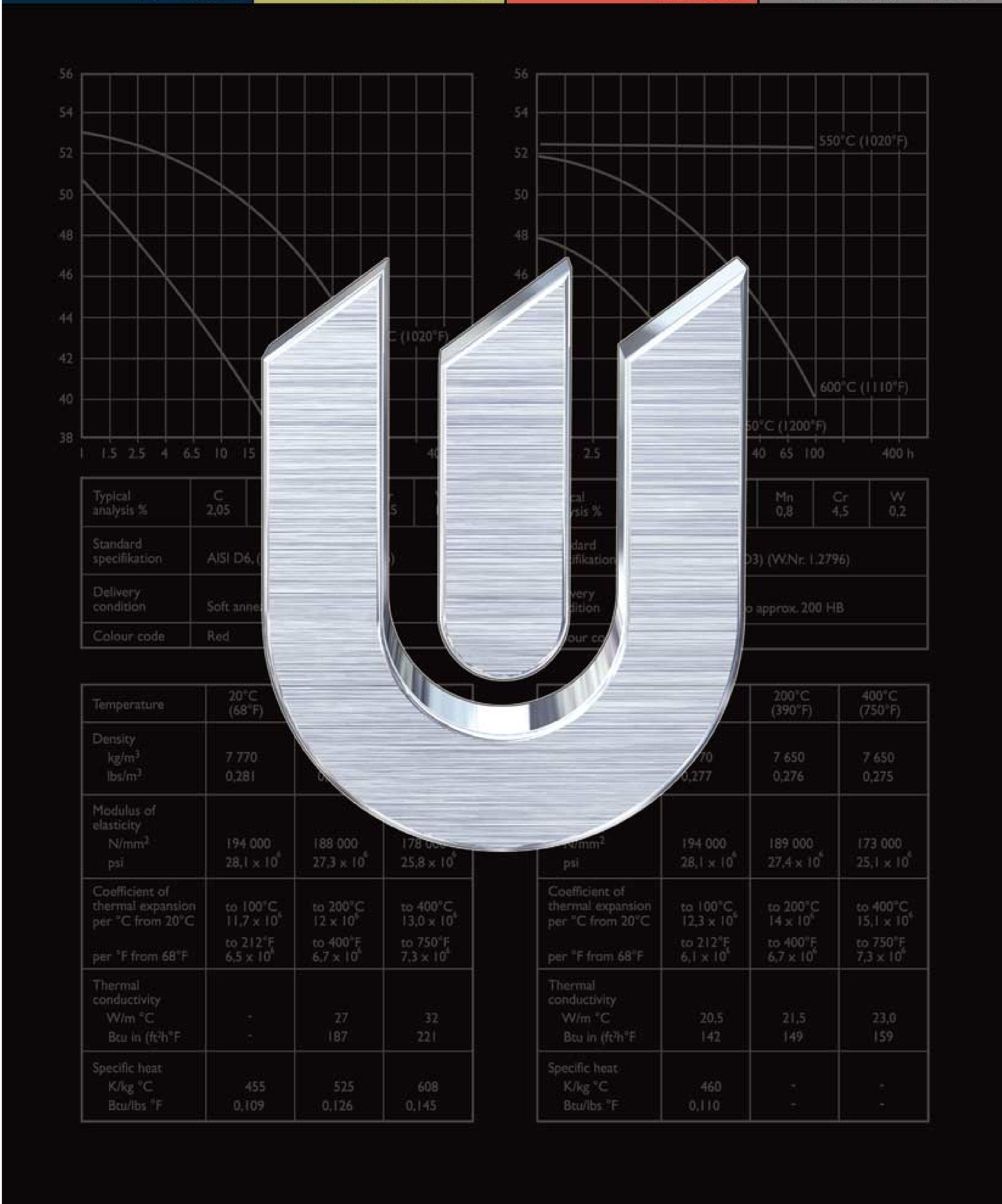
EDM of tool steel

COLD WORK | **PLASTIC** MOULDING | **HOT** WORK | **HIGH** PERFORMANCE STEEL



Contents

Introduction

The use of Electrical Discharge Machining (EDM) in the production of forming tools to produce plastics mouldings, die castings, forging dies etc., has been firmly established in recent years. Development of the process has produced significant refinements in operating technique, productivity and accuracy, while widening the versatility of the process.

Wire EDM has emerged as an efficient and economic alternative to conventional machining of apertures in many types of tooling, e.g. blanking dies, extrusion dies and for cutting external shapes, such as punches.

Special forms of EDM can now be used to polish tool cavities, produce undercuts and make conical holes using cylindrical electrodes.

