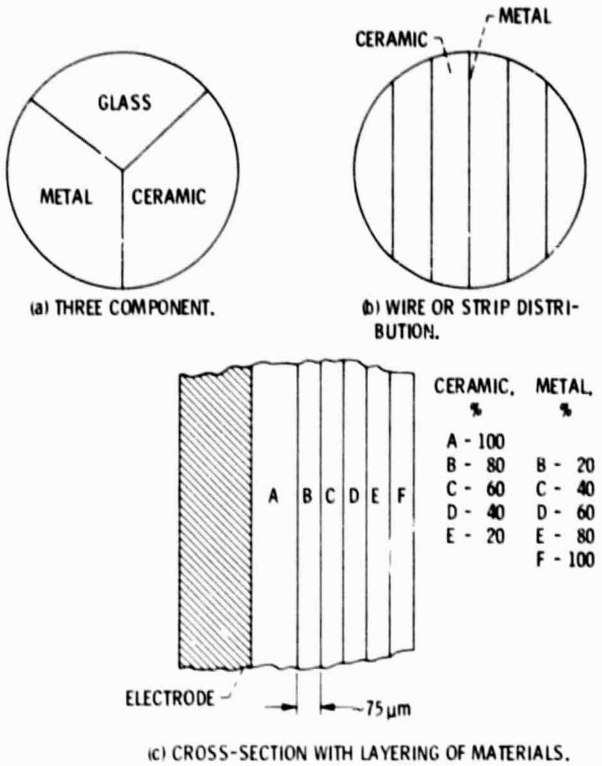

Figure 1. - Construction of sputtering targets.

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Figure2. - Two sets of ball bearing assemblies sputter-coated with MoS_2 films.

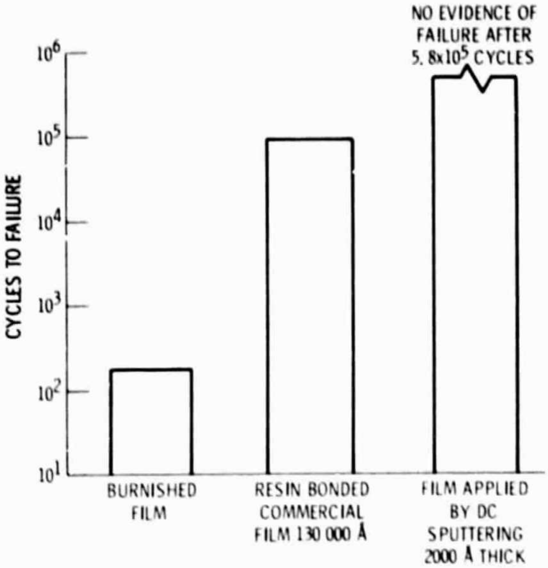


Figure 3. - Endurance lives of MoS_2 films applied by various techniques.

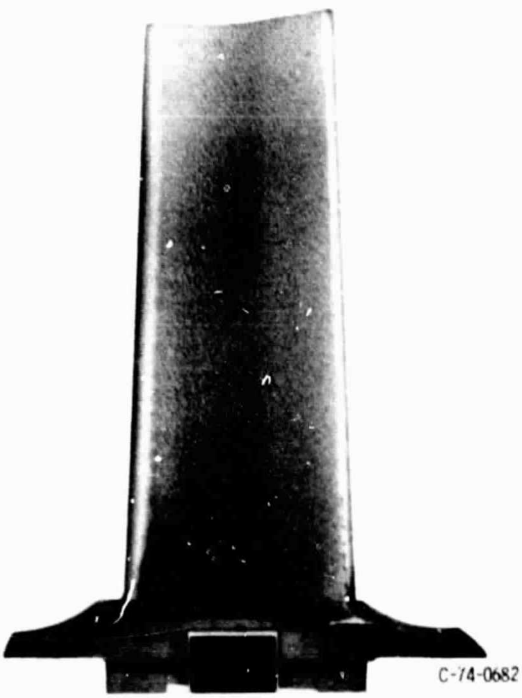
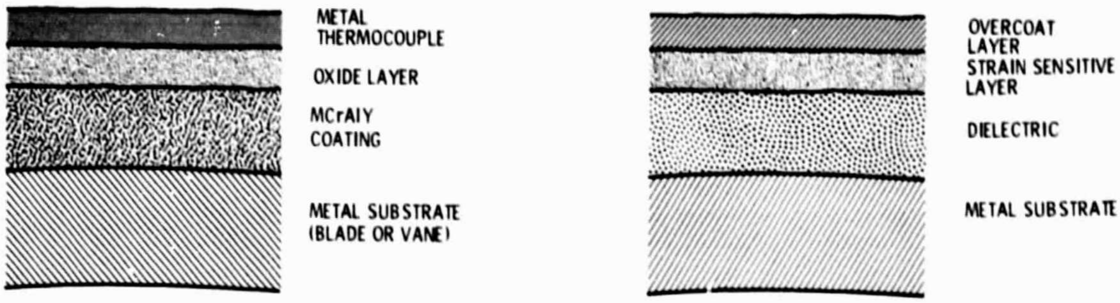


