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# Fatigue Life of Electrodischarge Drilled Inconel 718

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**Abstract**

The machining of complex shapes in difficult-to-cut materials is hardly achieved by traditional metal cutting. Particularly small deep holes are often a cause for premature tool failure or even a technological frontier. Yet, the use of Nickel-based alloys is common in high-temperature and aerospace applications, where thin shapes and deep holes are often required. In these cases non-contact processes, such as electrodischarge (ED) drilling, may be the only viable manufacturing solution. Morphology of ED machined surfaces is significantly different than obtained by metal-cutting operation and is known to jeopardize fatigue strength, but the extent needs to be gauged and related to the process parameters. The paper addresses the effect of ED drilled holes (0.8 mm diameter, aspect ratio 10) on the fatigue life of Inconel 718. Rotating bending fatigue tests are executed on specimens drilled under two ED setups, as well as with a traditional cutting tool. Specimens free from holes are fatigued under the same conditions for comparison. Extremal ED parameters are selected based on previous studies: conditions for best surface finish are contrasted with those for highest productivity. S-N curves show that the ED process causes a decrease of the fatigue resistance with respect to traditional drilling, whereas the effect of different ED setups is negligible. Maximum productivity can thus be pursued with no threat to fatigue performance. The fatigue limit variation is quantified by using the superposition effect principle: ED drilling causes an increase of the stress concentration factor around 25% if compared to traditional drilling. The macroscopic fatigue behavior is integrated with a study of the effects of the different drilling processes in the micro-scale, by means of a microstructural and fractographic analysis.

**Keywords:** Inconel, fatigue, electrodischarge, notch intensity factor, surface morphology.

## INTRODUCTION

High strength at high temperature and excellent corrosion resistance drive the use of Nickel-base superalloys under severe operating conditions, including gas turbines and aeroengines [1]. High toughness and severe work-hardening cause serious machining difficulties, particularly premature tool wear and surface damage or induced stresses in the workpiece [2,3].

Unconventional non-contact operations, such as electrodischarge (ED) processes, may offer a less critical alternative or even be the only viable solution if complex geometries, reduced thickness, and high aspect ratio holes were required [4]. A noteworthy application of small deep holes in fatigued components consists in lubrication holes through the shank of connecting rods for race engines. Some of the authors of this paper previously provided a comprehensive study of the peak hoop stress within the small end, from an analytical, photoelastic, and numerical viewpoint [5-7]. Here, the focus is moved to stress intensification at the bottom of the small end, where the geometrical effect of the hole and the microstructural modifications due to the drilling process combine.

The typical morphology of ED machined surfaces includes overlapping craters, globules of debris, a recast layer and, eventually, surface cracks [8]. All of these features endanger fatigue strength, together with wear- and corrosion resistance, which contrasts with the requirements of demanding applications [9]. Actually, the unspecific remark that EDM jeopardizes fatigue life [10] needs to be quantified and weighed against process set up. Electrodischarge parameters can be tuned for a desired surface finish. In the case of steel, remarkable loss in fatigue life has been observed for high discharge energy, chiefly associated with the occurrence and extension of cracks. Instead, negligible damage has been detected for low-energy finishing conditions. [11]. Tai and Lu deepened the effects of EDM parameters on the formation of cracks in the recast layer of SKD11 tool steel, in order to preserve the fatigue life [8].

Not much work has been reported in the field of ED drilling of Inconel 718. In [12], width and depth of craters, as well as the occurrence of micro cracks in the recast layer, have been related to peak current. The authors of this paper previously reported on the achievability of holes down to 0.25mm diameter, with aspect ratio as high as 40, in Inconel 718 [13].

The results demonstrated the relevance of pulse power in the optimization of material removal rate or surface finish. Similar results were obtained for ceramic matrix composites, with power being a discriminating factor between different process regimes and consequent surface morphologies [4]. As to morphology of the eroded surface in the case of Inconel, the main observations can be summarized as follows: no heat affected zone was detected, crater dimension and thickness of the recast layer increased with pulse power whereas intergranular corrosion was detected in the low-power regime [13].

