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Preparation of S960QC steel specimens for fatigue testing: Effect of machining and post-treatments on surface residual stress

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***Abstract*— The effects of machining parameters and several post-treatments on surface residual stress of round shaped specimens made of ultra-high-strength steel S960QC for fatigue testing have been investigated. Different machining parameters have been used for making the specimens and heat treatment, polishing and acid treatment have been performed to eliminate the surface residual stresses which were introduced to specimens by manufacturing process. Heat treatment proved to be the most effective method to reduce residual stresses although it did not relieve all of the high tensile residual stresses caused by machining. Turning parameters and material properties of S960QC seemed to be very essential factors and their combined effect often leads to high tensile residual stress state on the surface. Consequently, this should be taken into consideration when performing comprehensive material testing under fatigue loading, especially in high-cycle regime.**

***Keywords*— machining, turning, cutting depth, feed rate, heat treatment, residual stress, fatigue strength**

I. Introduction

In the view of the diverse objectives that have been the basis for research in fatigue or materials, there has been an almost unlimited variety of specimens employed. A specimen is a representative sample of the material under investigation and should be embodiment of the question the engineer is asking of the material. It consists essentially of three parts: the center of test section (gauge section), and two ends which serve only to transfer the load from the grips into the gauge section. Since the center section is the region under study, its cross-section is generally reduced so that this area is more highly stressed than the gripping which avoids the probability of failure in grips. The transition from gauge section to end should be smooth by introducing the fillets in order to minimize the stress raising effect.

The type of specimen (round or flat) will depend upon the objective of the investigation. In strain-controlled fatigue testing, the ASTM standard E606 [1] covers the selection criteria regarding this matter. Based on this standard, using round specimens (uniform-gage and hourglass) are preferable when they are made from plates thicker than 6 mm. For sheet material that is less than 6 mm thick, flat specimens are preferable. Similar recommendations can be found in Handbook of Fatigue Testing [2].

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It is well-known that fatigue is a surface phenomenon. Fatigue response strongly depends on specimen's surface quality and residual stress which are studied comprehensively in [3-5]. A surface zone with tensile residual stress can be favorable for crack initiation and surface zone with compressive residual stresses can be an effective barrier to crack growth. The main purpose of this study is to scrutinize the effect of different cutting methods and machining parameters following by post-treatments on the surface residual stress which plays a significant role especially in fatigue response of high strength materials.

II. Methodology

Direct quenched ultra-high-strength steel S960QC was used in this study. The material properties are shown in Table 1. This type of ultra-high-strength steels offers high strength and good workshop properties and is not directly compliant with any standards for structural steels. S960QC has a dual-phase microstructure consisting of bainite and martensite. The average grain size is in the order of magnitude of one micrometer.

TABLE 1: Material properties of S960QC

Yield strength, (MPa)	Ultimate tensile strength, (MPa)	Elongation, (%)	Impact strength	
			Temp., (°C)	Charpy, KV (J)
960	1000	7	-40	34

The 8 mm plate was used to produce the specimens. All the recommendations of the ASTM standard E606 were strictly followed. The fatigue specimen geometry is shown in Fig. 1. All dimensions have 0.2 % tolerance.

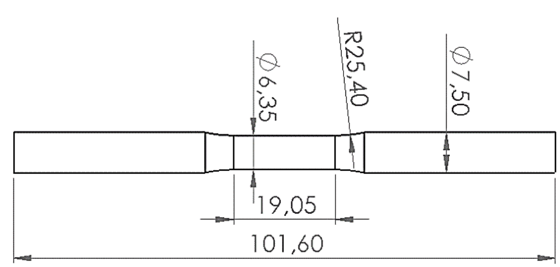

Figure 1. Fatigue specimen geometry.

Cutting, machining, post-treatments, and measurements were carried out in the Laboratory of Steel Structures at

Lappeenranta University of Technology. The experiments are explained in following sections.

