Fatigue assessment of cut edges in high strength steel - Influence of surface quality

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Abstract

The influence of surface roughness on the fatigue strength in high strength steels which was cut using different cutting processes were studied. Fatigue testing was conducted on S700 and S960 material of different plate thicknesses cut in dog bone specimens using oxygen, plasma, laser and waterjet cutting. The surface roughness was measured on all specimens and residual stress measurements were conducted. Estimations of the fatigue strength were made using the measured surface roughness and the ISO 9013:2002 standard for thermal cutting quality tolerances. The testing proved a 15-70% increased fatigue strength compared to the estimation, proving a weak connection between the surface quality levels in ISO 9013:2002 and the fatigue test results. Different codes and design recommendations (IIW, EC3 and EN 13001) for fatigue strength of cut surfaces were compared with the fatigue test results which clearly showed an increased fatigue strength with enhanced quality and steel grades and where the codes and design recommendations do not allow for any fatigue strength improvement with improved quality and increased strength.

Keywords

High Strength Steels, Fatigue assessment, Thermal Cutting, Oxygen cutting, Plasma cutting, Laser cutting, Waterjet cutting, Quality, Surface roughness, Welded structures, Cut edges

1 Introduction

The fatigue properties in welded and cut steel structures are in general controlled by other properties than only material data, i.e. the manufacturing processes have a dominating influence of the choice of material. There is an urgent need to develop design and manufacturing procedures for serial production of high performance structures. There has been an increased trend during the latest years to design for lightweight solutions and higher performance, particularly within vehicle and crane industry. Upgrades from mild steel grades (460 MPa) to high strength steels (700-1100 MPa) enables lightweight structures due to reduced thicknesses which will result in; lower fuel consumption, higher payload, reduced production costs and lower the CO₂ imprint [1, 2]. However, this requires both redesign of the structure with respect to HSS material and the high quality manufacturing that is necessary to fulfill these targets – Design for purpose.

Loader cranes are a typical application for such lightweight design; figure 1 illustrates a telescopic beam in a loader crane where high strength steel (HSS) have been introduced. By introducing more advanced steels, this strives to more advanced design and optimization solutions with higher allowable stresses in the structure. As a result of this it has been identified that the cut edges in some cases could be the design limitations. Therefore, it is mutual to investigate how the cut edges are related to the fatigue performance and verify if the design standards used today corresponds to the desired fatigue requirements.

Figure 1: A loader crane where upgrading to HSS in the structure would lead proper design of the cut surfaces.

In structural steel applications where thinner plates in high strength steel are used, the stress levels are increased. Consequently, the demand of enhanced material properties and produced quality in manufacturing are increased. In fatigue loaded structures, it is important that the introduction of high strength steels and enhanced product quality is conducted simultaneously since defects are commonly induced from manufacturing processes such as welding and cutting, these will eventually lead to crack growth and thus delimit the service life of the structure. The welded joint is in general the weakest link in terms of fatigue strength due to the increased stress concentration in the weld toe region (for non-load carrying welds) and residual stresses. In order to gain any improvement in fatigue strength when manufacturing welded structures in high strength steels, it is recommended by IIW to apply post weld treatment methods, such as TIG-dressing or High Frequency Mechanical Impact (HFMI) treatment [3] to remove critical defects, reduce the local stress concentration and the residual stresses, which in turn will reduce the risk of fatigue failure in the weld toe region. Thus, an increased weld quality will enable usage of thinner plates, which in turn will increase the overall stress level in the structure. However, as the overall stress level increase in the structure, other locations such as

thermally cut edges may become critical for fatigue failure unless they are not designed and manufactured with the same quality as the welded joint.

