DOCUMENT CONTROL SHEET

	ORIGINATOR'S REF. NLR-TP-2003-104		SECURITY CLASS. Unclassified

ORGINATOR

National Aerospace Laboratory NLR, Amsterdam, The Netherlands

TITLE

Influence of wire electrical discharge machining on the fatigue properties of high strength stainless steel

PRESENTED AT:

Thermec 2003, Madrid, Spain, 7-11 July 2003

AUTHORS	DATE	PP	REF
L. Velterop	February 2003	8	5

DESCRIPTORS

EDM	Stainless steel
Fatigue	Microstructure
High Strength steel	

ABSTRACT

Conventional Electrical Discharge Machining (EDM) can decrease component fatigue life and strength. On the other hand, wire-EDM might be less detrimental because the energy input is lower and consequently there is a thinner surface layer modified by the process. The influence of wire-EDM on the S-N fatigue properties of a high strength martensitic stainless steel was investigated. First the effect of four sets of wire-EDM parameters on the surface topography and surface layer thickness was determined. Subsequently, one set of parameters was chosen for the fatigue tests, which included reference specimens produced by abrasive jet machining.

At stress levels giving fatigue lives less than 10^6 cycles there was no difference in average lives between the reference and wire-EDM specimens. However, the latter showed a significantly lower fatigue strength.

Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-2003-104

Influence of wire electrical discharge machining on the fatigue properties of high strength stainless steel

L. Velterop

This report is based on a presentation held at Thermec 2003, Madrid, Spain, 7-11 July 2003.

Customer:	National Aerospace Laboratory NLR
Working Plan number:	S.1.A
Owner:	National Aerospace Laboratory NLR
Division:	Structures and Materials
Distribution:	Unlimited
Classification title:	Unclassified
	February 2003

Approved by author:	Approved by project manager:	Approved by project managing department:
12/3	12/3	13/3

Contents

(8 pages in total)

Influence of Wire Electrical Discharge Machining on the Fatigue Properties of High Strength Stainless Steel

L. Velterop

National Aerospace Laboratory NLR, Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands

Keywords: EDM, fatigue, high strength steel, stainless steel, microstructure

Abstract. Conventional Electrical Discharge Machining (EDM) can decrease component fatigue life and strength. On the other hand, wire-EDM might be less detrimental because the energy input is lower and consequently there is a thinner surface layer modified by the process. The influence of wire-EDM on the S-N fatigue properties of a high strength martensitic stainless steel was investigated. First the effect of four sets of wire-EDM parameters on the surface topography and surface layer thickness was determined. Subsequently, one set of parameters was chosen for the fatigue tests, which included reference specimens produced by abrasive jet machining.

At stress levels giving fatigue lives less than 10^6 cycles there was no difference in average lives between the reference and wire-EDM specimens. However, the latter showed a significantly lower fatigue strength.

Introduction

High strength steels are commonly used for highly loaded aerospace components. Currently there is a trend to use corrosion resistant stainless steels (CRSS) instead of the more traditional high strength low alloy steels (HSLA). Owing to better intrinsic corrosion resistance the CRSS steels may not need protective coatings like cadmium or chromium plate, which are undesirable from an environmental viewpoint since the plating processes involve toxic chemicals.

A second issue is production costs for the components. In this respect Electrical Discharge Machining (EDM) is of interest, especially for complex or thin-walled components. However, EDM has been reported to reduce fatigue life, with the reduction depending on the EDM parameters [1, 2]. Very mild machining (low voltage, low current, short on-time) hardly affects the fatigue life, whereas rough and quick machining is very detrimental.

The influence of EDM on the fatigue properties is due to a modified surface layer, consisting of a heat-affected zone and a recast layer on top of it. This EDM surface layer may have varying mechanical properties and contain residual tensile stresses, both depending on the EDM parameters. For example, a thicker surface layer owing to more severe EDM results in higher tensile residual stresses that can even cause cracking. The cracks then can act immediately as fatigue nuclei.