EDM continues to grow, therefore, as a major production tool in most tool making companies, machining with equal ease hardened or annealed steel.

Uddeholm Tooling supplies a full range of tool steels noted for consistency in structure. This factor, coupled with very low sulphur levels ensures consistent EDM performance.

This brochure gives information on:

- **The basic principles of EDM**
- **The effects of the EDM process on tool steels**
- **Achieving best tool performance.**

The basic principles of EDM

Electrical discharge machining (spark erosion) is a method involving electrical discharges between an anode (graphite or copper) and a cathode (tool steel or other tooling material) in a dielectric medium. The discharges are controlled in such a way that erosion of the tool or work piece takes place. During the operation, the anode (electrode) works itself down into the workpiece, which thus acquires the same contours as the former. The dielectric, or flushing liquid as it is also called, is ionized during the course of the discharges. The positively charged ions strike the cathode, whereupon the temperature in the outermost layer of the steel rises so high (10–50,000°C,18–90,000°F) as to cause the steel there to melt or vaporize, forming tiny drops of molten metal which are flushed out as "chippings" into the dielectric. The craters (and occasionally also "chips" which have not separated completely) are easily recognized in a cross-section of a machined surface. See Fig. 1.

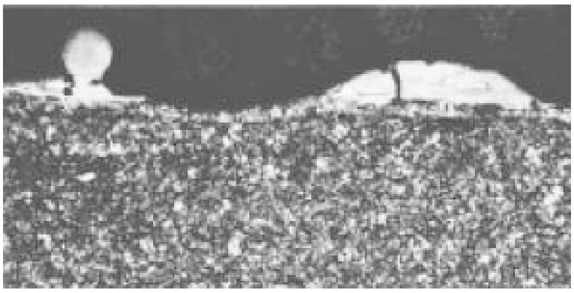


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Fig.1. A "rough-machined" EDM surface with a cross section through chips and craters. Material: ORVAR 2 Microdized.

Four main factors need to be taken into account when considering the operating parameters during an EDM operation on tool steel:

- the stock -removal rate
- the resultant surface finish
- electrode wear
- the effects on the tool steel.

The influence of the EDM operation on the surface properties of the machined material, can in unfavourable circumstances jeopardize the working performance of the tool. In such cases it may be necessary to subordinate the first three factors, when choosing machining parameters, in order to optimize the fourth.

The effects of the EDM process on tool steels

The influence of spark erosion on the machined material is completely different to that of conventional machining methods.

As noted, the surface of the steel is subjected to very high temperatures, causing the steel to melt or vaporize. The effect upon the steel surface has been studied by Uddeholm Tooling to ensure that the tool maker may enjoy the many benefits of the EDM process, while producing a tool that will have a satisfactory production life.

In the majority of cases, it has been impossible to trace any influence at all on the working function of the spark-eroded tool. However, it has been observed that a trimming tool, for example, has become more wear resistant, while in some cases tool failure has occurred prematurely on changing from conventional machining to EDM. In other cases, phenomena have occurred during the actual electrical discharge machining that have caused unexpected defects on the surface of the tool. This due to the fact that the machining has been carried out in an unsuitable manner.

"SURFACE STRENGTH"— AN IMPORTANT FACTOR

All the changes that can be observed are due to the enormous temperature rise which occurs in the surface layer.

In the surface layer, it has been observed that the four (main) factors associated with the all-important "surface strength" of the steel are affected by this temperature increase:

- the microstructure
- the hardness
- the stress condition
- carbon content.

Fig. 2 shows a section from a normal rough-spark-machined surface with the typical, different structural changes.

MELTED AND RESOLIDIFIED LAYER

The **melted and resolidified layer** produced during the EDM process is also referred to as the "white zone", since generally no etching takes place in these areas during metallographic preparation. Fig. 3, nevertheless, shows clearly that it is a rapidly solidified layer, where long pillar crystals have grown straight out from the surface of the metal during solidification. A fracture occurring in this layer invariably follows the direction of the crystals. In normal rough machining, this layer has a thickness of about 15–30 µm.

The carbon content in the surface layer can also be affected, for instance, by carburization from the flushing liquid or from the electrode, but decarburization can also occur.

REHARDENED LAYER

In the **rehardened layer**, the temperature has risen above the austenitizing (hardening) temperature and martensite has been formed. This martensite is hard and brittle.

