SURFACE AND SUB-SURFACE CONDITIONS RESULTING FROM ELECTRIC SPARK MACHINING

by

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INTRODUCTION

History

The electric spark machining process consists of passing a succession of electric discharges between a work piece and a tool electrode.

The removal of metal directly by an electric discharge was first reported by Joseph Priestly (6) in 1768. However, little note was taken of the possibilities in this area until shortly after World War II. In 1953 E. Teubner (8) was granted a United States patent for a "Method and Apparatus for Electrically Disintegrating Metal Material." Although there were prior foreign patents, Teubner's patent was the first important one in the United States. This lag in time between the work of Priestly and that of Teubner may be unique in the history of technical development. A usable electric circuit, and the desirable results of its use were known for nearly 200 years before the first improvement was made in the apparatus.

Since the electric spark maching process can be used to produce complicated shapes in even very hard metals, it has attracted much interest. Die sinking in tungsten carbide for instance, a process that normally requires the use of expensive diamond abrasives, can be accomplished inexpensively by means of electric spark machining.

Purpose

In conjunction with the recent increase in interest has come some disagreement as to the temperature reached at the point of operation and its effect on the workpiece. This research was undertaken to investigate the possible effects of high temperatures during the spark machining operation on the surface and sub-surface condition of 1045 steel.

Review of Literature

A survey of literature revealed agreement as well as disagreement among various authors.

In 1952 E. M. Williams (9) examined the residues from tungsten carbide and found no evidence of physical or chemical changes that might be associated with high temperatures or melting of the tungsten carbide. Crystallographic studies of machined surfaces of material with transformation temperatures slightly above the ambient showed that machined surface temperature rises were insufficient to produce such crystal transformations. He concluded that the material was definitely removed without melting.

Williams, in a statement appended to a later publication by Williams, Woodford, and Smith (10), suggested that the ultimate limit on machining rate would be imposed by the ability of the associated parts to dissipate heat. There was no mention of microstructure changes in the work, however.

Experimenters at Compagnie des Compeurs et Manometres, Liege, Belgium (3), stated that the relaxation circuit is limited to low powers and even then cannot be used for producing a surface entirely free from alterations due to heating or burns. Using a circuit and generator of novel design they were able to, "obtain perfect surface quality and to maintain unaltered the metallographic properties of the material machined" (3).

C. R. Alden (1) reported the following:

> All known methods of investigation which appear to be applicable support the conclusion that particle dislodgment is the result of forces mechanically applied. The effect of such heat as is inevitably associated with the passage of a spark which at most has a duration of from a fraction of one to a comparatively few microseconds, of itself has an entirely negligible effect upon particle removal. No evidence has been found that the removed particles achieve a temperature remotely approaching the molten state in process of removal. Photomicrographic studies of the workpiece surface show close agreement with surfaces fractured by mechanical means. None indicates the presence of heat as being contributory to the fact of particle removal.

H. Opitz (5), supported the following statement with some excellent photomicrographs of disturbed microstructure in steels:

> The various proposed theories adapted to explain the stock-removal mechanism will not be considered here. It may however be assumed with a high degree of certainty that the temperature generated along the spark channel formed or, respectively, on the impact points of these sparks plays an important and decisive part in the operation.

> The measurement of these temperatures involves considerable difficulties, so that results may vary from 10,000 to 50,000°C.
>
> As will be shown hereinafter, the appearance of a melting zone in the border area of the spark-eroded hard metals may signify temperatures of at least 3000°C. at the impact points.

While experimenting with residual stresses caused by plastic deformation due to thermal action, M. Barash (2) found that, during machining, mild steel strips became coated with a very thin hard layer that could not be filed. He attributed this layer to carburization by the dielectric.

Luther (4) reported finding evidence of localized heating on the surface of spark machined 1035 steel.

D. W. Rudorff (7), found that when a spark gap machine is operated with the gap breakdown voltage at seventy-three per cent of the source voltage, maximum metal removal rates were achieved and the sub-surface layer of the steel showed no heating effect. The same removal rates were found at a lower voltage, with higher current, but the sub-surface layers showed microstructure changes due to heating. He concluded that it was advisable to operate the machine with the gap setting based on the higher voltage and to accept the somewhat rougher finish that results, rather than to obtain a finer surface finish having a damaged sub-surface layer.

The literature search pointed up the need for further work in determining the temperatures reached by the associated parts during spark machining.

