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Fatigue Resistance and Cracking Mechanisms in an Aircraft AISI 4340 Steel with Surface Affected by Electro-Erosive and Water Jet Cutting

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Abstract: Alternative methods of material machining like electro-erosive or water jet cutting, respectively, represent modern technologies, which are perspective to be used as final end-to-shape operations due to their possibilities of automatization and cutting precision. The paper contains results of an investigation of resistance of an aircraft AISI 4340 steel against fatigue loading performed using specimens loaded by three point bending at ambient temperature and standard laboratory conditions. Results of fatigue tests of specimens with surface after electro-erosive and water jet cutting, respectively, are presented, whereas in the latter case, areas of water jet incidence and outfall are studied separately. The work programme contained metallographical analysis of material microstructure, hardness measurement and analyses of surface character from the macro- and microscopic viewpoints. In comparison with ground surface, both the technologies resulted in partial reduction of fatigue resistance and fatigue limit, by approximately 17 %, whereas the effect of both the technologies was comparable. The fact that fatigue strength did not depend on hardness of specimen bulk material, i.e. on strength, namely in a relatively large interval of values, which was affected by local microstructure differences, can be considered as surprising. The microstructure mostly was of ferritic-pearlitic type with local bainitic islands in some of the specimens. Contrariwise, reduction of fatigue strength with the hardness was observed in specimens with ground surface. These result indicate that in the studied case, development of preexisting microdefects in surface or subsurface layers was the deciding mechanism of fatigue damage rather than usual fatigue crack initiation on smooth surface. Fractographical analysis carried out confirmed these assumptions.

Keywords: Water jet cutting, electro-erosive cutting, aircraft AISI 4340 steel, fatigue resistance.

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1 Introduction

Cutting technologies using water jet or electro-erosive methods can be very advantageously used for difficult-to-cut materials like special metallic materials of high hardness, non-metallic materials like reinforced composites, ceramic materials but also glass plates [Zhu, Huang, Wang, Lu and Feng (2007)]. They are, however, being used even for usual metallic materials and thin sheets [Černý and Mikulová (2008)]. Glass reinforced composites, mostly hardly machinable, can be exactly cut to final shape using water jet [Černý, Jeronimidis, Mayer and Medlicott (2008)]. In addition, these technologies are usually very suitable for common metallic materials due to high cutting speeds and possibilities of process automation [Geren, Bayramoglu and Esme (2007)]. On the other hand, quality of the kerf and cut surface has to be carefully considered for specific materials and operation conditions of machined components, as unambiguous generally valid knowledge is still missing. The technologies are namely connected with a kind of surface irregularity, often depending on technology parameters [Chen and Siores (2003)].

Surface quality and roughness affect particularly fatigue properties, as fatigue initiation process is usually located on the surface [Polák (2007)]. Specific surface effects are connected with other parameters like material strength and microstructure, notch sensitivity, surface and subsurface residuals stresses etc. In general, high surface roughness results in reduction of fatigue strength. However, if the roughness is not too high, it can have a minor effect and other damage mechanisms can occur [Itoga, Tokaji, Nakajima and Ko (2003)].

In this work, results of an investigation of resistance of an aircraft AISI 4340 steel against fatigue loading with surface affected by electro-erosive and water jet cutting technologies with specific parameters used are presented and discussed considering some materials and microstructure aspects.

2 Experiments

Experimental works were performed on the aircraft steel AISI 4340 ANNEA AMS 6359 after cutting by water jet and electro-erosive methods. Thickness of the cut sheet was about 35 mm. Water jet cutting was performed using device WJ402B, cutting speed 81 mm/min. Abrasive particles in the jet were used, namely natural garnet of grain size 150 – 300 μm. Pressure was 3800 bar, nozzle diameter 1.02 mm. Electro-erosive cutting was carried out using HITACHI 355R device, with brass wire of 0.25 mm diameter, cutting speed 3.2 mm/min.

Fatigue tests were performed on SCHENCK PHG 3000 N machine under three point bending (3PB) with load asymmetry R = 0.1, test span 60 mm, load frequency 40 Hz. The specimens were of square cross section 7 x 7 mm. Besides fatigue tests of specimens manufactured with the two investigated technologies, a reference batch of specimens of the same material with surface after fine longitudinal grinding was tested to receive basic data which the technologies can be compared with.