Figure 4. - Turbine blade sputter coated with MCrAlY.



(a) THIN FILM TEMPERATURE SENSOR.

(b) THIN FILM STRAIN SENSOR.

Figure 5. - Cross-section of the sputtered thin film surface sensors.

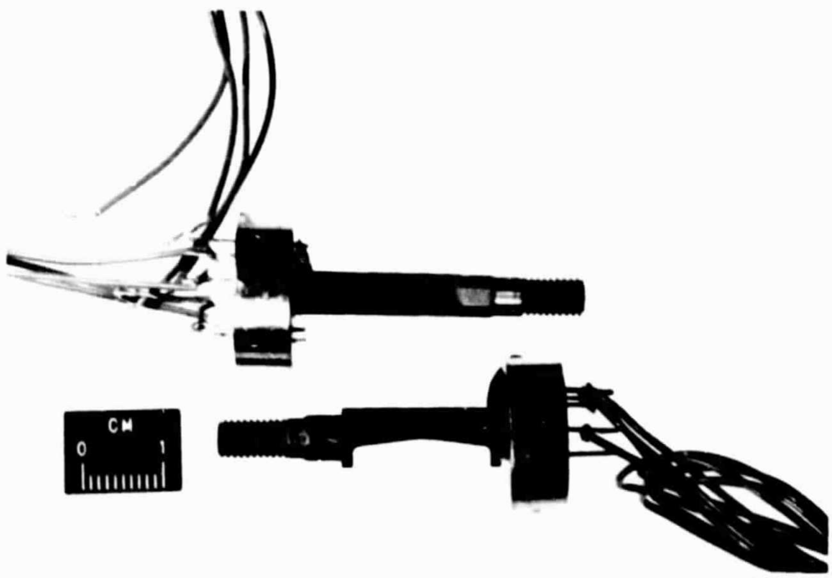


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Figure 6. - Sputtered strain gages on tested mechanical components.

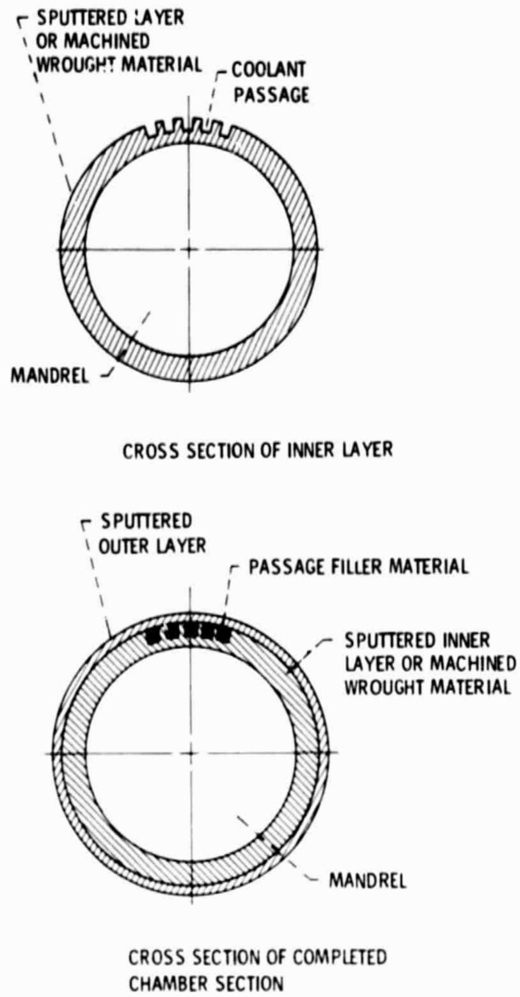


Figure 7. - Sputter fabrication of thrust chambers.