Theory of Spark Machining

Several theories have been advanced to explain material removal by electric spark and three of them still have supporters. These are the hypothesis of "flares, of mechanical action, and of thermal action"(2). Flares are metallic vapor jets that are supposed to stream from one electrode to the other and erode the electrodes in the process. The flare hypothesis seems the least likely of the three, since the phenomenon has been noted at voltages as low as 15 volts (2). The hypothesis of mechanical action is based on the assumption that the sudden influx of electrons causes a space charge that upsets the equilibrium in the electrode and the resulting electrostatic forces tear out particles of the material leaving a crater (9). This theory fails to explain why the erosion rate for tool steel is higher than that of mild steel in view of the fact that tool steel has the greater tensile strength. Also, the relationship between the maximum current and the rate of material removal as determined on the basis of this theory does not agree with the observed facts. The theory of thermal action is based on the assumption that the stream of electrons is decelerated in the anode and its energy is converted to heat. Likewise, a stream of ions would be decelerated in the cathode and this would explain erosion of the tool electrode. Barash (2), quotes a number of studies that show excellent agreement between this theory and observed phenomena.

The Circuit

The relaxation circuit used in most spark gap machines is shown in Fig. 1. It consists of a direct current power source, a control resistor R, a storage capacitor C, and the tool and workpiece electrodes which are normally immersed in a dielectric coolant.

When the power source is connected, the capacitor is charged through the resistor. For the initial discharge, the gap between the electrodes is decreased mechanically until it is small enough to be ionized by the potential V_g. At that time, the capacitor will discharge through the gap giving the desired spark effect. The capacitor will then recharge and discharge again if the gap has not increased. The time for discharge is on the order of a few microseconds. The time t, for recharging is normally somewhat longer and can be determined from the well known capacitor charging equation,

$$V_c = V_s \; 1 - e^{-\frac{t}{RC}}$$

where V_c = capacitor voltage in volts

V_s = source voltage in volts

e = the natural logrithm base, 2.71828

t = time in microseconds

R = resistance in ohms

C = capacitance in microfarads.

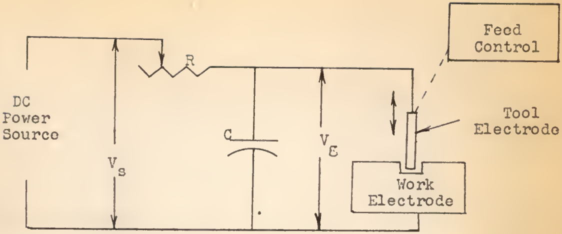

Fig. 1. Schematic diagram of basic relaxation circuit (1). V_s is the source voltage, V_ε is the voltage at the "gap" between the tool electrode and the work electrode.

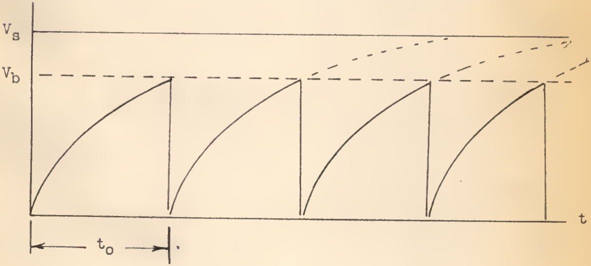

Fig. 2. Variation in condenser voltage with time V_s is the source voltage, V_b is the breakdown voltage (7).

The amount of metal removed per discharge varies with the energy of the discharge. The energy of the discharge is dependent on the size of the capacitor and the voltage across its terminals at the time of discharge in the following relationship:

$$E = \frac{1}{2}V_c^2C$$

where E = energy released per spark

V_c = voltage across the capacitor

C = capacitance

Figure 2, a voltage time curve, shows that the capacitor charging rate decreases as V_b, the breakdown voltage, approaches V_s. It is therefore, desirable to maintain the gap at a value that will hold V_b somewhat below V_s if maximum energy or metal removal per unit time is desired. To this end, it has been found that a breakdown voltage, V_b, of approximately seventy-three per cent of V_s will give maximum removal rates (10). Some commercial machines are equipped with servomechanisms that operate in response to gap voltage and mechanically adjust the gap to a predetermined optimum. Since both the tool and the workpiece are continually eroded, frequent or continuous adjustment is required for practical use of the machine.

Both tool and workpiece are submerged in a dielectric, normally a light hydrocarbon such as transformer oil, kerosene, or diesel fuel. The dielectric acts as a coolant and also carries away debris produced by the machining action.

Some machines have the dielectric pumped through a hollow tool electrode, others have a jet or stream directed at the gap between the tool and the electrode.

APPARATUS

The apparatus used is shown in Figs. 3, 4, 5, 6, and 7, and may be considered in the following three groups:

1. the electric circuit and power supply,
2. the mechanical or tool control portion,
3. the dielectric supply reservoir and pump.