Factors governing the fatigue strength in thermally cut sections are surface roughness (i.e. quality level), the material yield and ultimate strength and the presence of residual stresses induced by manufacturing. Sperle et al [4] conducted a comprehensive study in which material strength and surface roughness were assessed. Different steel grades were thermally cut using gas, plasma and laser cutting. An empirical model connecting the surface roughness and material strength to the resulting fatigue strength was developed, which is implemented in the SSAB Design Handbook [5]. The study was conducted using specimens of plate thickness $< 12\text{mm}$ and surface roughness $R_z < 120\mu\text{m}$. Remes et al [6] recently conducted a study in plate thickness 15-17 mm. These specimens were plasma cut, grinded and finally sandblasted. Surface roughness and residual stresses in plate surface and the cut surface was measured. It was concluded that the grinding provided a significant increase in fatigue strength mainly due to the induced compressive residual stresses, while the sandblasting after grinding (which is necessary prior to painting) reduced the beneficial compressive stresses, which gave a slight reduction in fatigue strength. Recent work within International Institute of Welding (IIW) [7] has proven that the current design guidelines are conservative in terms of fatigue strength and slope of the design curve. The focus has mainly been on connecting surface roughness to the fatigue strength for plates in thickness $< 6\text{mm}$ in S420 to S700 material and to some extent in 15mm for gas and plasma cutting in S355 material.

The international standard ISO 9013:2002 [8] provide quality tolerance limits for thermal cutting methods and classify geometrical tolerances and surface roughness into four different ranges, where range 1 is the highest quality and range 4 corresponds to the lowest quality. Each quality range is defined as the maximum allowed surface roughness R_z , depending of the thermally cut edge plate thickness, see table 1.

Table 1: ISO 9013:2002 [8] surface roughness quality ranges.

Quality range	Mean height of the profile, R_z [μm]
1	$10 + 0.6 \cdot t$
2	$40 + 0.8 \cdot t$
3	$70 + 1.2 \cdot t$
4	$110 + 1.8 \cdot t$

t plate thickness [mm]

In general, limited work has been carried out to study the influence of surface quality in thermally cut edges of high strength steels in thickness $> 12\text{mm}$ and $R_z < 120\mu\text{m}$. In many design applications such as infrastructure, offshore and construction equipment, thicker plates are commonly used in fatigue loaded structures. This paper presents a study where specimens in two different steel grades are produced using 4 different cutting methods in various surface conditions and then fatigue tested. The idea is to utilize the ISO 9013:2002 standard for assessing the produced surface roughness, i.e. quality classification of the specimens, and compare the expected fatigue performance with existing guidelines provided by IIW [9], SSAB Design Handbook [5], Eurocode 3 [10] and the cranes design standard EN 13001 [11].

2 Test specimens

The test specimens were produced of 16mm thick steel plates in S700 and S960 material. The specimens were cut in a dog bone shape as shown in figure 2 in order to minimize the stress concentration]. The thermal cutting methods are frequently used in industry; oxygen, plasma and laser. No change was done in cutting process parameters when cutting the plates in different steel grades. The cutting process parameters are given in table 2. Waterjet cutting were used to produce specimens without a Heat Affected Zone (HAZ), to serve as reference. These specimens were cut in S700 material of 6 mm plate thickness. The edges between the plates rolled surface and the cut surface were slightly chamfered using belt grinding.

Figure 2: Specimen shaped as dog bone for fatigue testing.

Table 2: Cutting process parameters.

Cutting method	Power [kW]	Speed [m/min]	Current A	Cutting gas
Oxygen		0.9		Oxygen
Plasma	15.6	1.06	105	Air
Laser	5.7	1.6	-	Oxygen
Waterjet		0.75		

3 Surface roughness measurement

A vision system, GFM Primos, was used for measuring the surface roughness and it was conducted in accordance to the principles given in ISO 9013:2002. A non-contact measuring system was chosen in order to avoid wear of a contact based measuring system, due to the rough surfaces which were expected. The resulting measurements, expressed as peak to valley height (R_z) and average height of the surface roughness (R_a) are shown in Figure 3. The quality requirements on surface roughness of thermally cut edges according to ISO 9013:2002 for the specimen thickness of 6 and 16 mm are also shown in Figure 3, along with scatter bands which are typical relations between R_z and R_a depending on the production method.

Figure 3: Surface roughness measurement on cut edges.