The present investigation aims at evaluating the loss in fatigue life as a consequence of different drilling set-ups and relating the outcomes to the obtained surface morphology. The results are quantified by calculating the notch intensity factor.

## EXPERIMENTAL

Round specimens of Inconel 718 are machined to the geometry shown in Fig. 1, as defined in ISO 1143:2010 [14].

Four groups of specimens are prepared:

- undrilled (here referred to as UD);
- conventionally drilled using a carbide bit of 0.8mm diameter, feed 0.01mm/rev, speed 4m/min (here named CD);
- ED drilled using a Sodick K1C machine with copper multi-channel electrodes of 0.8mm diameter, voltage 30V, peak current 39 A, pulse-on time 12 µs, pulse-off time 28 µs, pulse power 1170W, pulse energy 14mJ (EDDLR, where LR stands for low roughness);
- ED drilled similarly to the previous group, with voltage 50V, peak current 33 A, pulse-on time 30 µs, pulse-off time 8 µs, pulse power 1650W, pulse energy 50mJ (EDDHR, HR standing for high roughness).

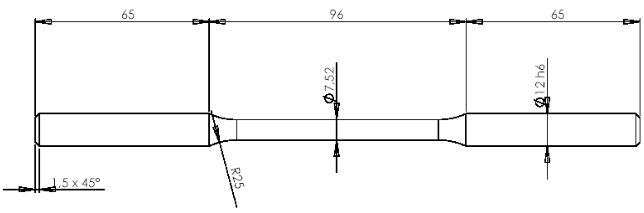


**Figure 1.** Geometry and dimensions of the specimens (ISO 1143 [14]).

ED drilling parameters are chosen accordingly to the results shown in [13], in order to determine the fatigue limit in the case of minimum surface roughness and longest drilling time (EDDLR), as well as in the opposite condition (EDDHR). As an indicator of productivity, material removal rate (MRR) is calculated for the two EDD conditions by dividing the lost mass by the drilling time. Tool wear is quantified by the ratio of the mass lost by the electrode to the drilling time (Electrode Wear rate, EWR).

Holes are measured using a Kestrel 200 measuring microscope, equipped with a Quadra-check metrology software (Vision Engineering).

Tensile properties are tested on undrilled samples using a speed of 2 mm/min, in order to determine UTS. The result was used to set the stress values for the fatigue tests. Rotating bending fatigue tests are performed at 25Hz. Infinite life is assumed after survival to $10^7$ cycles.

S-N values are elaborated upon to calculate the stress concentration factor $K_T$. Specifically, $K_T$ is calculated as the scaling factor to be applied to the values of stress, for each drilling condition, in order to maximize the linear fit of the whole set of experimental points, obtained by merging the results of the specific drilled group with the undrilled one. The computation of $K_T$ for CD specimens, for example, consists in finding the value $K_{T,CD}$ that maximizes the coefficient of determination for the linear fit of the dataset in Equation (1):

$$\{(\log n_i\,;\sigma_i), (\log n_j\,;K_{T,CD}\sigma_j)\} \tag{1}$$

where i and j span among the UD and CD specimens, respectively. Specimens surviving to $10^7$ cycles are not included in the dataset. Similar calculations are made for EDDLR and EDDHR groups. In each case, the variation of the coefficient of determination is studied beforehand, to verify the existence of a maximum.

Roughness inside the eroded holes is measured on the broken halves, through a high-resolution 3D chromatic confocal profilometer (ConScan, CSM Instruments) in accordance with ISO/DIS25178-2 and ASME B46.1, as described in [15,16].

Metallographic sections and fractured fatigue surfaces are investigated by optical and scanning electron microscope (SEM), in order to study the microstructure and the failure modes.

## RESULTS AND DISCUSSION

Mean diameter measured on the holes of the three groups is listed in Table 1.

**Table 1.** Measurements of mean hole diameter.

| | CD | EDDLR | EDDHR |
|---|---|---|---|
| Diameter [mm] | 0.869 | 0.898 | 0.952 |

In keeping with the results in [13], the radial gap in EDD increases for increasing pulse power or energy. That is to say that EDDLR holes, drilled with low energy input, are slightly smaller than EDDHR holes. MRR is measured to be on average 48.8mg/min for EDDLR set-up and 312.3mg/min for EDDHR setup. The upper-power EDD condition ensures 6 times higher productivity than obtained with 1170W pulse power. Correspondingly, almost 6 times quicker tool wear is observed for EDDHR (EWR=162.8mg/min) than for EDDLR (EWR=28.0mg/min).