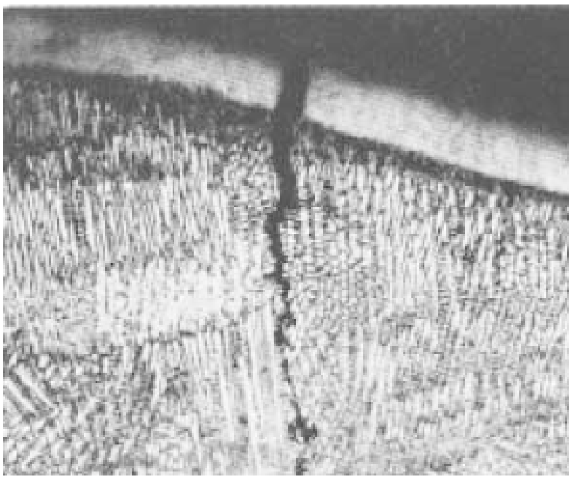

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Fig. 3. Pillar crystals formed during solidification.

TEMPERED LAYER

In the **tempered layer**, the steel has not been heated up so much as to reach hardening temperature and the only thing that has occurred is tempering-back. The effect naturally decreases towards the core of the material – see the hardness curve in Fig. 2.

In order to study the structural changes incurred with different machining variables, different tool steels—see table 1—were "rough-machined" and "fine-machined" with graphite electrodes.

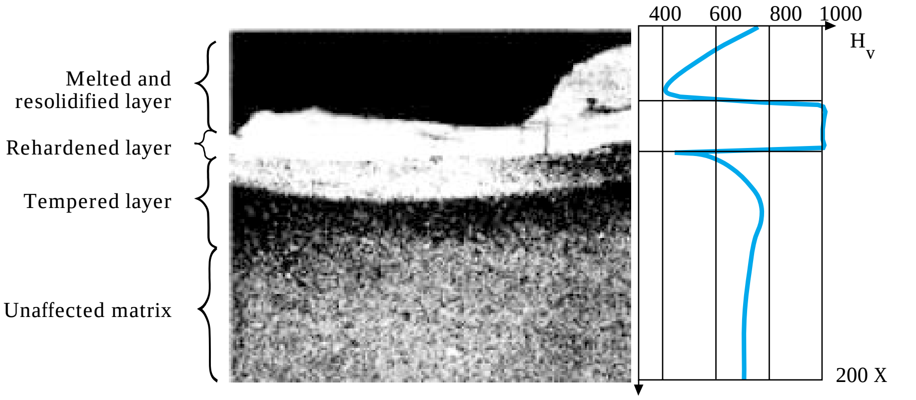


Fig. 2. Section from a spark-machined surface showing changes in structure. Material: RIGOR, hardened to 57 HRC.

Steel grade	AISI	**Austenitizing** Time 20 min Temperature °C	°F	**Tempering** Time 2 x 30 min Temperature °C	°F	Hardness Hardened HRC	Annealed HB
ARNE	O1	810	1490	220	430	60	190
CALMAX	–	960	1760	200	392	58	200
RIGOR	A2	940	1725	220	430	60	–
SVERKER 21	D2	1020	1870	250	480	60	220
GRANE	(L6)	840	1540	250	480	54	–
IMPAX SUPREME	P20	850	1560	580	1075	30	–
ORVAR SUPREME	H13	1025	1875	560	1040	50	180

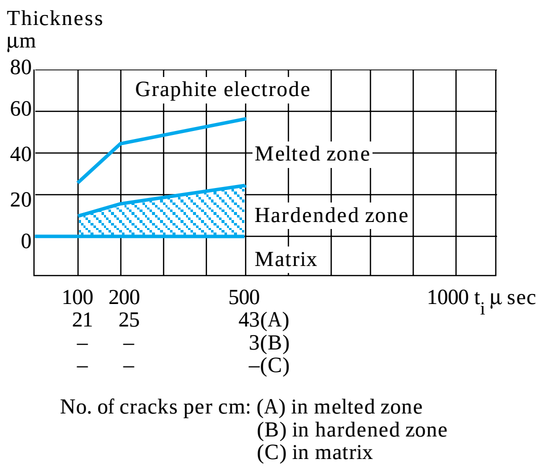
Table 1. The tool steels were tested in the hardened and tempered condition, and some of them also in the annealed condition.

Note: As *CORRAX* is a precipitation hardening steel the EDM surface has different characteristics. The “white layer” consists of melted and resolidified material with a hardness of approx. 34 HRC. There will be no other heat affected zone of importance.

Measuring the effects

The **thicknesses** of the heat-affected zones have been measured. The **hardnesses** in these zones have also been measured, as have **crack frequencies** and **crack depths**. **Strength values** have been obtained through bending tests.

The **layer thicknesses** appear to be largely independent of both steel grade and electrode material. On the other hand, there is a definite difference between the specimens which have been hardened and those which were in the softannealed condition. Fig. 4 shows, in the form of graphs, the layer thicknesses and fissure frequency with different pulse durations for *ORVAR SUPREME*. In the annealed material, the zones are thinner and the fissures fewer. The brittle, hardened zone is scarcely present at all (Fig. 4b).