The electric circuit included the following equipment:

1. a 240 volt, direct current, 30 ampere motor generator set,
2. a 10 ampere circuit breaker,
3. two, 110 ohm, 600 volt, adjustable rheostats,
4. nine capacitors of 10 microfarads each,
5. voltmeter 0 to 300 volts,
6. milliammeter with a suitable shunt,
7. wiring no smaller than No. 14 AWG to the capacitors and cable containing seven No. 14 AWG wires, from there to the electrodes,
8. copper faced vise jaws, electrically insulated from the vise, to hold the workpiece,
9. a heavy copper clamping device to hold the electrode,
10. a blade type switch to discharge the capacitors.

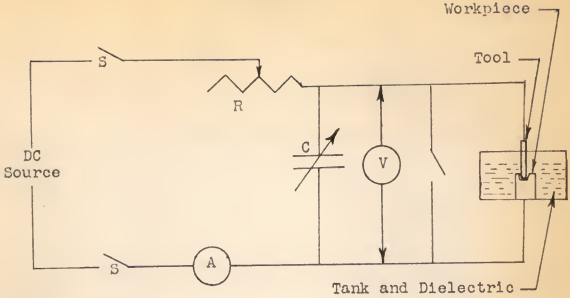

Fig. 3. Schematic diagram of the circuit.
S, is main switch, R, is resistance,
C, is capacitance, V, is voltmeter,
A, is ammeter.

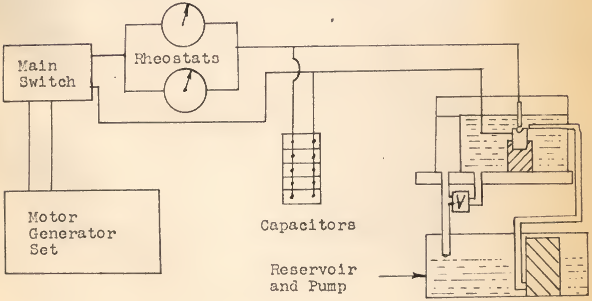

Fig. 4. Sketch showing the arrangement of the equipment.

Fig. 5. Apparatus used for spark machining.

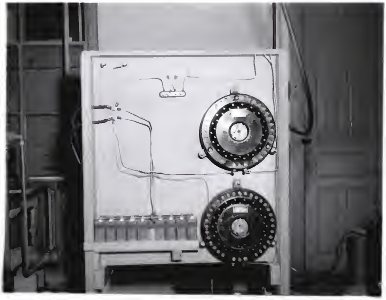

Fig. 6. Rear view of control panel showing circuit.

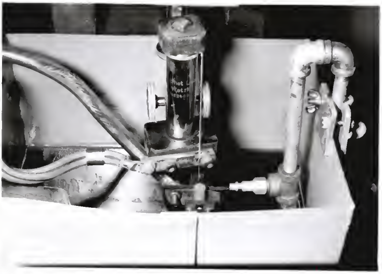

Fig. 7. View inside of tank showing tool and workpiece electrodes, holding devices, and dielectric discharge jet.

A frame was constructed of two by four inch lumber and faced with three-eighths inch pressed wood paneling. The capacitors and rheostats were attached to the back with the rheostat controls passing through the board and adjustable from the front. The voltmeter, ammeter, and shorting switch were placed on the front side.

The tank and feed devices were mounted on a George T. Schmidt stamping machine frame. The main frame provided a handwheel controlled vertical adjustment for the tank platform and a hand operated, lever cross feed working through a rack and pinion, for the tool electrode. There was no power controlled feed. The vertical adjustment was found to be too coarse so an adjusting mechanism from a microscope was fitted to the cross slide. The fine feed mechanism operated in a vertical direction and provided a feed or gap control of .0005 inch or less.

The dielectric tank mounted on the machine platform was constructed of sixteen gage mild steel and measured fourteen by ten, and seven inches deep. The vise with insulated jaws was brazed directly to the bottom of the tank. A partition of suitable height was fitted across one corner to maintain the dielectric fluid at the proper level. Fluid that flowed over this partition passed through an outlet at the bottom and returned to the reservoir. A drain valve for the tank was connected through a tee fitting to the return line. One-half inch inside diameter Tygon tubing was used for both pressure and return lines. The fluid reservoir was of galvanized sheet metal construction and measured fourteen by fourteen by eight inches. A centrifugal type pump was mounted on a one-fourth inch steel plate placed in the bottom of the tank. The dielectric fluid control valve was located on the pump end of the pressure line. The pressure jet was clamped to the side of the tank and could be adjusted for angle or moved to any position on the side of the tank. A jet diameter of one-eighth inch provided adequate flow and velocity.

PROCEDURE

The material used was one-half inch diameter round hot rolled S.A.E. C 1045 steel. It was cut into one and one-quarter inch lengths and annealed at 1500°F. for one hour in a neutral salt bath. At the end of the annealing time the samples were cooled slowly in ground asbestos. After cooling to room temperature the samples were marked for identification, then tumbled in abrasive, washed in water and dried to remove any traces of salt.

