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Case study

Analysis of cracks generated in the spinning-mandrel teeth

M. Haghshenas [*], R.J. Klassen

Department of Mechanical and Materials Engineering, Western University, London, Canada

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ABSTRACT

The spinning process, using a splined mandrel, is always prone to premature failure of the splined mandrels. Such a failure is thought to be related to the magnitude of the forming forces exerted on the mandrel by the forming rollers during the spinning process. In the present paper, the characteristic of corner cracks in the mandrel teeth (made of S7 tool steel) of a spinning process has been investigated. The rotational speed of the mandrel is about 300 rpm during spinning process and the sheet metal (*i.e.* AISI 1020) is in contact with mandrel teeth to get the mandrel shape at the end of process. During this process, the mandrel teeth eventually break away. Fractography analyses using scanning electron microscopy (SEM) clearly confirm "*fatigue*" as being the main reason for the failure.

1. Introduction

The spinning process using a splined mandrel (Fig. 1) is a very cost effective way to fabricate internally ribbed parts and has found particular application in the automotive industry [1–3]. An on-going problem with this technique is early, and unexpected, fracture of the protruding mandrel splines. During the service life of the mandrel, the tooth region experiences a significantly high number of repetitive, irregular force oscillations causing the mandrel to crack. Changes in section size, a sharp corner, or groove in the mandrel geometry all increase the chance of failure. Premature failure of the mandrel splines may result from either (i) the cyclic impact loading caused by the forming rollers or (ii) the presence of the sharp corners of the mandrel splines which are necessary to form the desired shape of internal ribs on the final part but which acts as stress concentrators.

In the present paper the premature fracture of an splined mandrel made of a shock resistance S7 tool steel (0.5C, 0.75Mn, 0.25Si, 3.25Cr, 1.40Mo), heat treated to a hardness of 57–59 RC, is assessed. S7 tool steel is an air or oil hardening tool steel that is characterized by very high impact toughness. The combination of strength and high toughness makes it a candidate for a wide variety of tooling applications. It can be used successfully for both cold and hot work applications. Also suitable for hot work tools where the operating temperature does not exceed 540 °C.

The microstructure of the mandrel contains bainite and martensite (Fig. 2). The bainite constituent contributes to fairly good toughness in this kind of tool steel (Fig. 3).

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[*] Corresponding author. Tel.: +1 519 777 8978; fax: +1 519 515 0020.
E-mail addresses: mhaghshe@alumni.uwo.ca, meyhagh@gmail.com (M. Haghshenas).

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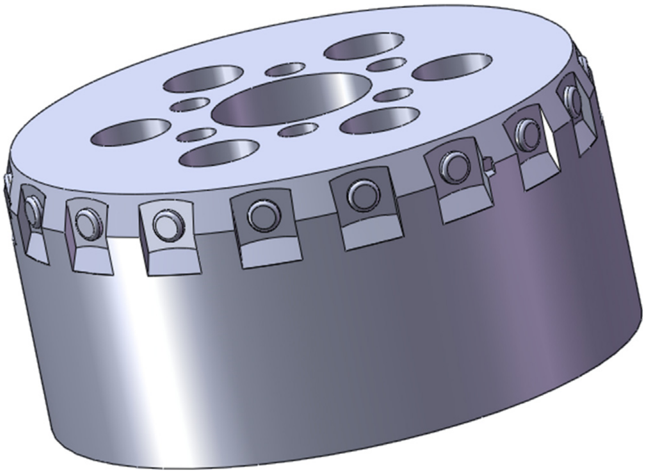

Fig. 1. Schematic representation of a splined mandrel used in the spinning process for producing internally splined components.