Tensile tests gave a yield strength (Y) of 350MPa and an ultimate tensile strength of 760MPa. Based on these values, stress levels for the fatigue testing of the UD specimens are set at 300MPa (0.86Y), 350MPa (Y), 400MPa (1.14Y) and 450MPa (1.29Y). Stress values for the drilled samples are of course lower, selected after preliminary tests in order to build up Wöhler diagram in the range $10^5$ to $10^7$ cycles. The S-N results for the UD samples, and for the three drilling conditions analyzed, are plotted in Figure 2.

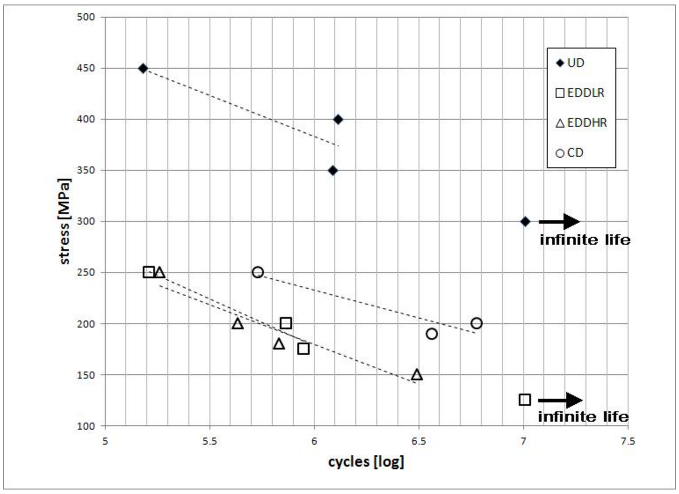


**Figure 2.** S–N comparative results of the four groups of specimens.

A detriment in fatigue life is of course observed when comparing UD specimens with all the drilled ones, the extent being greater for ED- than for conventional drilling. Some surprise may be occasioned, yet, by the two EDD setups being essentially undifferentiated. The results are best interpreted together with the measurements of average surface roughness ($R_a$) on the broken halves, given in the first row of Table 2. $R_a$ of CD holes is an order of magnitude lower than of EDD ones. As a consequence, for the sake of comparing the fatigue lives for the three drilling conditions, it seems reasonable to assume CD holes as geometrically ideal, that is to say to neglect their roughness. Under this hypothesis, the decrease of fatigue resistance between UD and CD tests can be ascribed only to the presence of the hole, and the further loss between CD and EDD specimens can be imputed to the effects of the ED process. When comparing the two EDD conditions, $R_a$ of EDDHR holes is roughly three times as high as of EDDLR. However, S-N results fall within the same area of the plot for the two groups. A more quantitative view is offered by the values calculated for $K_T$ that are listed in the second row of Table 2. The presence of the hole, with a very low (negligible for the comparison considered here) surface roughness causes a stress intensification of 60% compared to the undrilled state. The increase in the factor of stress concentration reaches 100% if the hole is drilled by electro-discharges, the deviation between the two ED setups being below 2%. ED parameters, either set to low- or high-power, prove to have little impact on the variation of fatigue life. If an attempt is made to apply the superposition principle, it may be concluded that the sole effect of EDD turns into a stress intensification of 25% in respect to the ideal hole.