The tool electrodes used were one-sixteenth and three-thirtyseconds inch diameter, Linde Heliarc tungsten electrodes. Tungsten was used because its good erosion resistance was expected to reduce or eliminate contamination of the sample as well as require less frequent adjustment to maintain a given gap. No attempt was made to control the shape of the electrode tip. It quickly developed from a flat end into a rounded form and remained in that shape. This form developed and stabilized during the initial trial runs so that all samples for the microstructure study were produced with the same electrode shape.

A ten ampere circuit breaker was used as a main switch. The rheostats, connected in parallel, were adjusted to give a short circuit amperage of just under ten amperes. Thus, they provided secondary protection against short circuit damage to the generator set as well as preventing the capacitors from recharging so quickly that a continuous arc might develop at the electrodes. The capacitors were used in groups to give either ten, fifty or ninety microfarads.

Prior to operation, the specimen to be machined was clamped in the vise, leveled, and the tool brought down to within approximately one-thirtysecond of an inch. The tank was then filled, the generator started and the capacitor shorting switch opened. The last step in starting the operation was to close the main switch.

The specimens were held with their long axis in a vertical plane so that all maching could be done on the top edge or end. If straight penetration was desired the tool was initially centered over the workpiece and fed straight down to produce a hole similar to one produced by a conventional drill. Only two samples were produced by this means.

The other method of operation consisted of passing the electrode entirely across the surface of the workpiece, feeding the tool down .0005 to .003 inch and making another pass in a manner analogous to that of a conventional shaper or milling machine. Repeated passes were made until a depth of one-sixteenth of an inch or more was reached. This was the most rapid and satisfactory method. As an additional benefit, the long surface produced permitted repeated sectioning as a polishing technique was developed and different etching reagents were tried. Twenty-two samples were produced by this method after it was perfected and they are recorded with the two previously mentioned samples in Table 1.

Two rates of tool travel and feed were used. The first or slow method consisted of passing the electrode over the workpiece at a rate of approximately ten inches per minute and feeding the tool down approximately .0005 inch before each pass. The second used a travel of approximately 200 inches per minute and a feed of .001 inch per pass. The slow rate of travel and feed produced a sound much like that of popcorn popping slowly. The individual discharges were separate and distinct. The fast travel and feed produced a sound like that of rapidly tearing a piece of woven cloth. The individual discharges were so close together in time that they were not individually distinguishable.

Table 1. List of samples.

Sample number	Electrode diameter in inches	Coolant K-kerosene D-diesel fuel	Capacitance microfarads	Travel* and feed	Plating Z-zinc C-copper I-iron
1	3/32	D	10	slow	Z
2	3/32	D	10	slow	Z
3	3/32	K	10	fast	Z
4	3/32	K	90	fast	Z
5	3/32	K	90	fast	Z
6	3/32	K	90	fast	Z
7	1/16	K	10	fast	Z
8	1/16	K	10	fast	Z
9	3/32	K	90	slow	C-I
10	3/32	K	90	slow	C-I
11	3/32	K	50	slow	C-I
12	3/32	K	50	slow	C-I
13	3/32	K	10	slow	C-I
14	3/32	K	10	slow	C-I
15	3/32	K	90	slow	C-I
16	3/32	K	50	slow	C-I
17	3/32	K	90	slow	none
18	3/32	K	90	slow	none
19	3/32	K	90	slow	none
20	3/32	K	90	slow	none

Table 1 (concl.).

Sample number	Electrode diameter in inches	Coolant K-kerosene D-diesel fuel	Capacitance microfarads	Travel* and feed	Plating Z-zinc C-copper I-iron
21	3/32	K	90	slow	none
22	3/32	K	90	single disc	none
23	3/32	K	50	single disc	none
24	3/32	K	10	single disc	none

*Slow feed, travel equals 10 in./min., feed 0.0005 per pass.
Fast feed, travel equals 200 in./min., feed 0.001 per pass.

When observing a single discharge it was possible to see very small particles, or the trails left by them, radiating out from the discharge point in the dielectric. The particles would be visible, and apparently traveling at a very high speed until they reached a distance of one inch or more. At that distance they seemed to be traveling much slower and became difficult to see.

After machining, the samples were plated. Samples one through eight were zinc plated in an alkaline cyanide bath, and samples nine through sixteen were copper plated first and then iron plated over the copper. The copper was plated from a copper cyanide bath and the iron from a ferrous sulfate bath. Samples seventeen through twenty-four were not plated.