2. Macro-cracks in the mandrel

The majority of work materials used in the spinning operations subject the tooling to wear, mixed wear and/or chipping and cracking. The shock resistance S7 tool steel mandrel used in the present spinning operation has been observed to frequently fracture prematurely in service. Metal spinning is a rotary forming process in which the probability that the failures occur by a high-cycle fatigue mechanism is very likely [4,5]. While most tools and dies fail in a brittle manner, fatigue failures are sometimes encountered. Three basic factors that are necessary for the onset of fatigue crack growth are: (i) an applied tensile stress of sufficiently high magnitude, (ii) a large enough magnitude of $\Delta\sigma$, and (iii) a sufficiently large number of loading cycles. In the present study over the course of the spinning mandrel life, high numbers of irregular force-oscillations are applied. This is mainly due to the material displacement in and around the spline region of the rotating mandrel by forming rollers.

Visual inspection shows that flaws frequently appear at the root of splines on the side at the opposite to the direction of mandrel rotation. That is, flaws are seen on the top edge near the upper right corner of splines on the mandrel. Visual inspection and mandrel history show that cracks began to appear after about 8200 formed parts; the time for producing of each part is about 42 s. That is, the first cracks began to appear in the mandrel after about 95.5 h continuous working service.

The locations where cracking meets the surface were inspected carefully in an attempt to identify major defects in the surface which may act as the initiation sites for this cracking. The crack path at the root of a spline in the mandrel using optical

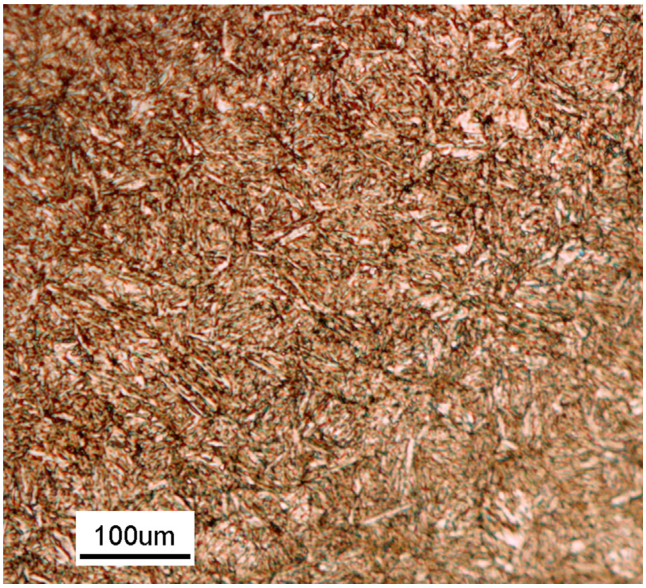

Fig. 2. The microstructure of the quenched and tempered shock resistance tool steel containing bainite and martensite phases.

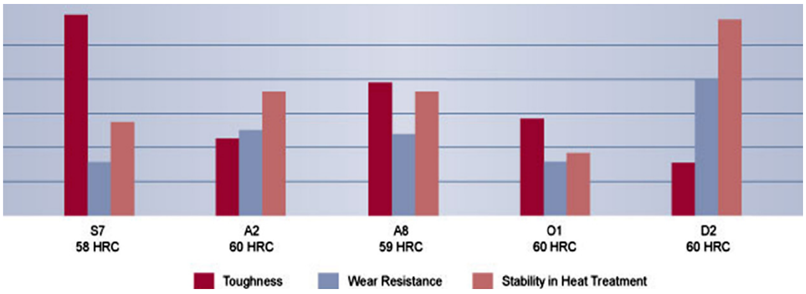

Fig. 3. A comparison of toughness in different tool steels [18].

microscopy and SEM has been shown in Fig. 4. The crack initiates at the rolling contact surface, caused by the accumulation of shear deformation due to repeated rolling–sliding contact loading and then propagates into the interior of the spline.

Failure analysis of mandrel indicates that mandrel fails due to fatigue cracking which is indeed a contact fatigue (CF) failure commonly seen in bearings and rail road tracks [6,7]. Contact fatigue is encountered most often gears and splined components where the surface stresses are high due to concentrated loads that are repeated many times during normal service. In the spinning process, common indications of specific operating conditions in conjunction with premature failures in the mandrel include (i) periods of heavy and dynamic loads/torques through a small contact area – leading to vibrations and rapid load changes and (ii) additional radial and axial forces due to the circumferential and axial motion of the rollers over the mandrel's splines.