A. Cutting Methods

From S960QC 8 mm plate, the rectangular billets (8 × 8 × 110 mm) for fatigue test specimens can be made by laser cutting or sawing. The orientation of the specimens were adjusted so that the fatigue loading direction of final test specimens were equal to plate rolling direction. In laser cutting, a 2.5 kW carbon dioxide (CO2) laser was used. The main parameters of the process were:

- cutting power: 2080 W
- cutting speed: 1.2 m/min
- cutting gas: oxygen (O_2)
- cutting gas pressure: 0.5 bar
- focal length: 5"
- focal position: -0.5 mm
- nozzle type: conical
- nozzle size: Ø 1.5 mm
- nozzle distance: 1.0 mm.

When cutting the billets with sawing, the proper parameters are:

- saw type: band saw
- saw blade: regular, 4/6 - 5/8 TPI
- feed rate: 25 - 35 mm/min
- speed: 85 - 95 m/min.

In this study, only the laser cutting was used to make the billets for machining. For comparison and in order to eliminate the heat affected zone of laser cutting, one rectangular billet was also manually machined from the 8 mm plate.

B. Machining Parameters

The final round shaped fatigue test specimens (fig. 1) were machined with CNC lathe. Two different tools with different coatings (PVD, CVD and Duratomic®) were used and also comparisons were made between new and worn tool. The parameters in CNC machining were:

- tool nose radius: 0.4 mm
- feed rate (f): 0.1 - 0.2 mm/rev
- cutting depth (d): 0.1 - 0.2 mm
- cutting speed (v_c): 50 - 70 m/min.

Cutting fluid was used during the whole turning. First layers of the specimens were coarse machined (f = 0.2 mm/rev, d = 0.2 mm, vc = 50 m/min) and the final dimensions and surface were produced with fine machining (f = 0.1 mm/rev, d = 0.1 - 0.2 mm, vc = 70 m/min). In fine machining, the cutting depth was varied in order to define the effect of that parameter on surface roughness and residual stresses.

C. Post-treatments and Residual Stress Measurements

After machining, several different post-treatments were performed. The effect of heat treatment, sandpapering, sandblasting, and acid treatment on the surface residual stresses were investigated. Based on the recommendations of the steel manufacturer [6], heat treatment was carried out at temperature of 390 °C and the soaking time was 30 - 60 minutes. In addition, one specimen was heat treated at the temperatures of 500 °C and 600 °C for 30 minutes. Polishing by sandpaper was performed manually with different grit sizes (P400 & P800) and the specimens were attached to a rotating lathe during the operation. Sandblasting was carried out by using glass beads (grain size 600 - 800 µm) as an abrasive media. In acid treatment, a 10 % solution of citric acid (C6H8O7) was used to etch the surfaces of test specimens.

The surface residual stresses were determined using an X-ray diffraction technique. The device includes a liquid cooled CrKα X-ray tube with beryllium windows. Measurements were focused in the center section and in longitudinal direction of the test specimens (i.e. in loading direction). The main parameters in X-ray measurements were:

- voltage: 30 kV
- current: 9.0 mA
- power: 270 W
- collimator: standard
- collimator diameter: 1 mm^2
- collimator distance: 11 mm
- detector distance: 50 mm
- diffraction angle: 156.45°
- tilt angles: ± 40°, 31.7°, 21.8°, 0°
- psi-oscillation: ± 2°
- shutter time: 32 s.

III. Results and Discussions

Machining introduces residual stresses, although it is not always clear whether it leads to compressive or tensile residual stress at the material surface. Actually, it must be expected that machining can lead to residual stresses in a thin surface layer. Machining implies that material is removed by a cutting process. Some material is torn away from the substrate material which is a small-scale failure phenomenon occurring with some local plastic deformation. Because of this plastic deformation it should leave a residual stress distribution depending on the material and the variables of the machining operation [7].

