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Surface Integrity and Fatigue Performance of Inconel 718 in Wire Electrical Discharge Machining

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Abstract

This paper presents a study to characterize the surface integrity in wire electrical discharge machining (EDM) of Inconel 718 and investigate its effect on the fatigue performance of the alloy in a four-point bending fatigue mode at room temperature. The EDM process generates a rough recast surface with multi-types of defects. Surface craters, micro-cracks and micro-voids within the recast layer have been found to be most detrimental from the point of view of fatigue as they could provide many preferential initiation sites for fatigue cracks. As a consequence, the specimens with an EDM cut surface show an approximately 30 % decrease in fatigue life compared to those with a polished surface, and multiple crack origins were observed on the fracture surface. The high tensile residual stresses generated on the EDM cut surface, on the other hand, are also believed to be partly responsible for the loss in fatigue life of the alloy machined by EDM.

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Keywords: wire electrical discharge machining (wire EDM); surface integrity; fatigue; crack initiation; Inconel 718

1. Introduction

Increased demand of energy efficiency in aerospace and energy industries has promoted a rapid development of high temperature resistant materials, such as Ni-based superalloys. The properties that make Ni-based superalloys an outstanding candidate for high temperature applications are also responsible for its difficulty of machining, e.g. the alloys often retain high strength at elevated temperatures, but it requires high cutting forces in mechanical cutting processes.

Electrical discharge machining (EDM) is a competitive alternative to machining Ni-based superalloys as it is based on thermal-electric energies between an electrode and the workpiece, regardless of the hardness or the strength of the material to be machined [1]. Meanwhile, EDM also allows machining of components with a complex geometry. Several research work [2,3] have been carried out to promote the wire EDM process as a manufacturing technology, replacing the traditional broaching operation, for the production of fir-tree slots on turbine discs. A further advantage of EDM is that generally little plastic deformation is induced beneath the machined surface since there is no contact between the electrode and the component during machining.

However, giant heat generation in EDM causes melting and even evaporation of the workpiece material on the surface, while a recast layer will form in the subsequent rapid cooling. Studies [4-6] have pointed out that the structure and hardness of this layer differs from that of the parent material, and micro-cracks are commonly created within the layer due to either the enormous thermal stress or the tensile stress during the cooling process. The relationship between the parameters applied in EDM and the surface crack formation has been systematically investigated by Lee et al. [6]. The existence of micro-cracks on a surface machined by EDM may lead to a reduction of the material resistance to fatigue. Studies performed by Tai and Lu [7] in a tool steel revealed that the EDM specimen containing surface cracks had a shorter fatigue life compared to those which are also produced by EDM, but showed no cracks in the recast layer.

Inconel 718 is widely employed as the disc material in turbine engines. With regard to EDM of Inconel 718, studies that have been conducted so far are mostly related to the effect

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of process parameters on the characteristics of surface integrity of the alloy, especially with a focus on the formation of the recast layer [5,8,9]. Little work, however, refers to its impact on fatigue resistance of the material. Jeelani and Collins [10] tested a number of EDM specimens of Inconel 718 with different cutting speeds and it has been shown that the fatigue life of the machined specimens was decreased slightly compared to the lifetime of the parent metal, but it remains nearly constant with variations in the cutting speed. The decrease in fatigue life as the consequence of the EDM operation was proposed to be attributed to the increased hardness of the recast layer.

2. Experimental procedure

The material used in this work was taken from a heat treated coupon of Inconel 718 disc forging with a chemical composition as given in Table 1. The forging was solution annealed at 970 ˚C followed by air cooling to room temperature, and then a two-stage ageing was performed first at 720 ˚C for 8 h and further at 620 ˚C for another 8 h, and finally air cooled to room temperature. After the heat treatment, the coupon obtained a bulk hardness of ~ 410 HB.

Table 1. Chemical composition in wt. % of the Inconel 718 disc forging.

	Fe	Ni	Cr	Mo	Nb	Ti	Al	C
Minimum	Bal.	50	17	2.8	4.75	0.65	0.2	
Maximum		55	21	3.3	5.5	1.15	0.8	0.08

The specimen geometry used for four-point bending fatigue tests and the loading configuration are illustrated in Fig. 1. The fatigue specimens were manufactured using a commercial FANUC wire EDM cutting machine with a brass electrode that had a diameter of 0.25 mm under a dielectric fluid. The cutting process was conducted at a working voltage of 43 – 46 V, a working current of 6.5 – 6.6 A, a pulse-on duration of 10 µs and a feed speed of 3.32 – 3.35 mm/min.