The purpose of the plating was to provide support for the sample at the edge and thus reduce rounding of the edge during subsequent polishing. Zinc plating was much faster than copper and so was used initially. However, it was found that the zinc gave cathodic protection to the steel and reduced the effectiveness of the etching reagent at the edge of the sample. This had little disadvantage for visual observation since it was only necessary to etch the sample for a longer time. Additional polishing after this would, of course, produce an undesirable rounded edge, since the zinc was reduced to a lower elevation than the steel. The repeated polish and etch cycle used to produce the much flatter edge required for photographic purposes dictated the use of a different plating material, therefore, copper plate covered with iron plate was used. Iron plate is desirable for edge support since it is harder than either zinc or copper, but it must be distinguished from the steel sample in some manner. For this reason, a thin covering of copper was used between the iron plate and the steel sample. Since both copper and pure iron react more slowly than steel with the etching reagent, they reduce the edge rounding effect even more during a repeated polish and etch cycle.

After plating, the samples were cut parallel with the axis of the sample in a manner that would give a section or cross section of the machined notch. During all cutting and subsequent grinding, care was taken to avoid heating the sample.

The portion of the sample with the maxhined groove in it was reduced by further cutting until it was approximately one-half of the original diameter and one-half inch long. The sample was then embedded in Bakelite plastic to facilitate grinding and polishing operations, as well as observation. The cylindrical plastic mounting was approximately one inch in diameter and one inch long. The plastic provided edge support in addition to that provided by the plating, as previously noted, but was not sufficient by itself, since it is quite soft.

After the samples were embedded in plastic they were prepared for microscopic examination by conventional methods. The samples were lapped with progressively finer abrasives until the desired etching reagent would just remove the last traces of scratches or deformation.

All micro-hardness tests were made using a Vickers diamond pyramid indenter with a ten gram load applied for ten seconds. A Bausch and Lomb Balphot metallograph was used for visual examinations, dimensional measurements and to photograph the surface area.

RESULTS AND CONCLUSIONS

Surface Condition

The machined surface was found to be composed of small craters. This was expected in view of the fact that virtually all authors studying surface phenomena have reported finding small craters on the surface. Figure 8 shows the appearance of a crater formed by a single discharge. The following crater diameters are the averages of thirty measurements from fifteen single discharge craters at each energy level:

1. 10 microfarads; 0.0188 inch
2. 50 microfarads; 0.0302 inch
3. 90 microfarads; 0.0364 inch.

Observation of the above average dimensions indicates that the crater diameter varies in a non linear manner with the energy of discharge. This is a reasonably logical result and agrees well with the results found by Luther (4). These values, with a suitable constant multiplier, also fall almost exactly on a curve by Rudorff (7) showing capacitance verses stock removal rate. If it is assumed that a given machine will normally operate at or near a given frequency of discharge, then the crater diameter is proportional to the stock removal rate.

Removed Material

Microscopic examination of the material removed during machining showed it to be composed entirely of spherical particles indicates that at some time during removal they were heated to the melting point.

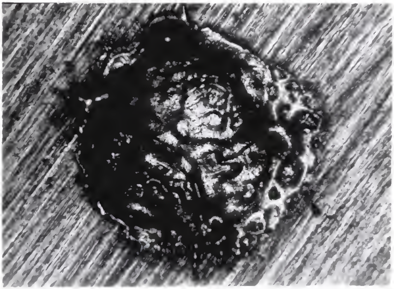

Fig. 8. Crater formed by a single discharge at 10 microfarads. Approximately 125 X.

Microstructure Study

A disturbed layer was found on the machined (spark machined) surface of every sample examined. The appearance of the layer is shown in Figs. 9, 10, and 11. The light band with small diamond pyramid hardness (DPH) indentions in Figs. 9 and 10 is the layer of disturbed material. Figure 11 has no DPH indentions. Note the shape of the surface layer which suggests that the area has been molten. The copper plating, just above the disturbed layer, appears dark in Fig. 9 and light in Figs. 10 and 11. The remainder or bottom seventy-five per cent is the parent material composed of ferrite and pearlite. Pearlite, which is composed of laminated plates of iron carbide and ferrite, is selectively attacked and roughened by the etching reagents, thus, it appears as the dark portions of the matrix. The ferrite grains are uniformly attacked and appear as the light areas.

The width of the band of disturbed hard material at the surface was measured as follows:

1. 90 microfarads; 0.0004 to 0.0014 inch,
2. 50 microfarads; 0.0003 to 0.001 inch,
3. 10 microfarads; 0.0001 to 0.0006 inch.