When the rectangular billets were laser cut, the residual stresses of cutting surfaces varied between -100 MPa to 70 MPa. In machined reference billet, the surface residual stresses were from 30 MPa to 200 MPa. The measurements of billets' raw plate surfaces showed mostly near zero or compressive residual stresses (from -140 MPa to 40 MPa). Although the billets had very variable residual stress states, the final turning produced generally high tensile residual stresses on the finished surfaces of round specimens.

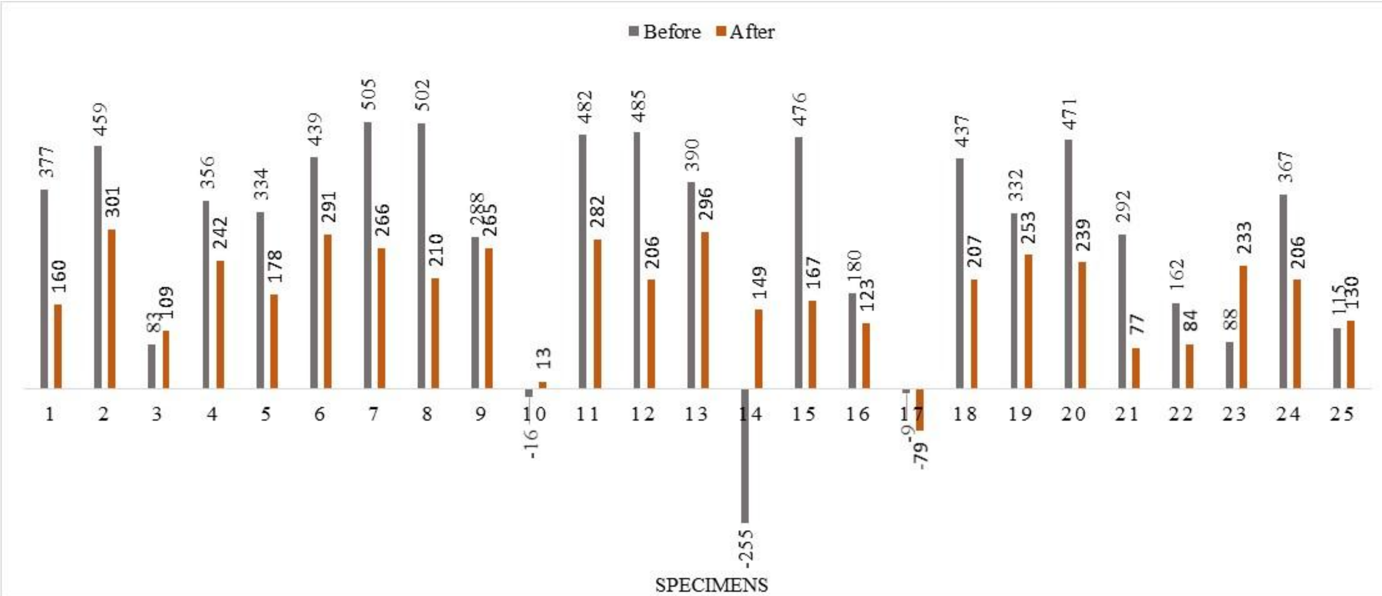

Figure 2: Residual stress (MPa) measurements before and after heat treatment.

The residual stress measurement for 25 specimens which were laser cut and fine machined are shown in Fig. 2. It was found that because of the surface grinding, the specimens are mostly experiencing tensile residual stresses as expected. To eliminate those and make sure that there is no detrimental effect of tensile residual stress affecting the fatigue behavior of material (especially in high-cycle regime), the stress relieving was necessary.

The heat treatment is the best choice to relieve the residual stresses, but based on the manufacturer recommendations, this material is not intended to heat treatment at temperature more than 400 °C which does not seem enough for relieving this much residual stress. All specimens were heat treated and cooled down in the furnace to see the effect of heat treatment on reliving the surface residual stress.

The results showed that the heat treatment was effective to decrease the residual stress levels about 40 % - 50 %. But still with these level of surface residual stress, the fatigue tests on high-cycle regime can be strongly affected.