Scanning electron microscopy (SEM) and electron channeling contrast imaging (ECCI) were employed then to characterize the surface morphology and the microstructure of the recast layer, while the surface residual stresses, in both the longitudinal direction (LD) and the transverse direction (TD), were measured on an EDM specimen by X-ray diffraction based on the "$\sin^2\psi$" method. A single measurement was performed on the EDM cut surface where it would be subjected to the cyclic tensile load in fatigue, and the residual stresses that remained after the fatigue test were also measured at the same point. The residual stress in LD is more significant as it is superimposed with the bending stress in fatigue. To prepare a reference group without any effect from the EDM cutting, mechanical polishing was conducted on several specimens; the surface that is loaded in tension during the bending fatigue was fine polished to 1 µm finish.

The polished and EDM specimens were fatigued at room temperature under load control on a servo-hydraulic testing frame with the Instron control system. The tests were carried out at a selected maximum load of 10 kN, a load ratio R = 0.1 and a frequency of 20 Hz with a sinusoidal waveform. The peak theoretical elastic stress on the surface is ~ 740 MPa which is below the yield strength of the Inconel 718 forging at room temperature. For each surface condition, two specimens were tested and the failed specimens were examined under SEM to compare the fatigue behavior under different surface conditions, and further to explain the resulting fatigue life.

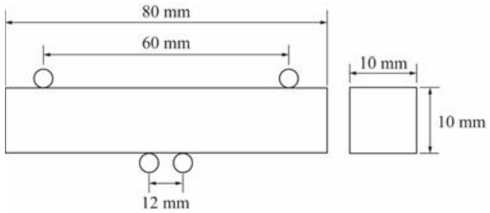

Fig. 1. A sketch showing the specimen geometry and the loading configuration used for the four-point bending fatigue.

3. Results and Discussions

The surface that has been machined by EDM shows a distinctive morphology, see Fig. 2. It consists of a number of characteristic features that have been widely observed on an EDM cut surface, such as fusing structures, craters, globular debris and micro-voids [5-7,9]. Unlike the case when EDM a surface of steels, micro-cracks were rarely reported in EDM of Inconel 718. However, it was found that surface micro-cracks in random orientations were formed under the machine settings employed in the present study and it seems that the sites where the micro-cracks initiated are associated with the micro-voids on the surface, see Fig. 3.

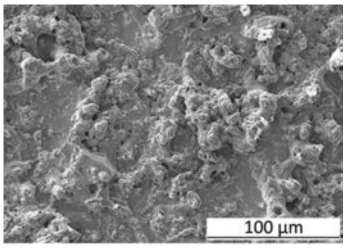

Fig. 2. Surface morphology of the EDM specimen.

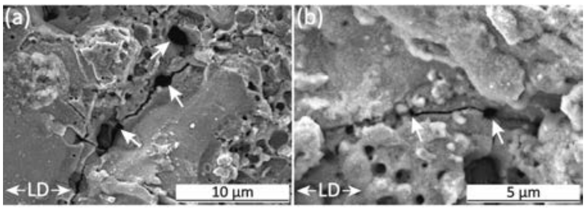

Fig. 3. Micro-cracks on the EDM cut surface; white arrows point out the micro-voids that are linked to the formation of the micro-crack.

Fig. 4 shows the cross-sectional view of the recast layer. It is predominantly discontinuous and non-uniform on the surface with a mixture of re-solidified metallic materials and oxides, while a considerable number of defects in terms of micro-voids and micro-cracks can also be observed within this layer, see Fig. 4(a). In Fig. 4(b), a corresponding ECCI image is given from which one could clearly identify the distinct microstructure of the recast layer from the parent material. However, it is important to stress that the oxides are irresolvable in Fig. 4(b) because of the high contrast; they appear as the same feature of the micro-voids and micro-cracks within the recast layer.

In general, the recast layer is comprised of substantial surface debris and a sub-layer. The globular debris were very likely re-solidified from the vaporized surface material during the cooling, deposited on the surface and weakly adherent to the sub-layer. With the assistance of ECCI, it was observed that some surface debris consists of a microstructure with ultrafine grains, see Fig. 4(c), while the sub-layer normally contains a highly diffused microstructure, see Fig. 4(d). In addition, Fig. 4(d) also reveals that below the recast layer, there is a heat-affected zone where the giant thermal stress in EDM caused plastic deformation of the parent material. The thermal impact also resulted in tensile residual stresses on the EDM cut surface. The specimen that was measured shows high surface tension with a similar magnitude in LD and TD, i.e. 418 ± 22 MPa and 397 ± 22 MPa respectively. It is consistent with the findings of Bleys et al. [11] that the machined surface generated by EDM is often associated with high tensile residual stresses.