These data were obtained by measuring the thickness at ten different points on the sample and demonstrated the relationship between the thickness of the surface disturbance and the energy

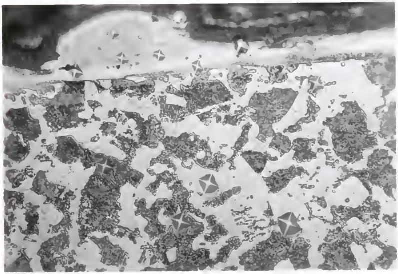

Fig. 9. Sample machined at 90 microfarads. Light colored layer with DPH indentions is hard surface layer resulting from spark machining. The dark layer above is copper plating, remainder is 1045 annealed basic structure. 500X, 2% Nital reagent.

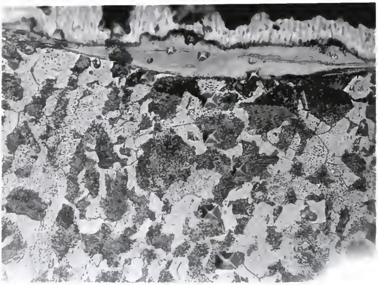

Fig. 10. Sample machined at 50 microfarads. Lightest layer at top is copper plate. Next down is disturbed surface layer showing small DPH indentions. Remainder or bottom 75 per cent is annealed basic structure of 1045 steel with DPH indentions. 500X, 2% Nital reagent.

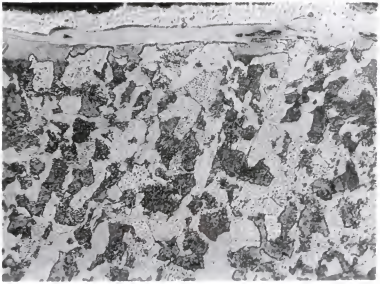

Fig. 11. Sample machined at 10 microfarads. Light rough appearing area at top is copper plate. Next area down, smooth and light colored, is disturbed surface layer resulting from spark machining. 500X, 2% Nital reagent.

of the discharge. Apparently, a decrease in the energy of the discharge results in a decrease in the width (depth) of the disturbed layer.

Since the area of the DPH indention is proportional to the hardness of the material, it can be seen that the surface layer is much harder than the parent material from which it presumably came. The hardness of the parent material away from the machined edge was normal and varied from 201 to 364 DPH (15 to 37 Rc) depending on whether the indenter fell on ferrite or pearlite. The thirty hardness readings taken on the surface layer varied from 916 to 1480 DPH (940 DPH corresponds to 68 Rc). These readings were higher than was expected and also exhibited an unusually wide dispersion. The wide dispersion of the hardness readings was found to be due to the heterogeneous nature of the disturbed surface layer. If plastic deformation is excluded, the two remaining methods by which hardening may have taken place both require heating to an elevated temperature.

The first or most likely possibility was that the surface was heated above 1330°F. and quenched. When steel containing carbon is heated above 1330°F., it transforms from pearlite and ferrite to austenite, and the iron carbide in the pearlite goes into solution with the austenite. If it is then cooled slowly it transforms back to pearlite and ferrite. However, if it is cooled very rapidly the carbon does not have time to form the laminated plates of iron carbide found in pearlite and a supersaturated solution or structure called martensite results. Martensite can only result from the heating and rapid cooling just described and will have a hardness of approximately 65 Rc (if the carbon content is 0.6 per cent or above) as opposed to a hardness of 5 to 40 Rc for ferrite and pearlite. Thus, heating and quenching of the machined surface gives at least a partial explanation of the hardness found.

The second possibility was that the steel had absorbed some material from the dielectric. Since 1045 steel contains only 0.45 per cent carbon, the maximum hardness is not above 59 Rc, even when ideally quenched. Thus, it is certain that the steel absorbed carbon or some other material that contributed to its hardness. Since the maximum hardness due to increased carbon content is 65 Rc, and readings far in excess of this were obtained in some areas, it is certain that some material other than carbon contributed to the hardness in these particular areas.

Figure 12 shows the appearance of the surface layer after tempering at 500°F. for one hour. Part of the disturbed layer appears dark having been affected by the etching reagent while other parts remain unaffected. This darkening, accompanied by a decrease in hardness, is normal behavior for martensite after tempering. Figure 13 shows the appearance of the surface layer after tempering at 800°F. for one hour. Again the normal

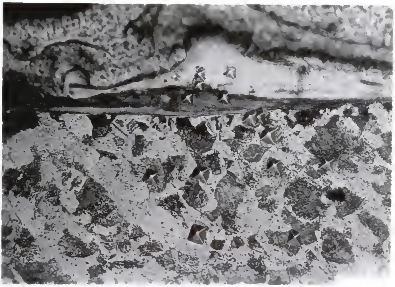

Fig. 12. Sample tempered at 500°F. for one hour. Dark area in surface layer shows softening and attack by etching reagent expected for martensite. Light areas show no change. 90 microfarads, 500X, 2% Nital reagent.