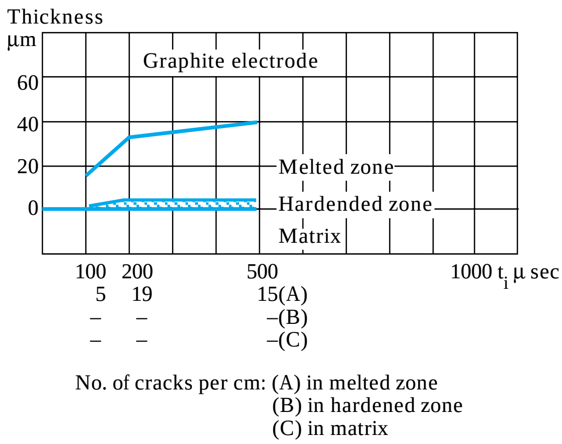


Fig. 4b. As above, but for electrical discharge machining of ORVAR SUPREME in the annealed condition.

The layer thicknesses can vary considerably, from 0 µm to maximum values slightly below the R_{max} specified in the machining directions. In the rough-machining stages (t_i ≥100 µ sec), the thicknesses of the layers vary far more substantially than in the fine-machining stages. The thickness of both the melted and the hardened zone increases with spark duration, which appears to be the most important single controlling variable.

The picture below shows the beneficial effect of “fine-finishing”, i.e. to produce a very thin remelted and heat-affected zone.

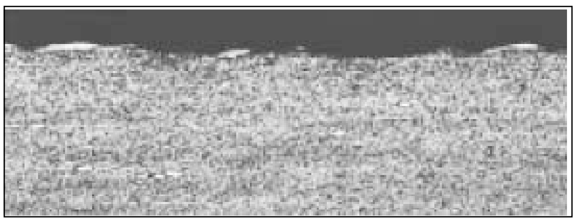


Fig. 5. Fine-machined RIGOR. Pulse duration 10 µ sec.

◄ *Fig. 4a. Layer thicknesses and fissure frequency in the surface layer in electrical discharge machining of hardened (52 HRC) ORVAR SUPREME at different pulse durations.*

STRUCTURES OF SPARK-MACHINED LAYERS

With longer pulse duration, the heat is conducted more deeply into the material. Higher current intensity and density (and thus spark energy) do, indeed, give a higher "amount of heat" in the surface, but the time taken for the heat to diffuse, never-theless, appears to have the greatest significance. The pictures below show how the surface zones are changed in *SVERKER 21* with different pulse durations and electrode materials.