Fig. 5 shows the macro-scale contact fatigue fracture surface using SEM which includes the whole area of the damage. As seen the fracture surface include three distinct regions (shown in Fig. 5 as zones "*A*", '*B*" and '*C*"). Fracture surface in the zone "*A*" consists of arranged lamellas (Fig. 6). The appearance of such a fracture is often called "platy" or "laminated". Zone "*C*" (Fig. 7) consists of a wavy appearance (rising (hills) and falling (valleys)) and zone "*B*" is a transition area between wavy and lamellae regions with irregular feature.

Cracks usually initiate in the high stress regions of a specimen (*i.e.* sharp corner, scratch marks, microstructural defects or inclusions). The fatigue crack initiates at the stress concentrators that are usually at, or near, the mandrel surface. This is the region where the cyclic stress amplitude is greatest and where material defects or residual stresses lessen the fatigue resistance of the component. Indeed, the local residual stress around the stress concentration can cause the tensile stress to become greater than the materials ultimate strength thus creating the crack initiation site. The crack will then propagate due to the cyclic loading. In most cases, the fatigue failure is observed to begin at a region where a mandrel spline changes in section size, or at a sharp corner, or at grooves.

Factors like heat treatment, fabrication (*i.e.* electron discharged machining (EDM)), or a multitude of operating conditions (alignment, feed, *etc.*) contribute to the fatigue failure in the sharp corners of the mandrel teeth.

It is known that in spinning contacts, the directions of the principal stress and strain tensors vary with time; they rotate as the contact load passes a given material point. In the spinning process, the material beneath the roller is subjected to nonproportional multiaxial load cycles. Here, the plastic flow is determined by the stress at the surface. The material near the

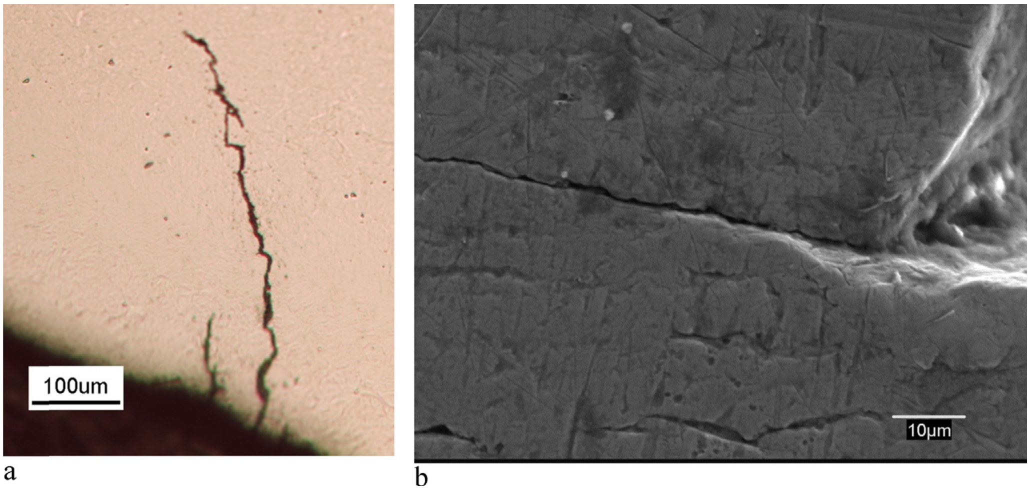

Fig. 4. Crack propagation in the spinning mandrel (a) optical microscopy, (b) SEM image; cracks emanate from the surface and propagate toward the center of the mandrel spline.