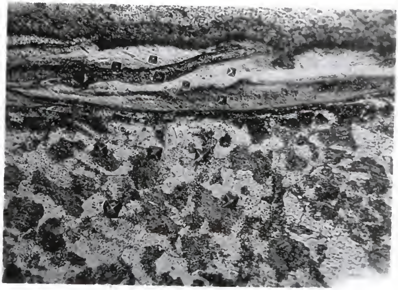

Fig. 13. Sample tempered at 800°F. for one hour. Dark area in surface layer shows softening and attack by etching reagent expected for martensite. Light areas show no change. 90 microfarads, 500X, 2% Nital reagent.

reaction of the tempered structure with the etching reagent was noted in part of the surface layer. Tempering at 500°F. produced slight softening in the dark areas but no measurable change in the light areas. Tempering at 800°F. produced further softening in the dark areas but still no change was observed in the light areas. Thus, the dark areas in the disturbed layer near the surface behaved in the normal and predictable manner, characteristic of martensite. The light areas, however, remained unaffected by tempering, retaining their hardness and resistance to attack by the etching reagent. This showed beyond any question that there was at least one other alloying element introduced into the steel by the machining process.

The fact that tungsten was available from the cathode, presented the possibility that some of it may have been introduced into the machined surface of the steel. Figure 14 shows the appearance of the surface layer after being held at 1450°F. for five minutes. The two large scratches were made by traversing a DPH indenter across the surface, one with only enough pressure to maintain contact and the other with a one gram load. They show that the surface layer remains slightly harder than the parent material. The appearance of the surface layer in Fig. 14 shows that the parent material and the surface layer are definitely different in composition. The parent material is still composed of pearlite and ferrite, while the surface layer shows a partially spherodized constituent closely resembling

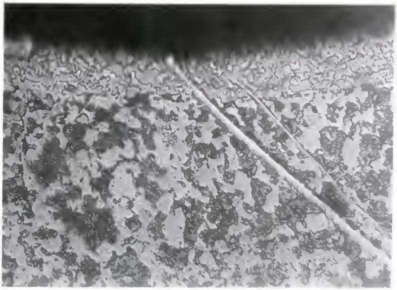

Fig. 14. Sample held at 1450°F. for five minutes. Scratches show surface layer to be slightly harder than parent material. Surface layer is partially spherodized indicating the presence of tungsten as an alloying element. 90 microfarads, 500X, 2% Nital reagent.

carbide precipitation found in high speed steel. Since tungsten is known to contribute to both the tendency to spherodize and the hardness, the effects found in Fig. 14 give strong indications of the presence of tungsten as an alloying element.

The light areas which had a hardness of over 916 DPH, (65 Rc) and did not respond to tempering, probably contain iron nitride. Nitrogen is known to be present as an impurity in mineral oils refined in certain areas from certain crudes and at least one other author has reported nitrogen absorption (7). A hardness of 1200 DPH in commercially prepared, nitride hardened steels, is considered common. A hardness of somewhat above 1200 DPH might reasonably be expected to result from the extreme circumstances at the center of an electric discharge. Since some of the hardness readings (up to 1480 DPH) were much higher than the maximum obtainable from carbon, (916 DPH) the presence of iron nitride seemed to be a likely explanation. The resistance to etching shown in Figs. 12 and 13, the high hardness, and resistance to tempering are all well known characteristics of a nitrided steel.

Observation of the tempered samples, Figs. 12 and 13, showed that the layers suspected of containing iron nitride were often overlapping and overlapped by, layers containing no iron nitride. A reasonable explanation for this was found in the requirements for forming iron nitride from nitrogen. The formation of iron nitride requires the presence of a chemically active nitrogen such as monatomic nitrogen rather than the inert N_2. It is known that disassociation of relatively stable compounds and diatonic molecules occurs at high temperatures such as those found in an electric discharge. Thus, the electric discharge present in spark machining could have caused a breakdown of N_2 or a nitrogen compound in the dielectric and permitted the formation of iron nitride. The steel suspected of containing iron nitride may have been near enough to the center of the spark to receive some chemically active nitrogen. The layers containing only martensite had either not received any nitrogen, but only heat, or if they had received nitrogen it had been driven off by subsequent reheating. Because of the short time involved in a spark discharge there is still some doubt as the actual mechanisms involved and the order in which they occur. However, the process of nitriding as used commercially follows well known principles which give some explanation. The formation of an iron nitride surface will occur at 800 to 1000°F. in a suitable atmosphere. Near 1450°F., both nitriding and carburizing will occur. At 1650 to 1700°F., carburizing will occur with little or no nitriding. This may explain why carburizing was indicated in some layers with no nitriding and nitriding in others possibly with carburizing.