**Table 2.** Surface roughness measured inside the holes, after the fatigue tests, and stress concentration factor calculated from the S-N results.

| | CD | EDDLR | EDDHR |
|---|---|---|---|
| $R_a$ mean (SD) [µm] | 0.32 (.03) | 1.23 (.09) | 3.39 (.28) |
| $K_T$ | 1.60 | 1.98 | 2.02 |

Morphologic features of EDD surfaces superpose the stress state in the hole neighborhood, so crack nucleation is anticipated and fatigue life is decreased. The mechanisms of failure and their relation to the eroded morphology are investigated by fractographic analysis. Several crack initiation points are generally observed. Figure 3 shows electron micrographs of the rupture surface for an EDDHR specimen. High pulse power produces a thick uneven recast layer, with many cracks. Yet, it is evident from the enlargement that such cracks remain confined to the recast layer and do not propagate into the base material. A much different morphology is observed for EDDLR holes, where the recast layer is almost absent and, by contrast, intergranular corrosion is often detected, as shown in Figure 4a. Nevertheless, such corrosion does not act as a crack initiator. The portion of rupture surface shown in Figure 4b is clearly free from cracks, the corroded grain boundary does not open during cyclic fatigue. On the whole, the above observations explain why none of the two studied ED setups is specifically detrimental to fatigue life.

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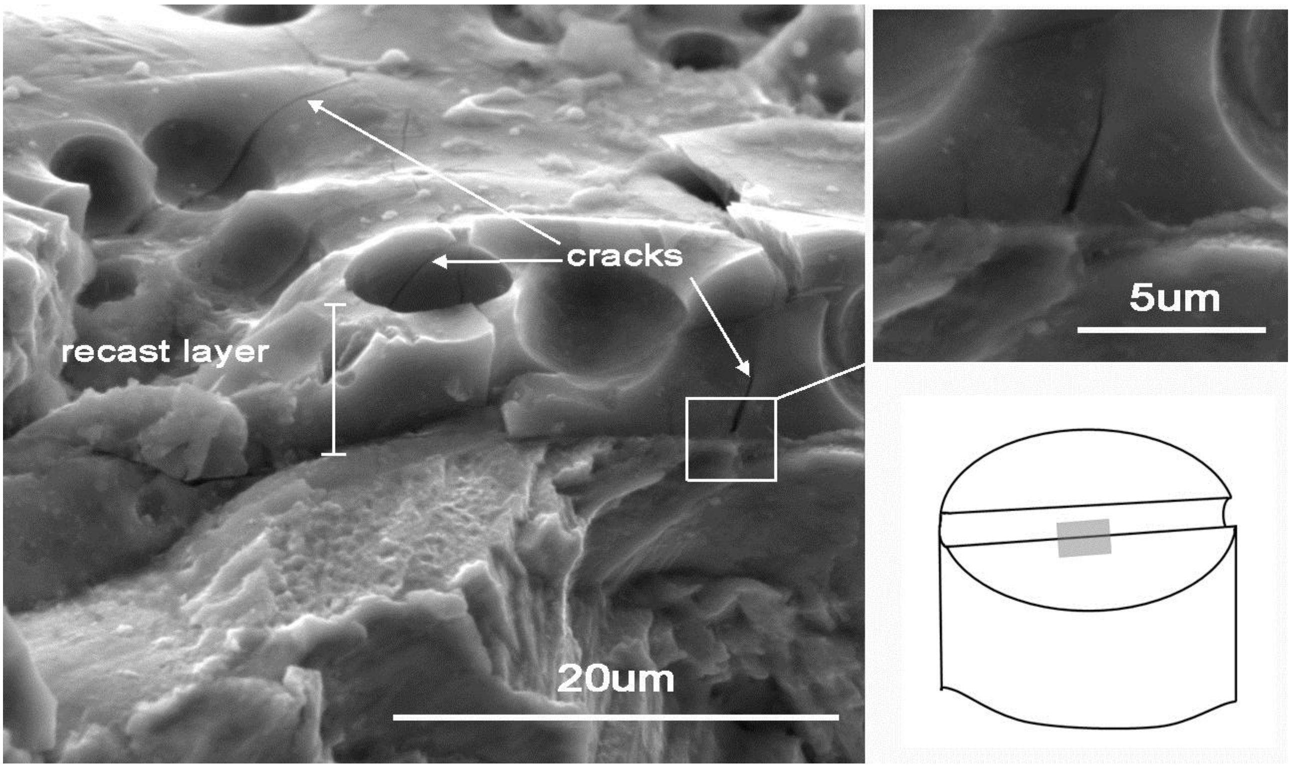


**Figure 3.** Rupture surface of a EDDHR specimen across the hole boundary. The grey rectangle in the scheme indicates the observation area.