In the present paper the effect of wire-EDM on the fatigue properties of a high strength precipitation hardening martensitic stainless steel is described. Firstly, the modified surface layer is characterised for four sets of wire-EDM parameters. Secondly, the S-N fatigue properties arising from a selected set of wire-EDM parameters are compared with fatigue data from reference specimens produced by abrasive jet machining.

Wire-EDM process and surface layer

In wire-EDM the electrode is a travelling metal wire, usually brass. The dielectric fluid is almost always de-ionised water. The voltage used depends on the wire diameter and is usually in the range 50-100 V [3].

The modified surface layer consists of a heat-affected zone and a recast layer, as mentioned in the introduction. The recast layer for martensitic steels is brittle, untempered martensite. The topography of this layer depends on the EDM process. Conventional EDM generally results in a cratered surface [4]. For wire-EDM this cratered surface is covered by a rough porous layer consisting of recast wire + workpiece metal [4].

The thickness of the modified surface layer depends on the EDM parameters. Standard wire-EDM and conventional finishing EDM result in surface layers 2-20 μm thick. Rough and quick conventional EDM results in surface layers 20-200 μm thick [4].

Experimental work

Surface layer. The influence of differing wire-EDM parameters on the modified surface layer was investigated using PH 13-8 Mo precipitation hardening steel in the H950 condition. The surface morphology was examined by Scanning Electron Microscopy (SEM) before and after chemical passivation according to specification SAE-AMS-QQ-P-35: passivation removes the rough porous recast layer. The thickness and microstructure of the modified surface layer were examined by optical metallography of cross-sections. The surface roughness was measured using a mechanical surface roughness measurement device.

Four sets of wire-EDM parameters were selected, see Table 1, corresponding to two different wire-EDM cuts using two EDM machines. One cut on each machine used the standard parameters. The other cuts used shorter on-times.

Table 1. EDM parameters used for cutting. Dielectric fluid: de-ionised water with an anti-corrosion agent. Wire: 0.25 mm diameter, uncoated, hard (i.e. cold deformed) brass. Workpiece is anode, wire is cathode

Sample number	1	2	3	4
EDM machine	Sodick	Sodick	Charmilles	Charmilles
voltage (V)	45	45	80	80
current (A)	7.1	7.1	4	4
on-time (μs)	4	2	1.2	0.6
off-time (μs)	19	19	11.4	11.4
cutting speed (mm/min)	7.3	3.6	10	5
power (W)	319.5	319.5	320	3.20
pulse energy (mJ)	1.28	0.64	0.38	0.19
on-time (%)	17	10	11	5
	(standard)		(standard)	

Note the differing sets of parameters for the two machines. The Sodick uses a 2-phase voltage: 0 V during the off-time and 45 V during the on-time. The Charmilles uses a 3-phase voltage: 0 V during the off-time, 80 V during most of the on-time, and an even higher voltage during a short initial part of the on-time in order to facilitate ionisation of the dielectric fluid. This easier and faster ionisation results in a more effective on-time and therefore a higher overall cutting speed.

Fatigue tests. S-N fatigue curves were determined for specimens made by wire-EDM and reference specimens made by abrasive jet machining. The wire-EDM parameters were chosen to give the highest surface roughness found in the first part of the investigation. The specimens were flat and waisted, $K_t = 1.06$, and were made from PH 15-7 Mo sheet in the TH1050 condition. This material was selected instead of PH 13-8 Mo because the latter was not available as sheet, and it was also considered that the modified surface layer’s effect on fatigue properties would be generic for this class of precipitation hardening martensitic steels. After machining, and before fatigue testing, the specimens were passivated according to specification SAE-AMS-QQ-P-35.

Constant amplitude fatigue tests were done using an Amsler Vibrophore high frequency resonance machine and a stress ratio, $R = S_{min}/S_{max}$, of 0.1. The test frequency was 75 Hz. Tests were done for S_{max} values ranging from 500 MPa to 1100 MPa. The fatigue limit (strength) was assumed to correspond to fatigue lives greater than or equal to 10^7 cycles.