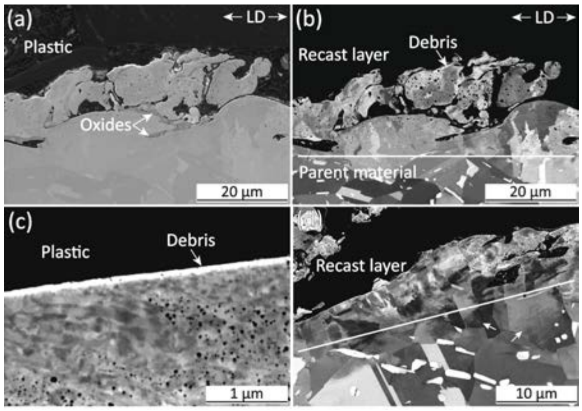

Fig. 4. (a) and (b) A secondary electron and corresponding ECCI image showing the cross-sectional view of the recast layer. (c) Ultrafine grains of the surface debris. (d) Plastic deformation of the parent material beneath the recast layer, as pointed out by white arrows.

Fig. 5 presents a summary of the fatigue lifetime for the specimens with two different surface conditions. As an attempt to minimize the influence from the crack propagation in the bulk material, the failure was defined as the number of cycles corresponding to an increase of 1 % in the deflection range. Although the data is slightly scattered, the fatigue life of the specimens machined by EDM in general was reduced by approximately 30 % in average compared to that for the specimens with a polished surface. A comparison of the appearance of the fracture surface is given in Fig. 6, where it can be seen that the primary crack in the polished specimen was created at the surface adjacent to the specimen corner, whilst there are multiple crack origins from the EDM cut surface. A similar failure mechanism was reported by Zeid [12] in the fatigue of an EDM cut tool steel. It was observed that fatigue cracks were initiated from many surface imperfections within the recast layer and it caused a great loss in fatigue life.

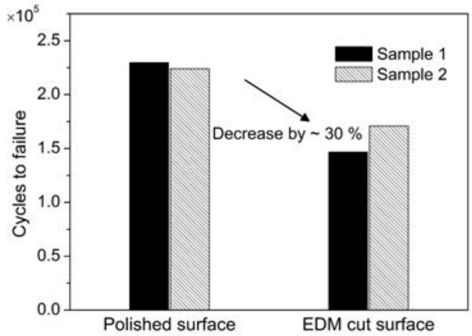

Fig. 5. A summary of the fatigue life for the specimens with two different surface conditions.

Fig. 7 shows a secondary crack that originated from the polished surface during the fatigue, where it is clearly seen that there is no global plastic deformation beneath the polished surface and the crack origin seems to be associated with the slip bands of the surface grain. It indicates that surface deformation most likely dominates the fatigue crack initiation for the polished specimens. In Fig. 8, some of the secondary cracks in the fatigued specimen with an EDM cut surface are presented. The crack initiation process is remarkably affected by either surface irregularities, e.g. surface craters, or by cracking of the recast layer. During the EDM process, the high cutting temperature causes micro-melt and evaporation of the material, leaving craters on the machined surface and they could act as crack initiation sites in fatigue as they increase the surface roughness, producing local stress concentrations.

Fig. 6 has shown that the recast surface developed by EDM has a high propensity to cracking when subjected to fatigue loads. Besides, comparing to the as-manufactured EDM surface, there is considerable multiplication in the number of cracks over the surface of the fatigued specimens. It could be explained, to a large extent, by the presence of the great number of defects within the recast layer. The pre-existing micro-cracks on an EDM cut surface has known to be detrimental to the fatigue resistance since fatigue cracks may start to grow from these flaws without an incubation of nucleation [7]. On the other hand, it is very likely that the

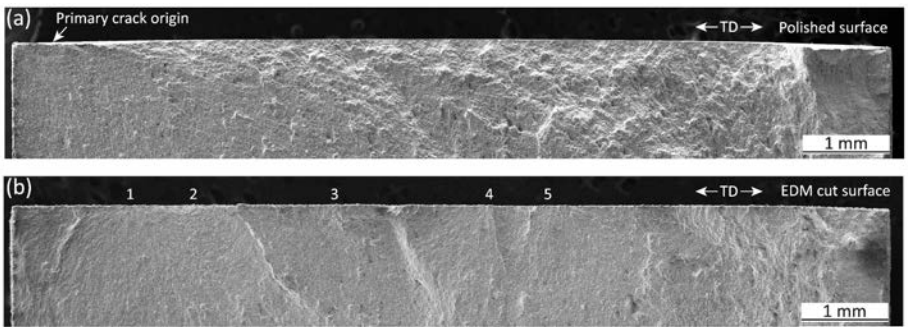

Fig. 6. A comparison of the fracture surface with two different surface conditions. There are multiple crack origins from the EDM cut surface, some of them are indicated by numbers in (b).