Material: *SVERKER 21* in hardened and tempered condition

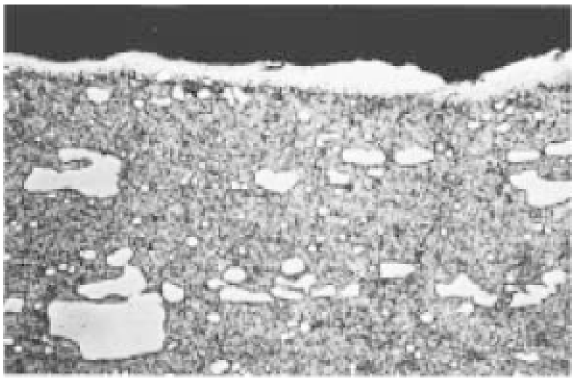


Fig. 6a. Copper electrode. t_i = 10 µs. Magnification 500 X

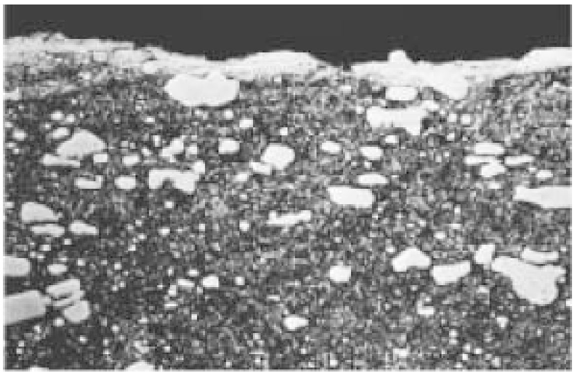


Fig. 6b. Graphite electrode. t_i = 10 µs. Magnification 500 X

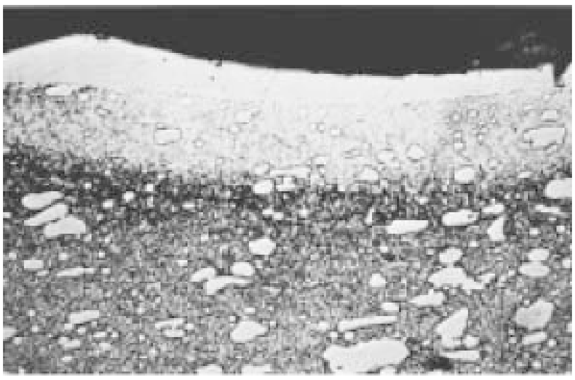


Fig. 6c. Graphite electrode. t_i = 100 µs. Magnification 500 X

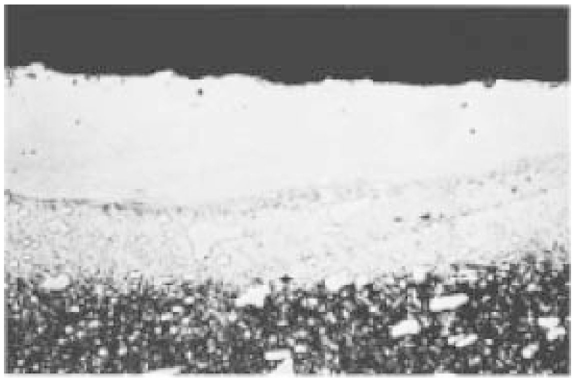


Fig. 6d. Copper electrode. t_i = 200 µs. Magnification 500 X

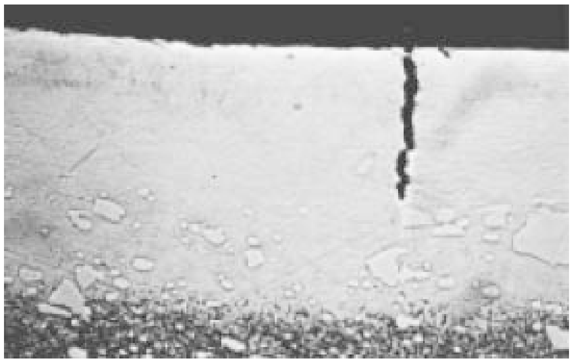


Fig. 6e. Graphite electrode. t_i = 500 µs. Magnification 500 X

THE CAUSE OF "ARCING"

Short off-times, or pause times, give more sparks per unit of time and thus more stock removal. During the off-time, the dielectric fluid must have time to become de-ionized. Too short an off-time can result in double sparking "ignitions" which lead to constantly burning arcs between the electrode and the work piece, resulting in serious surface defects. The risk of arcing is increased if flushing conditions for the dielectric fluid are difficult.

As a result of "arcing", i.e. a condition in which arcs are formed between local parts of the electrode and the workpiece, large craters or "burns" are formed in the surface. These have frequently been confused with slag inclusions or porosity in the material. Figs. 7 and 8 show the surface of a tool with a section through one of the suspected "pores".

One of the primary causes of this type of defect is inadequate flushing, or machining of narrow slots, etc., resulting in chips and other loose particles forming a bridge between the electrode and the workpiece. The same effect can be obtained with a graphite electrode which bears traces of foreign material. On modern machines featuring so-called adaptive current control, the risk of "arcing" has been eliminated.

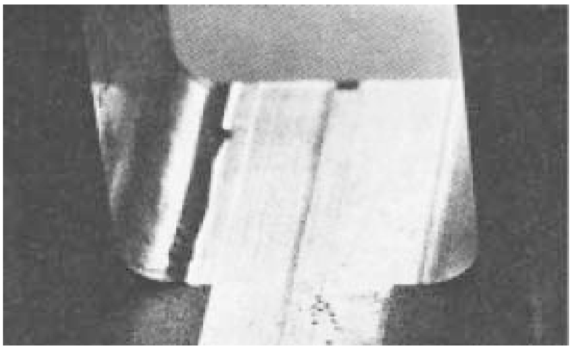


Fig 7. The suspected "pores" can be seen on the surface of the tool.

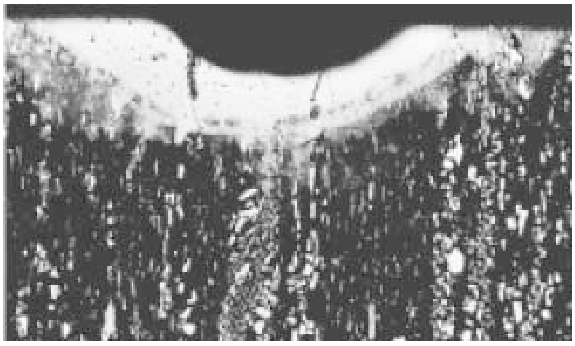


Fig 8. A section through one of the suspected "pores".