The plasma specimens prove to have the lowest surface roughness, distributed between quality ranges 2 to 4. The laser cut specimens has the smallest scatter in terms of surface roughness and is mainly within the lower band of quality range 4. The gas cut specimens shows the highest scatter and is distributed between quality range 3 to outside range 4. For the plasma and gas cut specimens it can also be seen that the surface roughness tends to slightly increase as the steel grade is moving from S700 to S960. However, this trend is not observed for the laser cut specimens. Plasma and laser cutting proves to provide the lowest variation in surface roughness, whereas plasma has the lowest roughness. The gas cut specimens has the highest scatter and also the highest surface roughness. The majority of the produced specimens are within or outside range 4, indicating a generally poor surface quality according to ISO 9013:2002, which should imply low fatigue strength. Thus, it could be expected that the plasma specimens will have the highest fatigue strength in this study, followed by the laser specimens and finally the gas cut specimens.

One explanation to the fairly rough surface in the laser cut specimens is that laser cutting is used for plate thickness < 20mm. A 16 mm thick plate requires high energy and the much localized heat input cause a very rough surface. This phenomenon is illustrated in figure 4 where S355 plates with thickness of 6, 8 and 15 mm show an increased surface roughness with the increasing plate thickness.

Figure 4: Laser cut edges of S355 plates with 6, 8 and 15 mm plate thickness.

4 Residual stress measurements

A Stresstech Xstress 3000 G2R X-ray diffractometer with $\text{CrK}\alpha$ radiation (30kV, 6.7mA) was used with a 2mm circular collimator to measure the residual stresses parallel to the loading direction along the cut surface. The measurements were conducted in accordance with EN 15305:2008. The Young's modulus and Poisson's ratio used for the determination of the residual stresses were $E = 211\text{GPa}$ and $\nu=0.3$. The resulting residual stress measurement is presented in figure 5. The cut surfaces in the S700 specimens are generally in compressive mode except for the plasma specimens, which proves to have minor tensile stresses. In summary, the majority of the specimens contain compressive residual stresses whereas the plasma cut specimens are generally in tensile mode, which was also observed by Remes et al [6].

Figure 5: Residual stress measurement at S700 cut surface

5 Fatigue testing and assessment

The fatigue testing was conducted using constant amplitude, pulsated tensile loading with $R=0.1$. The runout limit was set to 5×10^6 cycles and all specimens were tested to final failure. The hydraulic clamping in the testing machine allowed no angular flexibility during testing. Most specimens failed due to crack initiation at the corner between the rolled plate surface and the thermally cut surface. Some cracks were initiated in the rolled plate surface due to corrosion, these specimens are not included in the study.

It should be noted that for some test series there were an angular misalignment. This misalignment was measured for each individual specimen and a finite element model was developed to model the influence of the misalignment and the resulting bending component when the specimens were mounted in the testing machine, see figure 6a. One quarter of the specimen was modeled with a misalignment Δ , using 8-noded second order brick elements. Using linear regression in figure 6b, the additional bending component was determined to 57MPa per Δ . All specimens failed in the same corner where the misalignment provided the highest additional bending component.

Figure 6: Fatigue testing of specimens in S700.

The fatigue testing conducted within this study are presented in figure 7-8 with a summary in table 3-4, where the bending component due to misalignment is included. Results found in literature are presented in figure 9 and table 5, however for these specimens there were no reported misalignment.

Figure 7: Fatigue testing of specimens in S700.

Table 3: Summary of fatigue test results of S700 material.

Specimen	Run outs / Failed	Misalignment [mm]	Natural slope	Log C ¹ / Std dev.	Mean fatigue strength ¹ [MPa]	Char. fatigue strength ¹ P _r = 2.3% [MPa]
Oxygen	1 / 12	2.9 – 3.6	4.92	18.98 / 0.133	377	340
Plasma	3 / 9	0.2 – 0.8	3.66	15.08 / 0.204	250	202
Laser	2 / 6	0.2 – 0.9	3.33	14.42 / 0.064	274	254
Waterjet	3 / 7	0	4.26	17.03 / 0.066	328	310

¹ using natural slope

Figure 8: Fatigue testing of specimens in S960.

Table 4: Summary of fatigue test results of S960 material.

Specimen	Run outs / Failed	Misalignment [mm]	Natural slope	Log C^1 / Std dev.	Mean fatigue strength ¹ [MPa]	Char. fatigue strength ¹ $P_f = 2.3\%$ [MPa]
Oxygen	1 / 8	2.2 – 2.5	4.09	16.6 / 0.029	328	320
Plasma	2 / 9	0 – 0.7	5.57	20.03 / 0.143	291	264
Laser	3 / 9	0.7 – 1.0	5.2	19.34 / 0.152	323	289

¹ using natural slope

Figure 9: Fatigue test data from literature.