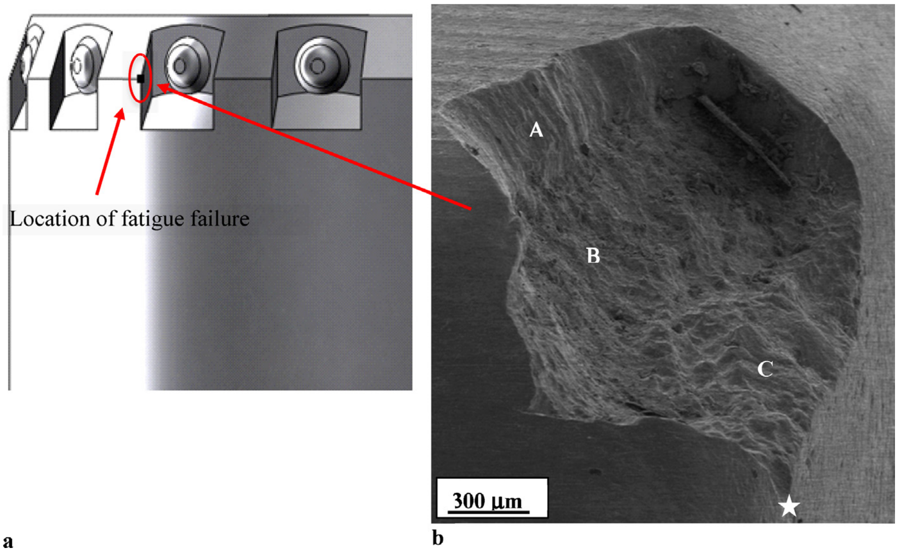

Fig. 5. (a) The location where mandrel typically fails. Mandrel fails by cracking or chipping which produces unacceptable defects on the formed parts. Cracking and chipping typically takes place on the corners of the slots either at the head of the spline/slot or at the base, (b) the scanning electron microscopy image taken of the fracture surface of the failed spline which consists of three distinct zones of (A) lamellar, (B) transition and (C) wavy.

surface experiences a nonproportional cycle of tension, followed by shear and compression [8]. This loading gives rise to an out-of-phase rotation of the principal stress and strain direction in time, which makes it difficult to predict the position and orientation of crack initiation. Therefore, there is a set of potentially critical planes that makes it possible to locate the initiation of a fatigue crack. It should be noted that crack initiation models that are based on uniaxial parameters and the equivalent stress or strain type parameters do not work well under these multiaxial conditions, since they have no physical interpretation in terms of multiaxial fatigue damage [8].

An important feature revealed in Fig. 5 is a transition from one type of fracture surface to another from the leading edge to the trailing edge. The fracture features of the two zones, *A* and *C*, differed markedly. The leading edge area appeared to contain a number of hills and valleys. Such a failure mechanism in the leading edge has been shown to be the characteristic fracture process in bearing steels [9,10]. The presence of cyclic stresses along the front corner of the spall could cause the fracture surfaces to rub together and thus might alter their appearance somewhat. There were indications that the ductile growth (hills and valleys) in the leading-edge area is a fatigue failure (*i.e.* relatively slow crack propagation due to alternating stress). This is confirmed with the presence of particles and globules of debris which suggest the fairly slow nature of the propagation process/stage. Spherical debris is often the product of high metal-to-metal contact, heavy fatigue loading and high frictional temperature. These are in consistent with previously reported results in the literature [11,12].

Considering the leading-edge area fails by fatigue, the difference in appearance of the leading- and trailing-edge areas can be explained. As the fatigue crack producing the leading-edge area becomes larger, the stress concentration increases to