Microstructure analyses were performed using optical microscopes Olympus and Neophot 32, respectively, both with computer digital image processing Fractographical analyses were performed and fatigue crack initiation mechanisms studied using scanning electron microscope JEOL JSM-35, equipped with digital image processing, too.

Mechanical properties of areas affected by the cutting, as well as bulk material were characterised and quantified by measurement of microhardness and hardness, namely HV 1, HV 10 and HV 30. Microhardness measurements were performed using Hanemann device being a part of the Neophot 32 microscope, hardness HV 1 using Zwick 3202 device and other hardness measurement using device Vickers HTM Ltd.

In case of water jet cutting, particular attention was paid to position of specimens as regards the jet incidence and outfall. Kerf quality connected with this technology, unlike electro-erosive cutting, namely depends on the distance from the surface of the jet incidence. Two different groups of specimens were tested and analysed from this point of view: specimens from the layer near the jet incidence and from the opposite layer near the jet outfall.

3 Results and discussion

Results of fatigue tests are shown in detail in Tab. 1 and in Fig. 1. Tests interrupted without specimen failure (runout) are indicated by arrows. Both the technologies used with the specific parameters resulted in reduction of fatigue strength and fatigue limit in comparison with the longitudinally ground surface, namely by 17 – 18 %. Fatigue limits of ground, water jet cut and electroerosive cut specimens were 670 MPa, 551 MPa and 546 MPa, respectively. In addition, in case of water jet cutting, fatigue strength depended on the position of specimens in the kerf. Fatigue strength of specimens with the surface near the jet outfall was further reduced.

Apart from the effects of cutting technologies, the fatigue S–N curves are characteristic by rather high scatter of results in terms of considerably low fatigue life of some specimens in comparison with the mean regression line. To clarify the scatter, further detailed analyses and measurements were carried out: hardness and microhardness measurements, metallographical and fractographical analyses.

The scatter of hardness values was unusually high, too. The values were therefore evaluated as a distribution function – Fig. 2. The HV 30 values were in the interval

Table 1: Results of fatigue tests

Test group	Stress range (MPa)	No. of cycles - failure	No. of cycles - runout
Ground surface	782	142100	
	722	260600	
	710	4550100	
	671	5492600	
	664		16866400
	647		10293600
Electro-erosive cut	702	224000	
	625	283600	
	625	324300	
	612	622700	
	608	593700	
	580	978500	
	571	510900	
	557	1087700	
	554		7755200
	550	728400	
	546	829300	
	536		17374100
	520		11136400
	519		3195200
Water jet -input	675	245100	
	664	233900	
	603	324700	
	582	430700	
	552	18054300	
	539	3202100	
WJ – outfall	668	126800	
	660	156800	
	607	68000	
	588	205700	
	551	315900	

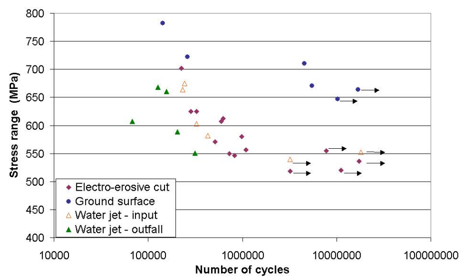


Figure 1: Summary diagram of fatigue tests results

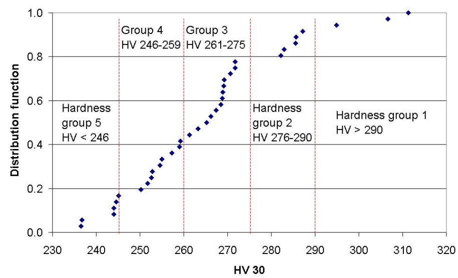


Figure 2: Actual distribution function of specimen hardness

between 237 and 311. After recalculation of these values to static strength according to approximative formulae, the corresponding interval of the strength values was considerably large, between 835 – 1108 MPa.

Fatigue strength of specimens with smooth surface is usually connected with material strength. Therefore, fatigue results were re-evaluated considering the hardness scatter. The following procedure was applied:

- The area of S-N curves with limited fatigue life was fitted with power regression lines. Logarithmic regression was tested as well, but with somewhat worse results.
- Fatigue life of each point was evaluated in terms of "relative fatigue life" expressed by ratio N_f / N_{reg}, where N_f is number of cycles to failure and N_{reg} is average number of cycles to failure according to the regression line, as schematically shown in Fig. 3. It means that N_f / $N_{reg} > 1$ corresponded to above-average fatigue life whilst N_f / $N_{reg} < 1$ to bellow-average life.
- Values of the "relative fatigue life" were plotted against specimen hardness HV 30.