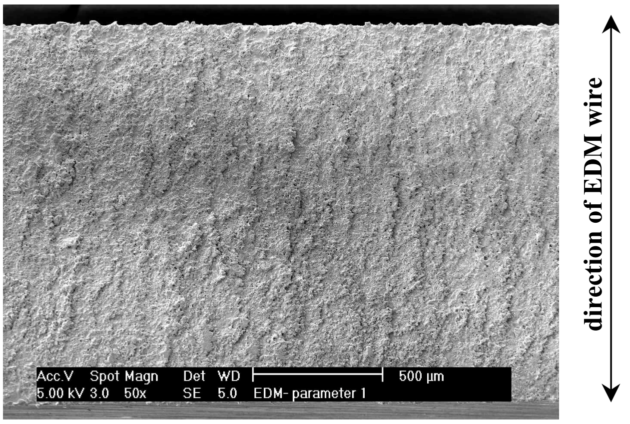

Figure 1. SEM micrograph of an unpassivated wire-EDM surface cut with standard parameters (specimen 1), showing the ridges parallel to the EDM wire.

Results

Topography and microstructure before passivation. The as-manufacture wire-EDM surfaces were copper coloured and very rough. The copper colour was due to a process layer of recast material, which chemical analysis showed to be more than 50 % brass. The thickness of the recast layer varied from 4 μm to 30 μm, even on one sample, and this wide variation obscured possible systematic differences between samples.

The main difference between the four samples was their surface roughness, listed in the first roughness value (R_a) column in Table 2. For each machine the samples made with standard wire-EDM parameters, and hence higher cutting speeds, were rougher: Sodick machine, compare samples 1 and 2; Charmilles machine, compare samples 3 and 4. Note also that the cuts made with the Sodick machine were rougher for the respective standard and less-severe sets of parameters: sample 1 to be compared with sample 3; sample 2 to be compared with sample 4. This was despite the higher overall cutting speeds obtained with the Charmilles machine, see Table 1.

Another difference in surface topography between samples cut with standard and less-severe sets of parameters was the presence of ridges, oriented parallel to the EDM wire, only on the samples cut with standard wire-EDM parameters, see Fig. 1.

Topography and microstructure after passivation. The passivation treatment removed the copper coloured layer and reduced the roughness, compare the first and second roughness value (R_a) columns in Table 2. The topography of the passivated surfaces was somewhat crater-like with rough high-standing ridges of recast material, Fig. 2. This recast material originated from the steel only.

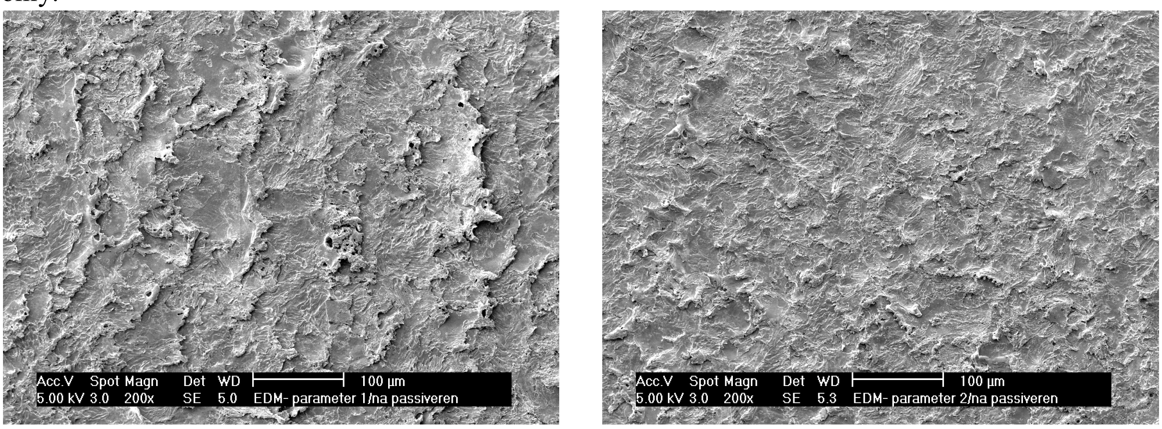

Figure 2. SEM micrographs of the passivated wire-EDM surfaces for standard (left, specimen 1) and slow (right, specimen 2) cutting parameters, showing the topography for standard cutting parameters and the lower roughness for slow cutting.