Fissure frequency also increases with pulse duration

With times in excess of 100 µ sec, all steels reveal several cracks in the melted layer. High-carbon and/or air-hardening steels show the highest frequency of fissures. The annealed specimens contain no cracks at all in the matrix.

The number of cracks which continue down into the hardened zone is roughly 20%, while only a very few cracks penetrate into the matrix. In the matrix, the fissure depth is seldom more than about some tens of a µm. Here too, it applies that cracks in the matrix are mainly encountered in the highly-alloyed cold-working steels.

Following table shows the occurrence rate of fissures in a number of tested tool steels.

	Melted zone	Hardened zone	Matrix
High-alloy cold-work steel *SVERKER* type	20–50	2–10	0–5
Hot-work steel *ORVAR* type	10–40	2–5	0–2
Cold-work steels *RIGOR* *ARNE* types	10–30	0–5	0–2
Plastic-moulding steels *IMPAX* *SUPREME* type	0–5	0–2	0

Table 2.

The difference in **stock-removal rate** amounts to a maximum of approx. 15% between the different grades of tool steel with the same machine setting data.

The **hardnesses** in the different layers can also vary considerably, but in principle the same pattern applies to all grades. Fig. 9 shows a typical hardness distribution. The difference in hardness and volume between the layers gives rise to stresses which, upon measurement, have been found to have the same depth as the affected surface layers. These stresses can be substantially reduced by extra heat-treatment operations.

Renewed tempering (235°C, 455°F, 30 min) of the specimen in the figure below resulted in lowering of the hardness level to the curve drawn with a broken line.

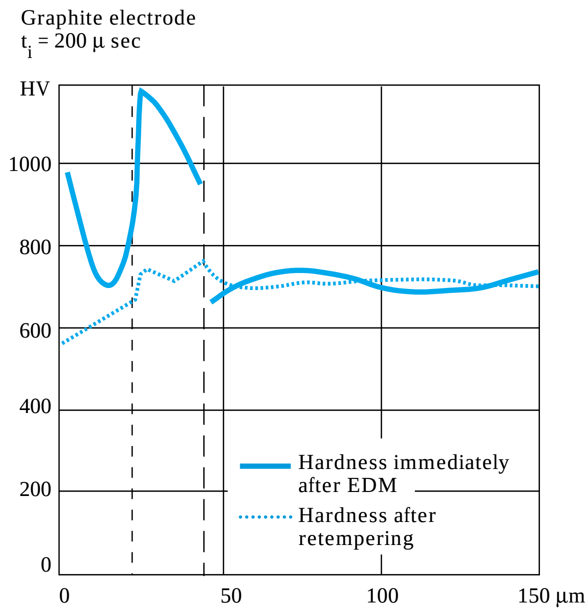


Fig. 9. Typical hardness distribution in hardened SVERKER 21 immediately after EDM and then after re-tempering.

If electrical discharge machining is properly performed with a final fine-machined stage, surface defects are largely eliminated. If this is not possible for one reason or another, or if it is necessary for all effects to be eliminated, some different related operations can be used:

- **Stress-relief tempering** at a tempering temperature approx. 15°C (30°F) lower than that previously used tempering temperature, lowers the surface hardness without influencing the hardness of the matrix.
- **Grinding or polishing** will remove both the surface structure and cracks, depending of course on how deeply it is done (approx. 5–10 µm in fine-machining).

BENDING TEST

To evaluate the likely effect of the remelted layer, surface irregularities and cracks produced in the EDM process on the strength of a tool, a bending test was carried out. Various combinations of EDM surface finish and post treatments, e.g. stress-relieving/polishing, were tested on 5 mm square test pieces of *RIGOR* at 57 HRC. The test pieces were spark-machined on one face to different EDM stages and bent severely, with the EDM surface on the outside of the bend.

Fig. 10 shows that the sample with a fine-spark machined finish which had been polished afterwards gave the best result. The rough spark-machined sample, without any post treatment, had the lowest bending strength.

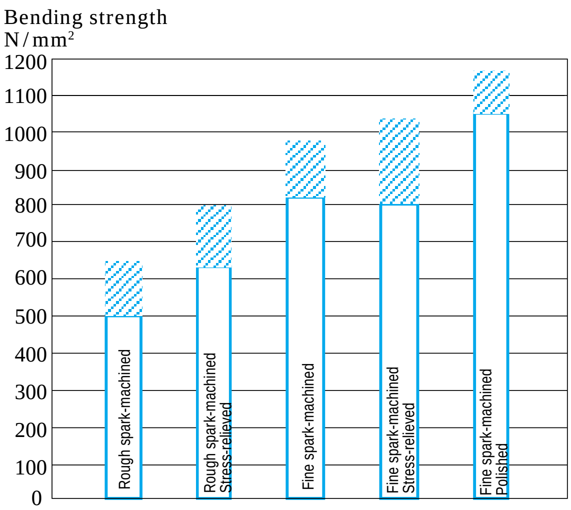


Fig. 10. Bending strength at different EDM stages and with different subsequent operation. Material RIGOR 57 HRC. The shaded areas show the spread of the results measured.