To check the effect of soaking time, the specimens were put into furnace for one more extra hour at the same temperature. Consequently, no noticeable change occurred which validates the assumption of temperature ineffectiveness to relieve the residual stresses.

Specimen 2 was chosen to check the effect of temperature increase on reliving its residual stress level. It was put into 500 °C and 600 °C for 30 minutes at each temperature. Heat treatments at these temperatures were able to relief the residual stresses down to level of 50 - 60 MPa. However, the hardness measurements showed decrease of 30 - 40 HV and 40 - 50 HV, respectively. The hardness values of untreated base material was 340 - 350 HV and after both heat treatments, it was reduced to below 300 HV. It means that the strength of material and consequently its fatigue properties are changed and the manufacturer recommendation regarding the allowable temperature for heat treatment should not be violated.

In order to check the other possibilities to relieve the specimens' high tensile residual stresses, polishing was tried. The effectiveness of electro-polishing on removing the slightly thin layer and decreasing the tensile residual stress had been validated by Al-Shahrani and Marrow [4]. It decreased the stress levels from 50 ± 44 MPa after fine machining to 3 ± 40 MPa in their investigation. In this study, polishing by sandpaper were performed on two specimens (1 and 18) with high residual stresses. After polishing, the residual stress levels dropped to minus 100 - 400 MPa which shows the effect of this treatment on thin layer of the specimen's surface. Although the values dropped dramatically from tensile stress to compressive stress, a through thickness measurement of residual stress distribution is necessary to check the effect of this surface treatment. The same result was gained by sand blasting of specimen 7 which after treatment, the residual stress levels were minus 450 - 500 MPa.

Acid treatment was the last treatment which was used to study its effect on the surface condition of the specimens. Although it seemed that it somehow cleaned the surface, no layer removal had happened. In comparison with stresses measured after heat treatment, slight increases and decreases can be seen (Table 2). Since all the measurements determined the stresses at surface points, this deviation would be expected and it can be concluded that acid treatment had no effect on the surface residual stress.

TABLE 2: Residual stress measurements after acid treatment.

Specimen, ID	**Point 1**		**Point 2**	
	Residual stress, MPa	Deviation (+/-), MPa	Residual stress, MPa	Deviation(+/-), MPa
3	59	5.6	52	6.6
4	285	13.0	241	6.2

5	239	5.8	255	9.0
6	322	12.1	306	7.4
8	274	7.1	269	6.5
9	310	10.3	312	9.7
10	102	7.0	96	7.4
12	254	7.6	239	6.1
13	117	7.2	119	6.7
14	-130	7.6	47	12.5
15	134	17.3	109	11.5
16	109	9.9	141	9.7
17	-106	3.7	-144	7.6
19	313	10.4	320	11.6
20	269	19.6	271	22.6
21	4	3.9	2	3.6
22	78	2.6	75	5.6
23	208	7.9	169	9.9
24	297	4.8	235	10.0
25	122	12.1	184	5.8

IV. Conclusions

Based on the experimental procedures and measurements, the conclusions are as follow:

1. Different manufacturing methods (laser cutting or machining) of rectangular billets did not have an effect on residual stress of the final round shaped specimen's surface.

2. The cutting tool coating and using new tool for machining each specimen did not have essential effects on the final surface residual stress. It means that the machining parameters have more effects on residual stress state than cutting tool; as was proven for different material in another study [3].

3. Heat treatment is the most effective method to relieve the residual stress. Although its efficiency is in question for materials which high strength is obtained by heat treatment, even when it is used at safe range, it can decrease the tensile residual stress.

4. Polishing techniques, such as sandpaper polishing does introduce the compressive residual stress to the surface and is not successful for surface residual stress relieving. Electro-polishing seems to be more promising based on the previous study [4], but its effect was not studied in this paper.

5. Acid treatment cannot be considered as a method for residual stress relieving. Although it leaves a clear surface by cleaning the surface layer, it cannot be considered same as polishing methods. It can have the detrimental effects on specimen's surface depending on its solutions and material in question.

Acknowledgements

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