Table 2. Results of the surface roughness measurements before and after passivation. Average and measured R_a values [μm] are listed.

Sample number	R_a unpassivated	R_a passivated (average)
1 (standard)	4.7	2.1
2	3.6	1.6
3 (standard)	4.5	1.9
4	2.5	1.7

Metallographic cross-sections confirmed the (shallow) crater-like topography and showed that the modified surface layer consisted of two components, namely, a recast layer (grey) and a heat-affected zone (white), see Fig. 3. The recast layer was untempered martensite, while the heat-affected zone was overaged. This zone had a constant thickness of about 2 μm, but the total thickness of the modified surface layer varied from 4-10 μm, depending on the thickness of the recast layer. Cracking of the modified surface layer was not observed for any of the specimens. Note also from Fig. 2 that the ridges produced by standard wire-EDM cutting showed some directionality, as was observed for the surfaces before passivation (Fig. 1).

Fatigue properties. Figure 4 shows the S-N diagram comparing the wire-EDM (Sodick standard parameters + passivation) and reference specimens. The fatigue strength of the reference specimens was 700-725 MPa, while that of the wire-EDM specimens was only 550-575 MPa. However, for fatigue lives less than 10^6 cycles there was no difference in average lives.

Examination of the specimens revealed that for all but one of the wire-EDM specimens fatigue crack initiation took place from the wire-EDM cut surfaces. The exception was a specimen tested at the highest stress level, 1100 MPa. For the reference specimens there was no preferential fatigue crack initiation surface: cracks began both on the original sheet-rolling surfaces and on the abrasive jet machined surfaces.

Discussion

Topography and micro-structure. The roughness of passivated wire-EDM surfaces is determined by the size of the machining craters and their degree of overlap. It is known that the crater size is determined by the pulse energy, whereby the voltage influences mainly the crater depth and the current the crater diameter [3]. On this basis, and with reference to Table 1, it was expected that crater depths would be greater for the Chamilles-machined samples, while the crater diameters would be larger for the Sodick-machined samples. This latter point was confirmed, and it was also seen that the crater diameters were smaller for the less-severe cutting parameters, which agrees with the pulse energy differences, see Table 1.

Since the crater diameters were larger for the Sodick-machined samples, one would expect the surface roughness to be higher for each set of wire-EDM parameters. However, the second roughness column in Table 2 shows this was not necessarily so (compare samples 2 and 4), and anyway the differences were small. This is probably due to crater overlap.

The constant thickness of the heat-affected zone agrees with literature information [3], as also the reasonably

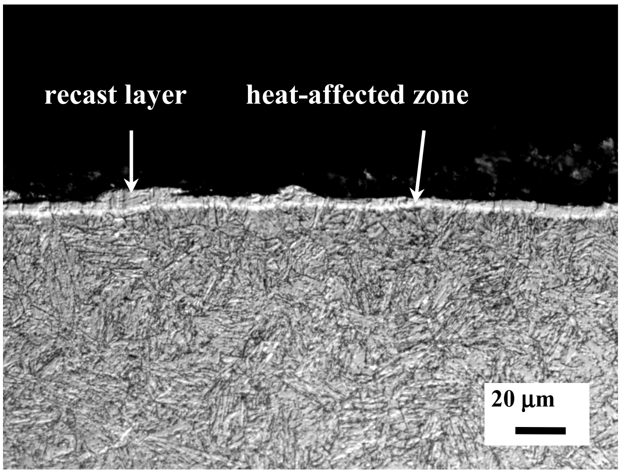

Figure 3. Optical micrographs of metallographic cross section of passivated wire-EDM surface of specimen 3, showing the recast layer and heat-affected zone.

constant thickness (4-10 µm) of the recast layer.