BACKGROUND TO THE BENDING TEST RESULTS

The hard, re-solidified rehardened layers cause, in the first instance, those cracks which are formed upon application of the load and in the second instance those which were already present to act as initiators of failure in the matrix. At 57 HRC, the matrix is not tough enough to stop the cracks from growing and consequently the failure occurs already on the elastic part of the load curve. Normally, there should have been a certain amount of plastic bending of a test bar in this material.

Achieving best tool performance

EDM USING SOLID ELECTRODES (COPPER/GRAPHITE)

As noted, in most cases where the EDM process has been carefully carried out no adverse effect is experienced on tool performance. As a precautionary measure, however, the following steps are recommended:

EDM of hardened and tempered material

A Conventional machining
B Hardening and tempering
C Initial EDM, avoiding “arcing” and excessive stock removal rates. Finish with “fine-sparking”, i.e. low current, high frequency.
D (i) Grind or polish EDM surface
or D (ii) Temper the tool at 15°C (30°F) lower than the original tempering temperature.
or D (iii) Choose a lower starting hardness of the tool to improve overall toughness.

EDM of annealed material

A Conventional machining
B Initial EDM, as C above.
C Grind or polish EDM surface. This reduces the risk of crack formation during heating and quenching. Slow pre-heating , in stages, to the hardening temperature is recommended.

Note: When EDM’d in solution annealed condition the toughness of *CORRAX* is not affected.

It is recommended that all EDM’ing is done after aging since an aging after EDM’ing will reduce the toughness.

It is recommended that the “white layer” is removed by grinding, stoning or polishing.

WIRE EDM

The observation made about the EDM surface in earlier pages are also mostly applicable to the wire EDM-process. The affected surface layer, however, is relatively thin (<10 µm) and can be compared more to “fine-sparking” EDM. Normally there are no observable cracks in the eroded surface after wire erosion. But in certain cases another problem has been experienced.

After heat treating a through hardening steel the part contains high stresses (the higher the tempering temperature, the lower the stresses). These stresses take the form of tensile stresses in the surface area and compressive stresses in the centre and are in opposition to each other. During the wire erosion process a greater or lesser amount of steel is removed from the heat-treated part. Where a large volume of steel is removed, this can sometimes lead to distortion or even cracking of the part. The reason is that the stress balance in the part is disturbed and tries to reach an equilibrium again. The problem of crack formation is usually only encountered in relatively thick cross section, e.g. over 50 mm (2") thick. With such heavier sections, correct hardening and double tempering is important.

Fig. 11. Wire erosion of a hardened and tempered tool steel blanking die.

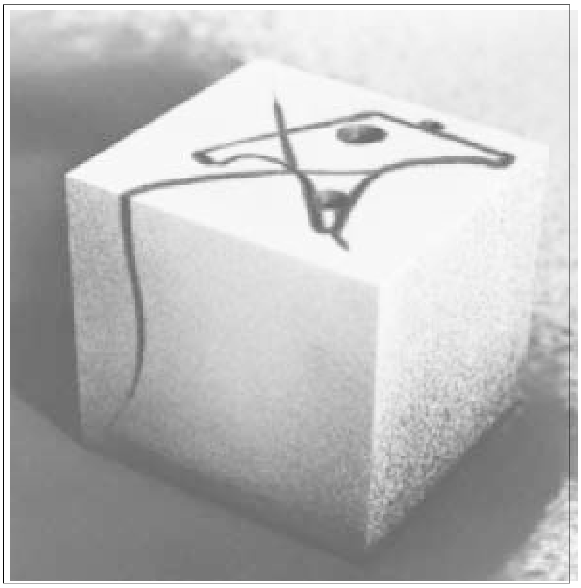


Fig. 12. This block of D2 steel, approx. 50 x 50 x 50 mm (2" x 2" x 2"), cracked during the wire EDM operation.

In certain cases the risk can be reduced through different precautions.

1: To lower the overall stress level in the part by tempering at a high temperature. This assumes the use of a steel grade with high resistance to tempering.