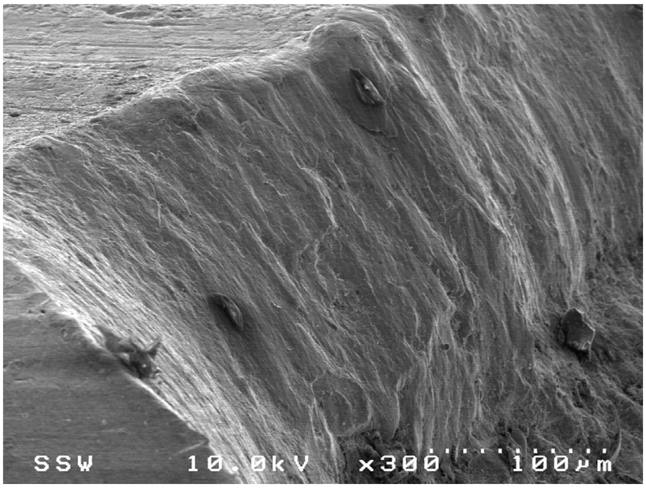

Fig. 6. SEM image of zone *A* (lamellar structure). These lamellar structures are attributed to the crack propagation stage.

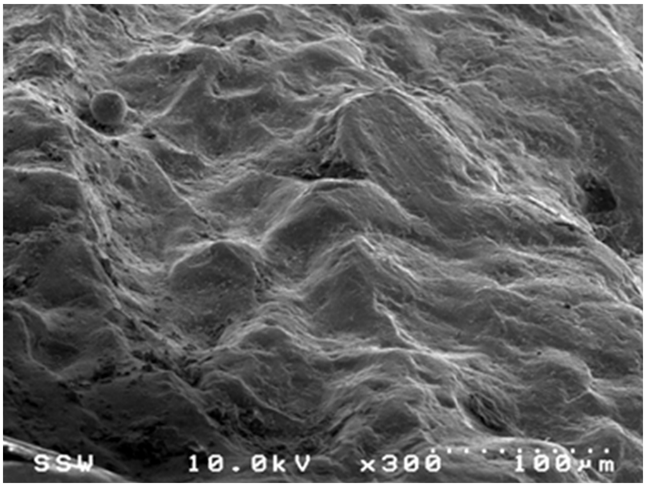

Fig. 7. SEM image of zone *C* (wavy structure). The presence of globules of debris and uneven structures are observed. The presence of debris confirms that the wavy structure progress slowly and therefore this region represents the crack propagation stage.

produce more rapid crack propagation in the remaining zone. This stress concentration could have been preexisting during the materials processing, or may have been caused by microstructural changes due to the cyclic loading of rolling/sliding contact.

It is suggested that contact fatigue failures are initiated in the leading edge area near the surface (shown with white star in Fig. 5). The fatigue crack then results in very rapid crack propagation which completes the failure and produces the different fracture surface appearance of the trailing-edge area (zone *C* contained fracture tongues or lamellas surrounded by smooth regions).

In worth noting that beach marks (at low magnification) and striations (at higher magnification) are well-known features of fatigue cracks but are not always present or visible (*i.e.* the present study). For example, relatively brittle metals (*i.e.* hardened steel and cast iron) do not always form microscopically identifiable striations and macroscopic beach marks in cyclic failures [13]. Furthermore, beach marks are usually more readily observed upon unidirectional loading than alternating loading.

The energy-dispersive spectroscopy (EDS) elemental analyses in the crack path and in a region away from the crack path are shown in Figs. 8 and 9 and Table 1. As seen, the amount of sulfur (S), as being the most detrimental element in the steel, is significantly higher near the crack path than in regions away from the crack path. Table 2 indicates that the specific grade of tool steel, S7 in this study, possess a fairly low fatigue resistance compared with other tool steels and is therefore susceptible to fatigue fracture.

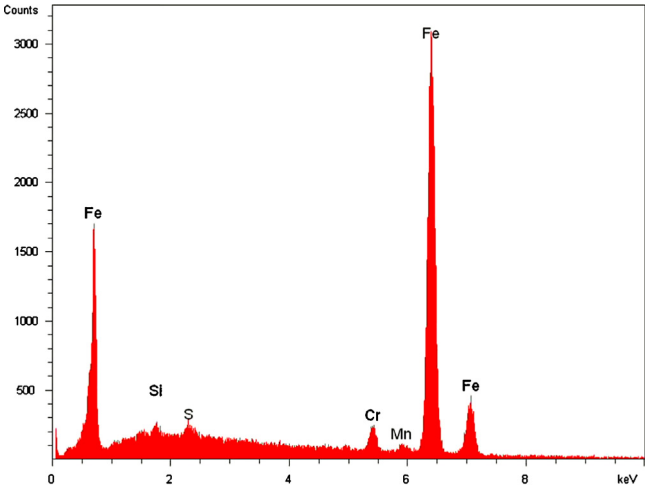

Fig. 8. The EDS analysis of the crack path showing significant amount of sulfur in the structure.