Table 5: Summary of fatigue test results taken from literature.

Specimen	Yield strength [MPa]	Thickness [mm]	Stress ratio	Run outs / Failed	Natural slope	Log C ¹ / Std dev.	Mean fatigue strength ¹ [MPa]	Char. fatigue strength ¹ P _f = 2.3% [MPa]
S355 – Oxygen [7]	416	15	0.1	2 / 11	4.32	16.41 / 0.133	225	203
S355 – Plasma [7]	416	15	0.1	2 / 8	5.52	19.67 / 0.09	265	249
S355 – Plasma [13]	425	8	- 1	1 / 12	11.05	35.86 / 0.149	474	451
S355 – Laser [13]	425	8	- 1	1 / 11	11.4	36.5 / 0.181	446	420
S420 – Plasma [7]	450	6	0.1	3 / 8	6.89	23.47 / 0.11	310	292
S420 – Laser [7]	450	6	0.1	0 / 9	11.16	34.42 / 0.14	330	315
S690 – Plasma [6]	747	15	0.1	2 / 8	2.85	13.15 / 0.133	254	213
S700 – Plasma [7]	732	5	0.1	3 / 9	6.83	24.09 / 0.099	402	380
S700 – Laser [7]	732	5	0.1	2 / 16	4.06	16.46 / 0.246	319	254
S900 – Laser [4]	945	6	0	2 / 20	4.1	16.65 / 0.125	336	286

¹ using natural slope

None of the test specimens produced within this study exceeded 1e6 number of cycles during the testing. The load ranges were selected to correlate with conditions which are typical for loader cranes. Figure 7 and 8 shows a general improvement in fatigue resistance when increasing the yield strength of the material. The plasma and laser cut specimens show an improvement of 16-18% in mean fatigue strength and here the slope of the natural mean curve is also increased. The oxygen cut specimens on the other hand show a 13% decrease in mean fatigue strength. This might be explained by the rough surface of the oxygen cut specimens and the increased sensitivity to defects between S700 and S960 material.

5.1 Design recommendations according to SSAB Handbook

To compare the test data by extrapolating each data point to a common reference, preferably 1e6 cycles since the fatigue baseline by Sperle [4] is derived for 1e6 cycles, it is necessary to select a slope which has an adequate correspondence to each test series. Figure 10 show a comparison of the slopes of the SN-curves for the different test series within this study and also the published data for similar specimens. The scatter bands for each series are derived using the ASTM E 739 Standard [14] and represents a 95% confidence band for the median SN-curve of each series. For the thicker test specimens presented in figure 10a (15 and 16mm), the mean slope is within the range of 2.8 to 5.6, the other specimens in figure 10b whose thickness are between 5-8mm, the slope varies from 4.1 to 11.4, this indicates a thickness effect on the slope of the SN-curve. Sonsino et al [15] stated that for thick welded joints (thickness > 10mm) a slope of approximately $m=3$ is generally observed under axial loading. It can be concluded that the slope $m=3$ is appropriate

for the thicker specimens and the slope $m=5$ is appropriate for the thinner specimens within this study.

Figure 10: Slope of SN-curves for specimens in this study compared with published data, a) Specimens in thickness 15-16 mm, b) Specimens in thickness 5-8 mm.

Figure 11 show the extrapolated FAT value for the S700 and S960 testing conducted within this study. The limit lines which define range 1 to 4 are derived using the fatigue strength baseline by Sperle [4] where the Rz input corresponds to the ISO 9013:2002 given limits for each thickness. All specimens proves to have 15-70% higher fatigue strength compared to what could have been expected from the surface roughness measurement in figure 3. The majority of the oxygen cut specimens were below range 4 and were therefore expected to have a fatigue strength of 230MPa at the best, as seen in figure 11 it ranges from 290MPa to 480MPa, which is range 1 to

2. The plasma cut specimens were expected to have a fatigue strength corresponding to range 3 and 4, the testing proved to be within range 1-4 with one outlier. The laser cut specimens were mainly within range 4 according to the surface roughness measurement, although the testing proved to be within range 1-3. The waterjet specimens were expected to have a fatigue performance in the lower band of range 2, whereas the testing proves to be within range 1.