micro-voids with a stress concentration effect are also the preferential sites where fatigue cracks develop as the number of surface cracks was greatly increased after fatigue, while the majority of the cracks appeared to be orientated perpendicular to the applied stress in LD and with an origin from micro-voids, as shown for example in Fig. 9. Oxides may also enhance the formation of fatigue cracks from micro-voids due to their brittleness, as one of the secondary cracks shown in Fig. 8(b). Furthermore, of particular importance from Fig. 8(b), it is that the cracks start from the surface recast layer contribute to the final failure of the specimen only when it could proceed downward into the substrate. Thus, the cracking of the surface debris may not be of great significance due to the fact that most of the debris have a weak bond with the sub-layer. In contrast, the defects induced by EDM in the sub-layer of the recast surface could be detrimental in terms of the crack initiation during fatigue.

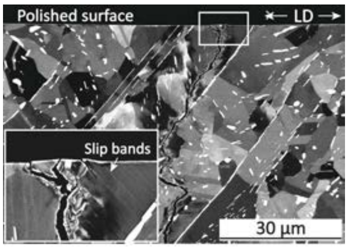

Fig. 7. Cracking at the polished surface associated with surface deformation.

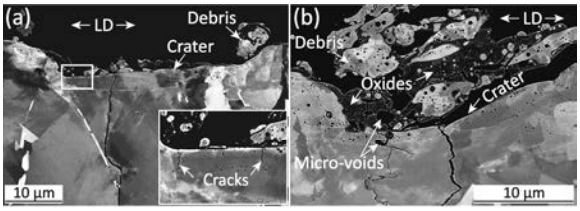

Fig. 8. Secondary cracks created in the fatigue of the EDM specimens.

Compared to the polished surface, the poor surface integrity found on the EDM cut Inconel 718 provides many natural sites at the surface where fatigue cracks preferentially initiate. This change of the crack initiation behavior explains the multiple crack origins on the fracture surface and the premature fatigue failure of the EDM specimens. It differs from the findings of Jeelani and Collins [10] where the increased hardness of the recast layer was proposed to be primarily responsible for the decreased fatigue life of Inconel 718 machined by EDM. On the other hand, residual stresses have been long recognized to play an effect that is not negligible in the fatigue of a machined component. Studies by Ghanem et al. [13] indicated that for high cycle fatigue the presence of the tensile residual stress played a large effect on the declined fatigue resistance of the EDM workpiece of a tool steel, whilst the cycling strains led to a great residual stress relaxation in low cycle fatigue. Hence, in this study where a low applied stress was employed, the high tensile surface residual stresses created by EDM could also contribute to the measured shorter fatigue life. This was further supported by the measurement showing that over 50 % of the tensile residual stresses on the EDM cut surface was remained after fatigue, 225 ± 28 MPa in LD and 302 ± 19 MPa in TD.

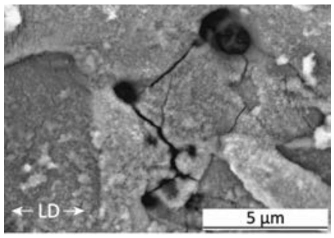

Fig. 9. Appearance of the cracks that were most commonly observed on the EDM cut surface after fatigue.

4. Conclusions

The results of this study highlight the relationship between the surface integrity and the fatigue performance of an Inconel 718 component after wire EDM cutting. The specimens machined by EDM have a noticeable decrease in fatigue life compared to those with a polished surface. Examination of the fracture surface indicates that instead of one primary crack initiation site in the case of a polished specimen, there are multiple crack origins at the EDM cut surface. The reason is that the surface produced by EDM consists of vast potential sites for the crack initiation in fatigue. It has been found that fatigue cracks preferentially develop from either surface craters or the pre-existing defects in the recast layer, such as micro-cracks and micro-voids. The surface irregularities, high propensity of the recast layer to cracking, together with the large surface tensile residual stresses are proposed to be responsible for the loss in fatigue life of the EDM specimens.

Acknowledgements

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