The dependence is shown in Fig. 4. The results can be considered as interesting and unexpected. At the hardness interval between HV 240 and HV 300, in case of indefective material, one could expect a considerable increase of fatigue life with hardness, i.e. with material strength. Actually, fatigue life of specimens after both water jet and electroerosive cutting was independent on the hardness. Before the evaluation, just the specimen VD3 with abnormally reduced life was excluded. Another situation occurred in case of ground material surface, when a very unusual reduction of relative fatigue life with growing hardness was shown. Regression evaluation was carried out just from four points in this case, which could affect final results, it is true. Nevertheless, the character of the fatigue life dependence on hardness was rather untypical in all three cases and likely was connected with mechanisms of fatigue crack initiation, which will be discussed later.

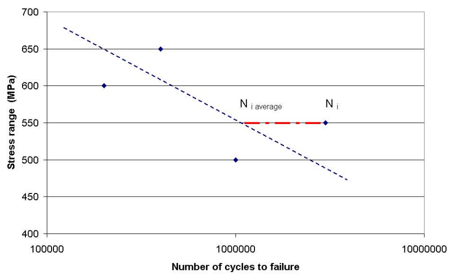


Figure 3: Evaluation method of relative fatigue life

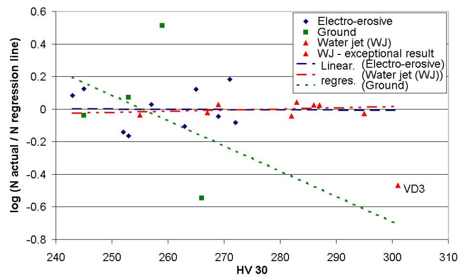


Figure 4: Dependence of relative fatigue life on specimen hardness

Microstructure of all the analysed specimens was generally of ferritic-pearlitic type with fairly wide zones of ferrite and pearlite observed in the section area – Fig. 5. However, besides the ferritic-pearlitic microstructure, bainite zones also could be observed – Fig. 6. These structure inhomogeneities likely were connected with the hardness scatter. Numerous inclusions occurred in the structure, locally with various size and density, mostly randomly distributed. Just in the specimen VD3 (indicated in Fig. 4 separately), the inclusions were concentrated into bands, which was obviously connected with the considerably low relative fatigue life and different fracture morphology of this specimen.

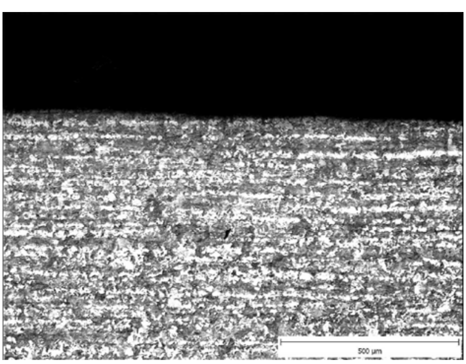


Figure 5: Ferritic-pearlitic microstructure of specimens

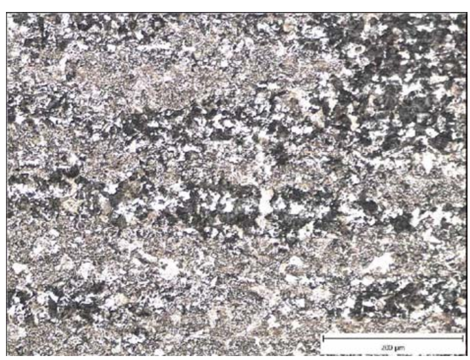
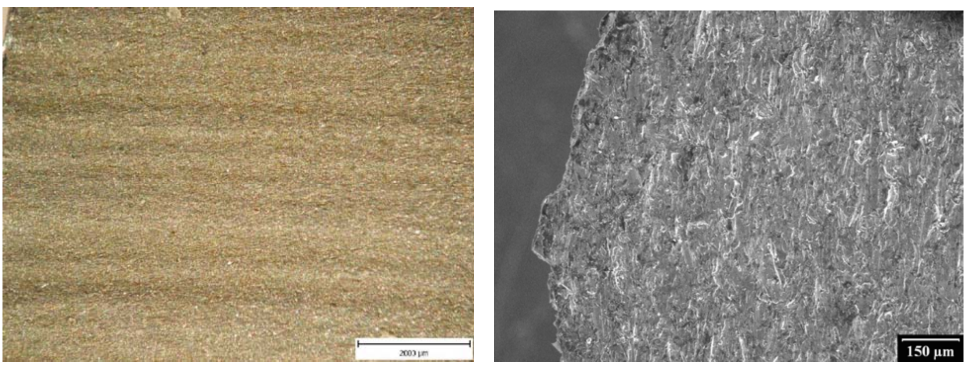