The oxygen and plasma specimens show a decreased scatter in fatigue strength when increasing the yield strength, this can be explained by the surface roughness being generally higher for the S960 material compared to the S700 material. The laser cut specimens on the other hand show little or no difference in surface roughness between the S700 and S960 material, although the scatter is increased for the S960 specimens.

Figure 11: Median fatigue strength and limit lines derived using the baseline by Sperle [4] and surface roughness limits from ISO 9013:2002.

5.2 Design recommendations according to IIW [9]

The IIW recommendations [9] provide different design curves depending on the cutting process. It is distinguished between mechanized and manual cutting procedures, where mechanized is assumed to provide less scatter in production and thereby achieve an improved fatigue performance compared to manual cutting. The two FAT classes for mechanized thermal cutting are FAT125 and FAT 140 with an inversed slope of $m=3$, the FAT160 class is valid for rolled and extruded steel with grinded edges and no imperfections, detailed requirements are given in figure 12. There are requirements such as no visible imperfections and grinded corners, although such requirements are unambiguous and subjective. There are no stated recommendations such as cut surface quality and its influence when using high strength steel, which result in conservative design recommendations.

Figure 13 shows fatigue test results within this study and from literature. The results are well above the design curve except for cycles $< 10^5$, for which the natural slope of the test data is 7 and 11. It is observed that the thicker specimens align well with a design curve with slope $m=3$, but for the thinner specimens a slope of $m=5$ is more appropriate, which is in accordance with the observations by Sonsino et al [15].

No.	Structural Detail	Description (St.= steel; AL= aluminium)	FAT St.	FAT AL	Requirements and Remarks
100	Unwelded parts of a component				
111		<p>Rolled or extruded products, components with machined edges, seamless hollow sections.</p> <p>$m = 5$</p> <p>St.: For high strength steels a higher FAT class may be used if verified by test.</p> <p>AL: AA 5000/6000 alloys AA 7000 alloys</p>	160	70 80	<p>No fatigue resistance of any detail to be higher at any number of cycles!</p> <p>Sharp edges, surface and rolling flaws to be removed by grinding. Any machining lines or grooves to be parallel to stresses!</p>
121		<p>Machine gas cut or sheared material with subsequent dressing, no cracks by inspection, no visible imperfections</p> <p>$m = 3$</p>	140	---	<p>All visible signs of edge imperfections to be removed. The cut surfaces to be machined or ground, all burrs to be removed.</p> <p>No repair by welding refill!</p> <p>Notch effects due to shape of edges have to be considered.</p>
122		<p>Machine thermally cut edges, corners removed, no cracks by inspection</p> <p>$m = 3$</p>	125	40	<p>Notch effects due to shape of edges have to be considered.</p>

Figure 12: FAT classes for rolled plates and mechanized thermally cut plates [9].

Figure 13: IIW design curves with fatigue testing.

5.3 Design recommendations according to Eurocode 3 [10]

Section 1-9 Fatigue within Eurocode 3 [10] provide different design curves similar to the IIW recommendation, where it is distinguished between a mechanized or manually conducted cutting process, it also contains requirements such as removal of visible defects. It provides three different FAT-classes, each similar to the IIW recommendation, with the exception that the FAT-class for rolled and extruded components has a slope of 3 whereas the IIW recommendation allow a slope of 5. The Eurocode does not allow any design benefits of utilizing high strength steel, it does however, for the lower FAT-class, refer to EN 1090 [16] which require range 3 or 4 in ISO 9013:2002 depending on the execution class. Detailed requirements are given in figure 14.