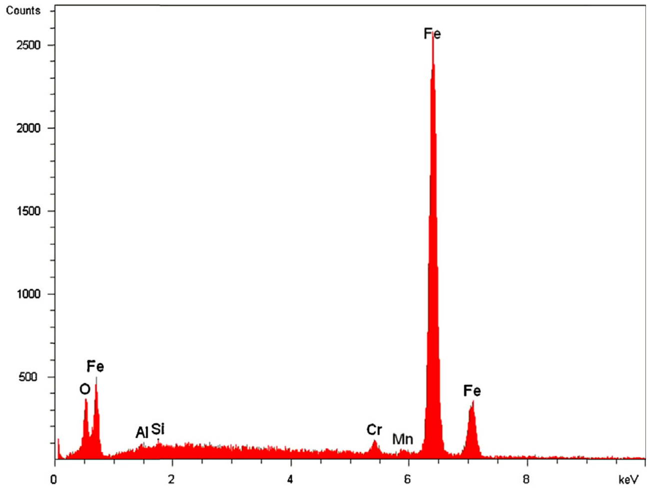

Fig. 9. The EDS analysis of base metal (away from crack path; reference area).

3. Factors contributing to the fatigue failure

The origin of the premature fatigue fracture of splined regions of the mandrel was attributed to one or a combination of the followings:

3.1. Ineffective tempering; this failed to reduce the brittleness of the tool steel. Indeed, heat treatment of the mandrel should be selected to maximize toughness and minimize untendered martensite and retained austenite.
3.2. Presence of sharp corners, which acted as a stress raiser. Compressive strength of mandrel's steel, S7, is very low (Table 1) and therefore mandrel's teeth cannot tolerate the compressive force of rollers and workpiece during forming. Therefore, the working situation (applied stress and number of cycles) will be in the un-safe area in the S/N curve and highly susceptible to fatigue fracture.
3.3. Employing EDM to make the teeth on the mandrel which makes the teeth corner locally harder (and more brittle) than other regions.
3.4. High amounts of sulfur and oxygen in local regions of the mandrel. These regions may be sites for easy fatigue crack initiation and propagation. Fig. 10 shows the elemental composition of iron oxides which are distributed in the base metal.
3.5. Combination of fatigue and impact caused by metal (mandrel)-to-metal (work piece) contact which will be more detrimental. Metal/metal, AISI 1020 as work piece and S7 as mandrel, contact will reduce fatigue limit sharply [14].

4. Remedial actions

4.1. Material selection

The EDS analyses show that the quality of the S7 tool steel is poor. The amount of oxygen and sulfur as two main harmful elements in steel is quite high (Figs. 10–12 and Table 2). It is suggested to use a higher quality (clean) steel for the splined mandrels. The steel shall contain lower oxygen and sulfur content and thus less oxide/sulfide inclusions. Our assessment of the fracture surface of failed splines on the mandrel indicates that oxide/sulfide contribute to the pre-mature fatigue failure.

The design of the tool steel used for the mandrel will heavily impact inherent resistance to fatigue cracking. Microstructural strength, steel cleanliness (absence of defects), and fine carbide formation/distribution are all key factors.

The chemical composition of a higher grade alloy, which we suggest as one possible material that could be used for these mandrel components, is given in Table 3.

Table 1
Elemental composition at reference area and crack path (at%).