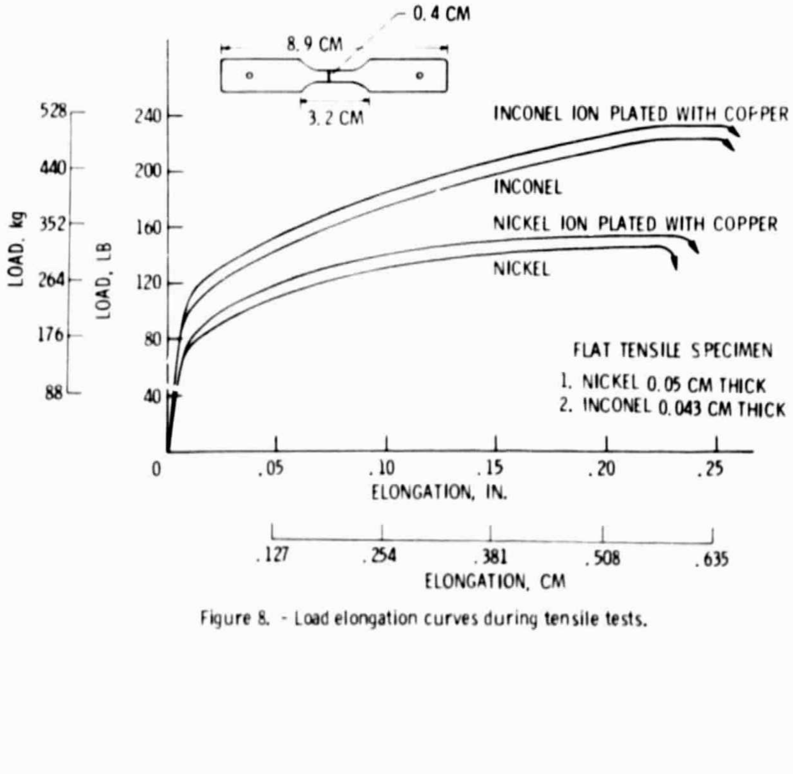


Figure 8. - Load elongation curves during tensile tests.

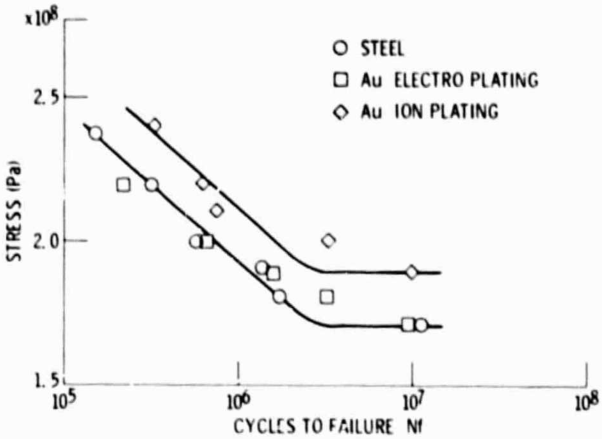
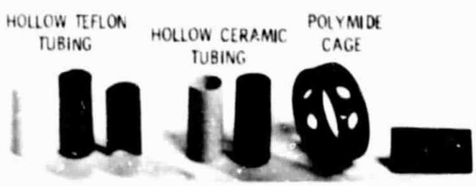
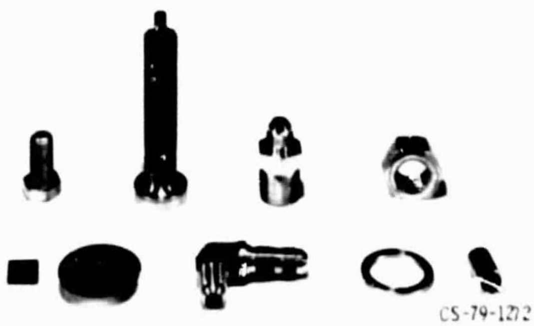


Figure 9. - Effect of ion plating on the fatigue property of low carbon steel (ref. 13).