Detail category	Constructional detail	Description	Requirements
160	<p>NOTE The fatigue strength curve associated with category 160 is the highest. No detail can reach a better fatigue strength at any number of cycles.</p>	<p><u>Rolled and extruded products:</u></p> <p>1) Plates and flats; 2) Rolled sections; 3) Seamless hollow sections, either rectangular or circular.</p>	<p><u>Details 1) to 3):</u></p> <p>Sharp edges, surface and rolling flaws to be improved by grinding until removed and smooth transition achieved.</p>
140		<p><u>Sheared or gas cut plates:</u></p> <p>4) Machine gas cut or sheared material with subsequent dressing.</p>	<p>4) All visible signs of edge discontinuities to be removed. The cut areas are to be machined or ground and all burrs to be removed. Any machinery scratches for example from grinding operations, can only be parallel to the stresses.</p>
125		<p>5) Material with machine gas cut edges having shallow and regular drag lines or manual gas cut material, subsequently dressed to remove all edge discontinuities. Machine gas cut with cut quality according to EN 1090.</p>	<p><u>Details 4) and 5):</u></p> <p>- Re-entrant corners to be improved by grinding (slope $\leq \frac{1}{4}$) or evaluated using the appropriate stress concentration factors. - No repair by weld refill.</p>

Figure 14: FAT classes for rolled plates and mechanized thermally cut plates [10].

Figure 15 show the fatigue testing with the design curves given in Eurocode 3. For cycles $>2e5$, the fatigue testing aligns well with the FAT 160 design curve, for cycles $<2e5$, some test series are below the design curve. As seen, the oxygen cut specimens which were prescribed to be in accordance with ISO 9013 range 4 are well above the FAT125 design curve.

Figure 15: Eurocode design curves with fatigue testing.

5.4 Design recommendations according to crane design standard EN 13001 [11]

Annex D in the Crane design standard provide different design curves for thermally cut edges. In contrast to the IIW recommendation and Eurocode 3, the crane design standard provide different design curves depending on material strength and enhanced cut surface quality, where the quality is defined in accordance with different ranges in ISO 9013. All design curves use slope of $m=5$ and they are presented in table 5.

Table 5: Design curves according to Crane design standard EN 13001 [11]

Yield strength f_y [MPa]	FAT ($m=5$)	Cut surface requirements
Independent of f_y	140	Range 3 in ISO 9013
$220 \leq f_y \leq 500$	160	Range 3 in ISO 9013
$500 \leq f_y$	180	Surface Roughness $R_z \leq 100\mu\text{m}$
$320 \leq f_y \leq 500$	200	
$650 \leq f_y \leq 900$	250	Range 1 in ISO 9013
$900 \leq f_y$	280	

Figure 16 – 18 presents each design curve in table 5 with the corresponding fatigue testing. All the test data in figure 16 is above the FAT200 design curve which requires a surface roughness within range 1 in ISO 9013, which is $13\mu\text{m} \leq R_z \leq 19\mu\text{m}$ for the test specimens. Thomas et al [13] reported a surface roughness of $R_z > 70\mu\text{m}$ for both the laser and plasma cut specimens, and Lefebvre et al [7] reported a surface roughness of $24\mu\text{m} \leq R_z \leq 130\mu\text{m}$ for the S355 and S420 specimens.

The testing for S690 and S700 material in figure 16 are well above the FAT180 curve for range 3 in surface roughness. The high quality FAT250 design curve corresponds to surface roughness range 1 in ISO 9013. Although the oxygen, plasma and laser cut specimens are within range 3 to 4 and the waterjet cut specimens are within range 2, these specimens still show a higher fatigue strength than the FAT250 design curve. Remes et al [5] reported a surface roughness of $7\mu\text{m} \leq R_z \leq 16\mu\text{m}$,

thus being within range 1 and Lefebvre et al [6] reported a surface roughness of maximum R_z 38 μ m, which classifies as range 2. This implies that the prescribed cut surface quality is conservative in terms of fatigue strength.

Figure 16: Design curves for $f_y \leq 500$ with corresponding fatigue testing.

Figure 17: Design curves for $650 \leq f_y \leq 900$ with corresponding fatigue testing.

The testing for S900 and S960 material in figure 17 show that the majority of the specimens are above the high quality design curve. However the plasma series is

slightly below the design curve, despite a surface roughness within range 3-4, compared to the laser and oxygen cut specimens, which are within range 4 or below. Sperle [4] reported a surface roughness of $R_z = 10.9 \mu\text{m}$, thus being within range 1.

Figure 18: Design curves for $900 \leq f_y$ with corresponding fatigue testing.