Fatigue. The differences between the wire-EDM and abrasive jet machined specimens, i.e. the lower fatigue strength of the wire-EDM specimens and preferential fatigue crack initiation on the machined surfaces, can be explained by the presence of a brittle layer of untempered martensite on the wire-EDM surfaces, and the fact that all precipitation hardening martensitic steels show notch-sensitive fatigue behaviour [5]. In other words, cracks that form in the brittle untempered martensite will propagate to cause failure even at stresses below the fatigue strength of more conventionally machined specimens.

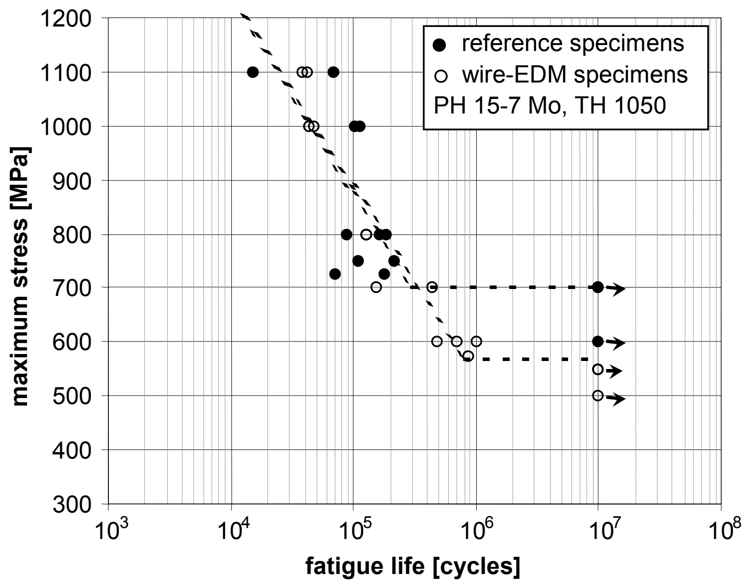

Figure 4. S-N curves for reference specimens and specimens made with wire-EDM, showing reduced fatigue strength for the passivated wire-EDM specimens.

The almost identical fatigue lives at higher stresses indicate that fatigue crack initiation soon occurred in all specimens and that the fatigue lives were determined primarily by crack growth.

Finally, it must be said that the detrimental effect of wire-EDM machining on the fatigue strength cannot be reduced or eliminated by decreasing the severity of the EDM parameters. This is because the modified surface layer had a reasonably constant thickness. Instead recourse must be made to a finishing treatment that removes this layer, e.g. by grinding, polishing or chemical milling. Another point is that a decreased severity of the EDM parameters will reduce the cutting speed and increase the process costs.

Conclusions

- Wire-EDM machining significantly reduces the fatigue strength of a precipitation hardening martensitic steel.
- Decreasing the severity of the EDM parameters will most probably not reduce the detrimental effect on fatigue strength. Instead there has to be a finishing treatment, e.g. grinding, polishing or chemical milling, to remove the modified surface layer, especially the brittle, untempered martensite.

Acknowledgements

This work was carried out in a research project entitled “Properties of high quality steels” sponsored by the Netherlands Agency for Aerospace Programmes. The author is grateful to SP Aerospace and Vehicle Systems B.V. for specimen delivery.

References

1. O.A. Abu Zeid: J. Mater. Process. Tech. Vol. 68 (1997), p. 27
2. R.D. Rhew: in Proceedings of the ICIASF 18-21 Sept. 1989 (IEEE Service Centre, Piscataway, NJ 1989) p. 477

3. J.E. Fuller: in *Metals Handbook*, Ninth Edition, Vol. 16 (ASM, Metals Park, Ohio 1989), p. 557
4. P. Miller and A. Guha: J. Inject. Mold. Tech. Vol. 2(3) (1998), p. 128
5. Military Handbook 5H, *Metallic Materials and Elements for Aerospace Vehicle Structures* (Department of Defence, USA, 1998) p. 2-116