	Si	S	Cr	Mn	Al	Fe
Reference area	0.24	0.04	2.34	0.9	0.48	Bal.
Crack path	0.49	0.53	2.77	0.6		Bal.

Table 2
The comparison of tool steels properties at various hardness values. “A^{++}” and “E^{+}” represent the best and the worst conditions, respectively (PM: powder metallurgy).

Hardness	Steel	Toughness	Compression strength	Fatigue resistance
56	1.2379	B	D	D
	AISI S7	A^{+}	E	D
60	1.2379	C	C	C
	Vanadis 4 (PM)	B	A^{+}	B
62	1.2363	A	C	B
	Vanadis 4 (PM)	A^{+}	B	B
	Vanadis 10 (PM)	A	B	B
64	ASP 30 (PM)	B	A	A
	1.3343	C	A	B
	Vanadis 10 (PM)	A	A	A
>68	ASP 60 (PM)	C	A^{+}	A^{+}
	Cemented carbide	E^{+}	A^{++}	?

4.2. Heat treatment

The investigation of the heat treatment records supplied by the mandrel supplier indicates that the mandrel hardened from the high side of the austenitizing temperature range and only slightly tempered with a low temperature treatment (400 °C) which is likely insufficient to fully reduce the brittleness of the mandrel. The heat treatment guide, for used S7 tool steel calls this steel to be tempered at 480–540 °C. Double or triple tempering is usually necessary for tool steels. The first temper relieves the stresses from the as-quenched martensite and at the same time conditions the retained austenite to transform into martensite upon cooling from the tempering temperature. If the second tempering is omitted, the tool will remain in the as-quenched condition and will eventually break. Correct hardening and double tempering is important. A third tempering is advisable for heavy cross sections such as this mandrel.

4.3. EDM characteristics

Numerous teeth on the mandrel surface are made by EDM technique. EDM provides the means to machine materials with high strength/hardness (*i.e.* tool steel) with very high degrees of precision even at very small characteristic scales (*i.e.* mandrel’ teeth).

When EDMing, main parameters (most notably the pulse current and the pulse-on duration) should be adjusted properly in order to obtain satisfactory results. Tai et al. [15] and Lee et al. [16] reported that surface crack formation is directly related to the EDM parameters (*i.e.* surface cracking can be suppressed by increasing the pulse current and reducing the pulse-on duration).

During the EDM operation the surface layer of the heat-treated steel is rehardened and is consequently in a brittle state. This very often results in chipping, fatigue cracking and a shortened tool life. The EDM’d components are commonly used in the extreme conditions (*i.e.* high temperature, high-stress, and high fatigue load). Under such conditions, the cracks on the machined surface act as stress raisers and lead to a considerable reduction in the fatigue life of the component [17].

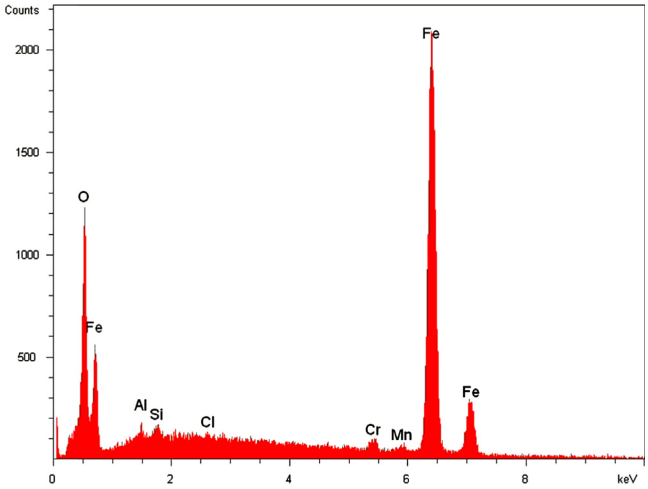

Fig. 10. The EDS analysis of iron oxide in the mandrel steel.