Figure 6: Local microstructural zones with bainite

As regards surface kerf character, two types of unevenness could be observed in case of water jet cutting: (i) macroscopic unevenness (Figure 7a), also called as "striations" in the literature (should not be confused with microfractographical striations) and (ii) microscopic roughness of a fine grain character, partially orientated with the water jet direction – Figure 7b. The striations were more distinct in the area of water jet outfall in comparison with the water jet incidence, as in [Lebar and Junkar (2004)]. Kerf roughness of the electro-erosive cutting was of a similar character, but without the "striations" and orientation.

Fractographical analysis was carried out in selected specimens with low relative fatigue life. Particularly in reference specimens with ground surface, fatigue life was affected by inclusions – Figure 8. However, some effects of inclusions were observed even in specimens with surface machined by the water jet and electro-erosive methods.



a) b)

Figure 7: a) Macroscopic and b) microscopic character of water jet cutting surface

The mechanism of fatigue crack initiation on surface and subsurface inclusions is likely connected with the abnormality that fatigue life of specimens did not depend on material strength or, more exactly, on various hardness shown in Fig. 4. Fatigue life of steels is commonly proportional to strength. However, when inclusions or surface defects are present, fatigue limit and life are determined particularly by material resistance against growth of physically short cracks and so, material with higher strength can then be less resistant against fatigue loading.

4 Conclusions

The most important results of the experimental investigations of effects of water jet and electro-erosive cutting technologies with specific parameters on microstructure

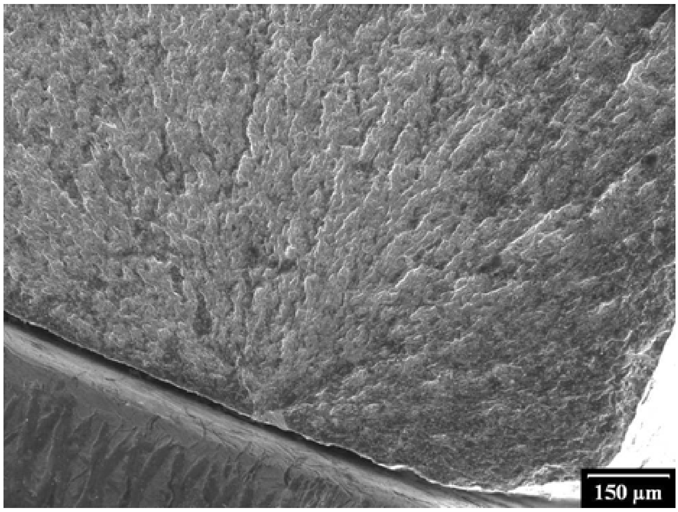


Figure 8: Crack initiation on inclusion on ground surface

kerf character, mechanical and fatigue properties of an AISI 4340 ANNEA AMS 6359 steel can be summarised as follows:

- In comparison with reference ground surface, fatigue limit after electro-erosive cutting was reduced by 17 – 18 %. Water jet cutting resulted in a comparable deterioration, but in the water jet outfall area, fatigue limit and life reduction was even more significant.

- Basic material was not ideally homogenous, as regards both microstructure and hardness. The hardness HV 30 values were between 237 and 311. Microstructure was mostly of ferritic-pearlitic type with local bainite zones. Numerous inclusions were present in the material, locally concentrated into chains.

- No dependence of fatigue resistance on material hardness was found in water jet and electro-erosive cut specimens. In ground specimens, this dependence was opposite to the usual one – reduction of the relative fatigue life with increasing hardness.

- The kerf surfaces were characteristic by surface roughness, orientated in case of water jet cutting.

- The scatter of fatigue properties was affected by an occurrence of surface or subsurface inclusions. Large inclusions predominantly initiated fatigue cracks in ground specimens. In the cut specimens, a superposition of kerf roughness and effect of inclusions was the most frequent fatigue crack initiation mechanism.

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