6 Discussion

6.1 ISO 9013

According to the surface roughness measurements in figure 3 the plasma cut specimens was predicted to have the highest fatigue strength of the thermally cut specimens, followed by the laser and then the oxygen cut specimens. However the testing show the opposite relation, where the oxygen cut specimens has the highest fatigue strength followed by the laser and then the plasma cut specimens. Studies regarding residual stresses in welded joints confirm [12] that the residual stress state plays a major role for the fatigue strength in comparison to the shape of the imperfection. Therefore the residual stress state in figure 5 and the resulting surface roughness measurement should be considered. Even though the surface roughness is lower for the plasma and laser cut specimens, the fatigue performance should be similar. The gas cut specimens has the highest surface roughness but also the largest compressive residual stress state, and the plasma specimens proves to have the lowest roughness, but the residual stresses are practically zero compared to the oxygen and the laser cut specimens. The resulting fatigue strength is generally higher compared to the predicted using the limits given by ISO 9013 and the model derived by Sperle [4], even though the specimens in terms of thickness and cutting methods are within the scope for the ISO 9013 standard. Therefore it can be concluded that the limits for each surface roughness range in ISO 9013 has a weak connection to fatigue performance. The resulting surface conditions in terms of surface roughness, hardness, residual stresses varies depending on the cutting process and plate thickness. Based on the results in this study, the ranges for

surface roughness in ISO 9013 should be dependent on the cutting process in order to achieve a statistically adequate connection to fatigue strength.

The process of waterjet cutting is not within the scope of the ISO 9013:2002 standard, since it only applies to thermal cutting. Waterjet cutting was included to serve as a reference series with no influence of a heat affected zone. The resulting cut surface quality is in general higher compared to thermal cutting, which makes the method more suitable for structural fatigue critical applications where high quality is required, instead of utilizing thermal cutting followed by edge grinding.

6.2 Cut edge preparation

The IIW design recommendations, Eurocode 3 and the Crane design standard prescribes grinding of corners in order to remove critical defects. The Eurocode states that any scratches from grinding operations can only be parallel to the stresses, any other direction of the scratches from grinding will serve as crack like defects. Unfortunately, it is common in industry that designers specifies grinding as edge improvement method, without stating the required direction of possible scratches from grinding. Therefore it is necessary to clarify the effect of performing inadequate grinding in fatigue applications. It is also economically interesting to distinguish between edges with edge grinding and as cut conditions. Two additional test series in S960 material were produced using plasma cutting, one series with no edge preparation (as cut) and one test series with edge grinding where the scratches were perpendicular to the loading direction, for which disc grinding were used. These specimens are illustrated in figure 19 and the resulting fatigue testing is presented in figure 20 with a detailed summary in table 6.

Figure 19: Different edge conditions using a) belt grinding, b) disc grinding and c) as cut conditions.

The belt grinded specimens, where the grinding scratches are parallel to the loading direction had the highest fatigue strength. The as cut specimens proved to have a 25% higher fatigue performance compared to the disc grinded specimens, whereas the belt grinded specimens had a 12% fatigue strength improvement compared to the as cut specimens. There is also a distinct decrease in natural mean slope of the SN curve when utilizing disc grinding.

Figure 20: Fatigue testing of plasma cut S960 material with alternative edge conditions.

Table 6: Summary of fatigue test results of S960 material with alternative edge conditions.

Specimen	Run outs / Failed	Misalignment [mm]	Natural slope	Log C ¹ / Std dev.	Mean fatigue strength ¹ [MPa]	Char. fatigue strength ¹ P _f = 2.3% [MPa]
Belt grinded	2 / 9	0 – 0.7	5.57	20.03 / 0.143	291	264
Disc grinded	1 / 9	0 – 0.7	3.42	14.21 / 0.109	205	182
As cut	1 / 8	0 – 0.7	4.40	16.9 / 0.082	258	240