In summary, the study of the microstructure of spark machined surfaces has shown the following:

1. The existence of a very hard, disturbed layer of material at the machined surface.

2. All known disturbance effects were either caused by or made possible by high temperatures at the surface.
3. A temperature of 1330°F. was exceeded in all surface areas of all samples examined.
4. The melting point of the material (2700°F.) was probably exceeded at the surface of the steel.
5. At least one alloying element was introduced into the sub-surface by the process.
6. Both tungsten and nitrogen were probably alloyed with the sub-surface layer, in certain areas.

DISCUSSION

As the initial questions were answered at the completion of this study, new questions rose giving suggestions for future work. For instance, no reason could be found to completely explain the existance of layers presumed to contain iron nitride, side by side with layers shown to contain little or no iron nitride. A study of this phenomena might be conducted by repeatedly polishing and examining a surface containing many single discharges. This might show the distribution of the two structures within the individual crater. That is, since the confusing effects of overlapping craters would be eliminated, it might be determined that iron nitride was formed only in certain portions of the crater.

The surface and sub-surface effects disclosed in this study are not necessarily adverse. Some surface roughness is inevitable just as it is with nearly all conventional machining operations. The nature of the surface roughness is different from that of conventional processes, however. It may be that the spark machined surface, with or without additional mechanical polishing, would exhibit unusual lubricating or lubricant retention properties. The hardening encountered in the surface layer could certainly contribute to the wear properties. In fact, steps might be taken to encourage the formation of such a hard layer.

It is also possible that the formation of a hard surface layer is not inevitable. The decreases in thickness of the layer with decreasing energy of discharge noted, indicates that the hardening effect may entirely disappear at lower powers. Some authors, (1), (3), (7), and (9) have reported the ability to produce a surface free from heating effects. The ability to produce a hard surface layer, or not, at will, would certainly add to the value of the process in some applications. If the disturbed surface layer were proven to occur only above certain removal rates, elimination of the effect would only require a finish pass, such as now used with many conventional metal removal processes.

The spark machining process in its present state of development should not be considered as a replacement for conventional milling and lathe turning operations. Its largest advantage lies in cutting metals that are normally considered non-machinable. Diesinking in tungsten carbide and the shaping of turbine blades are a type of application where spark machining works very well. Another and very different use is in cutting and shaping materials that are so thin and structurally weak that they will not stand conventional mechanical cutting methods. Since spark machining exerts little or no mechanical force on the machined part it can be used to shape the foil honeycomb used in some modern aircraft or very tiny, delicate components used in miniaturization of electronic equipment. These unusual, but important uses point to a highly useful and successful future for spark machining.

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SURFACE AND SUB-SURFACE CONDITIONS RESULTING FROM ELECTRIC SPARK MACHINING

by

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Various authors have reported different sub-surface effects resulting from spark machining. Some have found disturbance due to heating and contamination of the spark machined surface, while others have found only mechanical disturbance. The purpose of this research was to determine the possible effects of high temperature during the spark machining operation on the surface and sub-surface condition of 1045 steel.

A machine was constructed and operated according to the principles set forth by other authors using the accepted capacitor relaxation circuit. The particles of material removed during machining and the surface and sub-surface of the spark machined samples were studied.

The removed material was found to consist entirely of spheres of varying sizes. This indicated that temperature above the melting point of the material had been reached at some time during their removal.

The surface was found in a cratered condition with characteristics agreeing well with the work of others in this field. (There is general agreement on surface condition).

A heat affected layer or zone of disturbed metal was found in all the machined surfaces examined. This layer was shown to have properties that were distinctly different from those of the original undisturbed steel. That the surface of the steel had been heated was shown by the hardness, which could only result from heating and quenching, and by the absorption of alloying elements, which again requires elevated temperatures. In some areas the hardness observed was higher than the maximum obtainable for alloy steels indicating the probable presence of iron nitride. The appearance, degree of hardness, and behavior after tempering again gave strong indications of the presence of iron nitride. Nitrogen was suspected of being present, as a contaminant, in the dielectric. The hardness of other areas was found to be normal for high carbon or alloy steel and these areas tempered normally. Tungsten was available from the cathode and its probable presence in the disturbed surface layer was demonstrated by the spherodized structure present after holding the sample at 1450°F. for five minutes These observations indicated that not only were alloying elements absorbed but that the material was heated above the thermocritical and cooled rapidly to produce maximum hardness.

In the discussion the author pointed out that the changes found might be desirable for certain applications and for applications where the surface effects were undesirable they might be removed by operating the machine below a certain suspected critical power range. A useful future is visualized for spark machining because of its unique ability to cut very hard metals and any metals under certain difficult conditions.