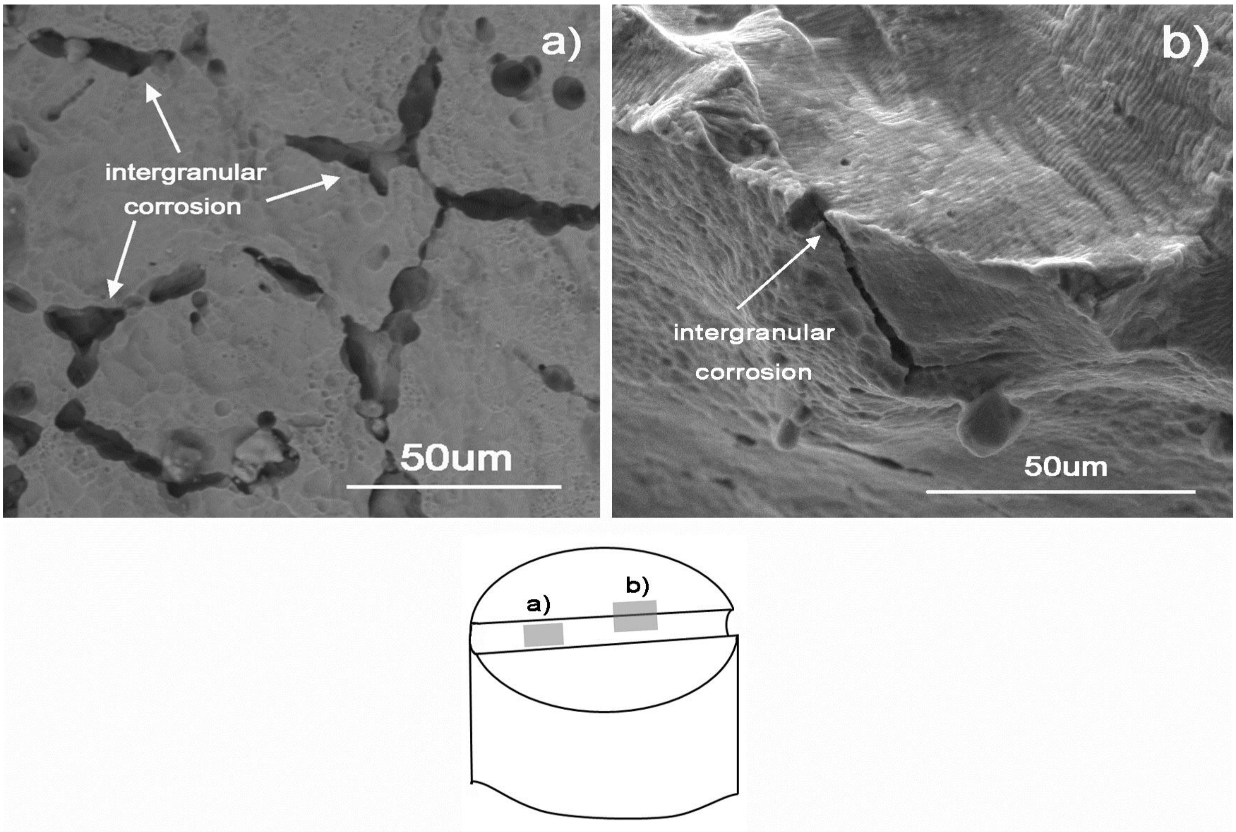


**Figure 4.** EDDLR specimen: a) hole inner surface; b) hole boundary.

## SUMMARY

A controlled decrease of fatigue resistance is obtained for EDD as compared to traditional drilling, which can be ascribed to the order of magnitude of surface roughness and to the surface morphology caused by the ED process. The effect can be quantified by an increase of the stress concentration factor around 25%. The latter is substantially independent on the particular ED setting. The effect of different ED setups is proven negligible, both by the S-N results (and consequently by the stress concentration factor) and by the observation of the failure mechanisms. Maximum productivity can thus be pursued with no threat to fatigue performance.

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