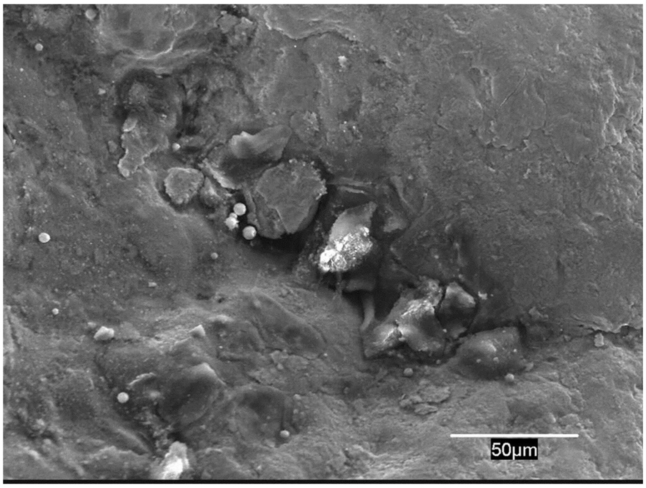

Fig. 11. Coarse inclusions and debris in the flaw surface.

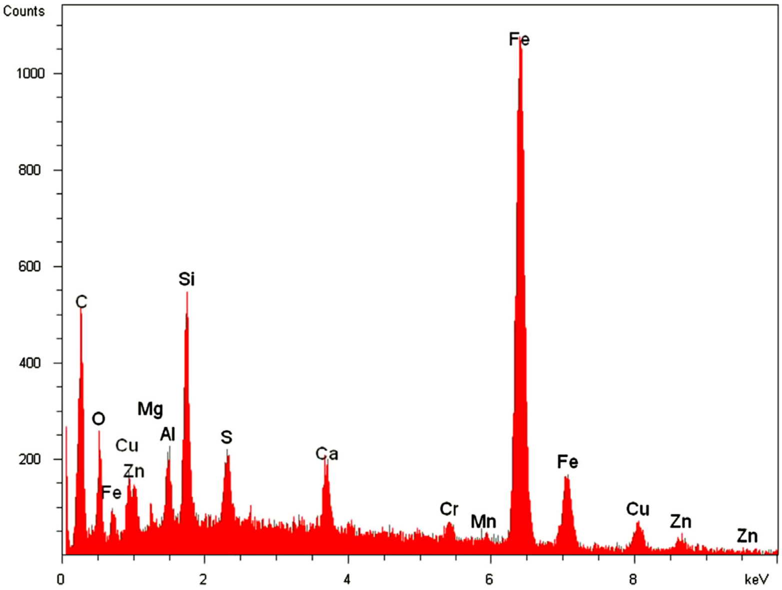

Fig. 12. The EDS analysis of inclusions in Fig. 11.

Table 3
Chemical composition of recommended tool steel for lower mandrel (wt%).

	C	Si	Mn	Cr	Mo	V	<S
Recommended alloy	0.55	0.35	0.70	3.25	1.40	0.25	<0.005

It is therefore suggested that the EDM process, used to create the splines on the mandrel, be performed in a multi-step process where the final step consists of a "fine-sparking" EDM pass which will remove the bulk of the brittle surface layer that was created by previous EDM rough cut passes.

4.4. Residual stresses

Cracking requires tensile stress to propagate. High residual compressive stress counteracts tensile stress and hinders the growth of cracks. Any measure which increases residual compressive stress should increase the life of a mandrel by suppressing cracking. Shot peening treatments introduce residual compressive stresses in the surface layer and prolong the fatigue life of a component. Furthermore, the condition of the surface of the tool is extremely important in addressing fatigue failures. High surface finish minimizes surface imperfections where fatigue cracking can initiate. It also reduces friction, which lowers the intensity of the applied load on the mandrel.

4.5. Process tuning

Fatigue life of a tool is generally dependant on two factors: stress intensity and number of cycles. Reducing the stress intensity (lower forces) may result in an increased tool life. Therefore, adjusting the process to reduce feed and increase speed should not significantly affect cycle time, but may result in improved tool life.

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