2: By drilling several holes in the area to be removed and to connect them by saw-cutting, before hardening and tempering. Any stresses released during heat treatment are then taken up in the pre-drilled and sawn areas, reducing or eliminating the risk of distortion or cracking during wire-erosion. Fig. 13 illustrates how such pre-cutting may be done.

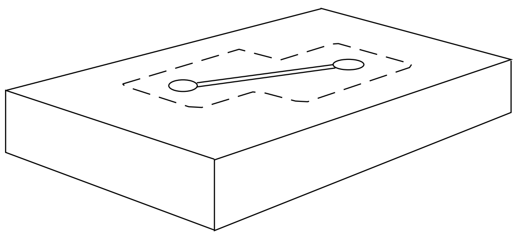


Fig. 13. Pre-drilled holes connected by a saw-cut, before hardening and tempering, will help to prevent distortion or cracking when wire-eroding thick sections.

WIRE-EROSION OF CUTTING PUNCHES

When producing a cutting punch by wire erosion, it is recommended (as with conventional machining) to cut it with the grain direction of the tool steel stock in the direction of the cutting action. This is not so important when using PM steels due to their non-directional grain structure.

Polishing by EDM

Today some manufacturers of EDM-equipment offer, by a special technique, possibilities to erode very fine and smooth surfaces. It is possible to reach the surface finish of about 0.2–0.3 µm. Such surfaces are sufficient for most applications. The greatest advantages are when complicated cavities are involved. Such cavities are difficult, time consuming and therefore expensive to polish manually, but can be conveniently done by the EDM-machine during a night-shift, for example.

Investigations made on our grades *IMPAX SUPREME, ORVAR SUPREME, STAVAX ESR* and *RIGOR* show that the hard remelted white layer produced is very thin and equal in the these grades. The thickness is about 2–4 µm. Since there is no sign of any heat-affected layer, the influence of the EDM on mechanical properties is negligible.

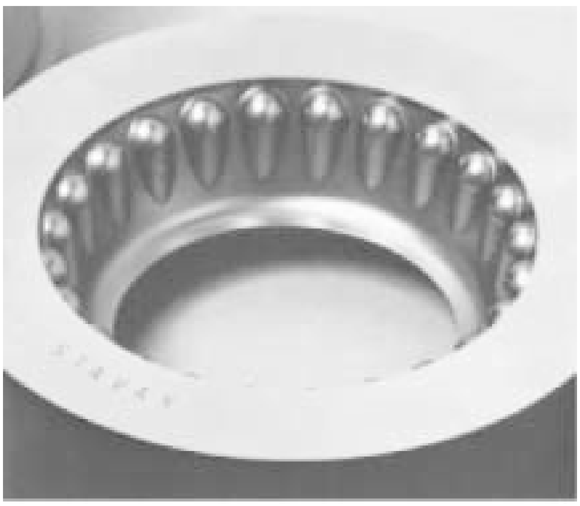


Fig. 14. This STAVAX ESR mould insert was finished by EDM "polishing".

Summary

In summing up it can be said that properly executed electrical discharge machining, using a rough and a fine machining stage in accordance with the manufacturer's instruction, eliminates the surface defects obtained in rough machining. Naturally, certain structural effects will always remain, but in the vast majority of cases these are insignificant, provided that the machining process has otherwise been normal. Structural effects, more-over, need not necessarily be regarded as entirely negative. In certain cases the surface structure, i.e. the rehardened layer, has—on account of its high hardness—improved the resistance of the tool to abrasive wear. In other cases it has been found that the cratered topography of the surface is better able to retain lubricant than conventional surfaces, resulting in a longer service life. If difficulties in connection with the working performance of spark-machined tools should arise, however, there are some relatively simple extra operations that can be employed, as indicated above.

A slightly striped appearance has been reported in materials rich in carbides, such as high-carbon cold-work steels and high-speed steels, where there is always a certain amount of carbide segregation or in material with high sulphur content.

The difference in bending strength between rough-spark-machined and fine-spark-machined test-pieces is largely due to the difference in the distribution of the cracks and to the presence of the in spots distributed white layer on the fine-spark-machined specimens. The rougher surface finish of the rough-machined specimen has not really been significant. Regardless of circumstances, such surface irregularities are relatively harmless as crack initiators compared with the solidification cracks. During the polishing of the fine-machined test-piece which was carried out, the depth of the white and rehardened layer was merely reduced and not completely eliminated.

Further polishing would probably result in complete restoration of the bending strength. Highly stressed tools and parts thereof, e.g. very thin sections that are far more liable to bending, can justify an extra finishing operation.

The lower the hardness in the matrix, the less sensitive the material will be to adverse effects on the strength as a result of electrical discharge machining. Lowering of the hardness level of the entire tool can, therefore, be another alternative.