(a) COATED INSULATORS.



(b) COATED INTERNAL AND EXTERNAL METALLIC SURFACES.

Figure 10. - Ion plated insulators and objects with metallic coating.

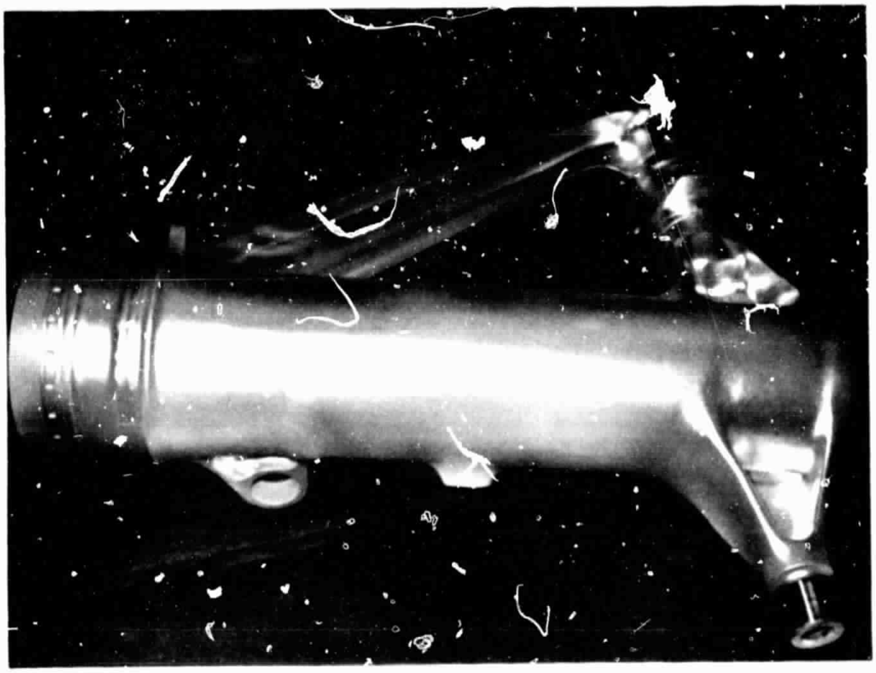


Figure 11. Main landing gear cylinder for F-15 ion plated with aluminum.

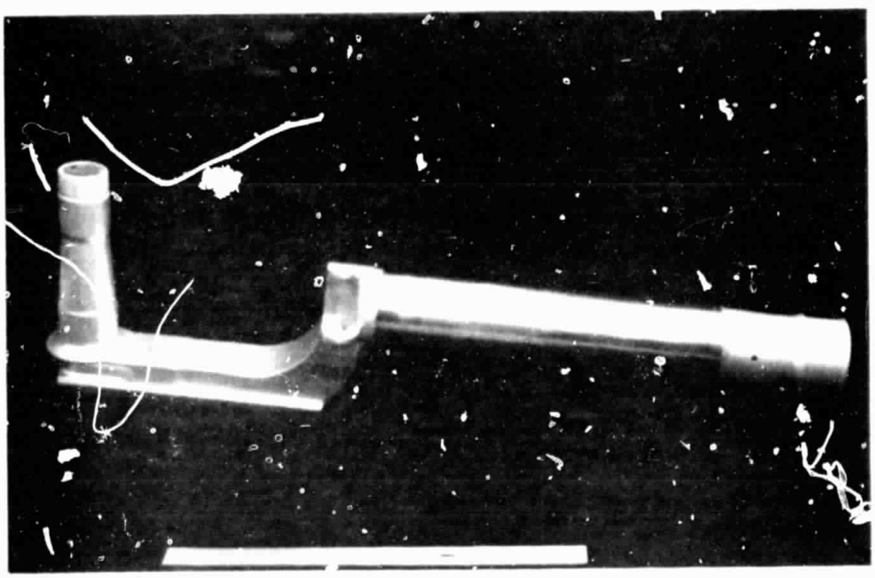


Figure 12. Piston axle assembly for F-4 ion plated with aluminum.