¹ using natural slope

6.3 Slope of S/N curves

It should be noted that the results within this study are entirely based on specimens tested in well-defined loading conditions. However in real design applications there are several other parameters influencing slope and fatigue strength. Based on figure 10 a slope of the SN-curve, $m=3$, were appropriate for the thicker specimens included in this study and a slope of $m=5$ for the thinner specimens. Sonsino et al [15] stated that various parameters determine the slope of the SN-curve; thickness, flexibility during loading, stress concentration, loading mode (axial, bending, torsion), stress ratio, yield strength in relation to the knee point of the SN-curve and residual stresses from fabrication, cutting and welding. These parameters interact with each other, which makes it difficult to identify the main governing parameter for the fatigue strength and slope of the SN-curve. Therefore it is important to distinguish for which load level the slope is defined for each material. The knee point for the thicker run out specimens is somewhere at $1e6$ cycles and at $2e6$ cycles for the thinner run out specimens. The load level at the knee point is 40-60% of the material yield limit, which should be compared with welded specimens which have a knee point at 20-30% of the material yield limit at $2e6$ to $10e6$ cycles. Again, these results are for

small scale test specimens, in real design applications with more complex loading situations due to rigidity, residual stresses from manufacturing and assembly, the resulting fatigue strength may be lower.

6.4 Bending contribution and residual stresses in the material

Some test specimens contained an angular misalignment prior to the fatigue testing. The underlying reason for this could depend on the thermal cutting procedure or the fabrication process of the steel sheets. A higher heat input during cutting will cause an irregular deformation during cooling compared to a low heat input. It should be noted that the manufacturing process of the steel plates also induce residual stresses, which varies depending on the rolling direction.

7 Conclusion

In this study, fatigue testing was conducted on dog bone shaped specimens in different steel grades which were cut using oxygen, plasma, laser and waterjet cutting. The surface roughness were measured for all specimens and compared to existing quality tolerances standard ISO 9013:2002. The resulting fatigue strength, along with results found in literature, was compared to existing codes and design recommendations. The following conclusions can be made:

- Testing proved to have 15-70% higher fatigue strength compared to what could have been expected using ISO 9013:2002 and the model developed by Sperle [3].
- The ISO 9013:2002 is conservative and has a weak connection to fatigue strength.
- Current IIW design guidelines and Eurocode 3 does not account for increased yield strength and enhanced quality.
- The crane design standard EN 13001 allow increased design curves when increasing the yield strength and improving the quality.
- The post cutting edge preparation has a significant role in fatigue strength of high strength steel.
- There is a need for an update of the design guidelines and codes to allow design benefits when using high strength steels and improved surface quality.

8 Acknowledgement

The authors would like to thank SSAB and Volvo Construction Equipment for contributing with material and cutting to this study, and KTH – Department of Production Engineering for providing the waterjet cutting.

9 References

- [1] B. Jonsson, Z. Barsoum, J.-O. Sperle, *Weight optimization and fatigue design of a welded bogie beam structure in a construction equipment*, Engineering Failure Analysis, vol. 19, pp. 63-76, 2012.
- [2] Jernkontoret, Swedish steel producers association, *Environmental benefits of high strength steel in cranes*, 2015.

- [3] P.J. Haagensen, S.J. Maddox, IIW recommendations on methods for improving the fatigue strength of welded joints: IIW-2142-110 Woodhead Publishing Ltd., 2013.
- [4] J.-O. Sperle, *Influence of Parent Metal Strength on the Fatigue Strength of Parent Material with Machined and Thermally Cut Edges*, Welding in the World, vol. 52, no. 7, pp. 79-92, 2008.
- [5] SSAB Design Handbook, 1st edition, Österbergs Tryckeri AB, Nyköping, 2012.
- [6] H. Remes, E. Korhonen, P. Lehto, J. Romanoff, A. Niemelä, P. Hiltunen, T. Kontkanen, *Influence of surface integrity on the fatigue strength of high-strength steels*, J. Construction Steel Research, vol. 89, no. 9, pp. 21-29, 2013.
- [7] F. Lefebvre, H.P. Lieurade, I. Huther, L. Jubin, *Proposal for fatigue classes applicable to thermal cutting*, IIW-Doc XIII-WG4-138-15, International Institute of Welding, 2015.
- [8] International Standard: ISO 9013 Thermal cutting – Classification of thermal cuts – Geometrical product specification and quality tolerances, second edition ISO 9013:2002, Geneva, Switzerland, 2002.
- [9] A. Hobbacher, *IIW recommendations for fatigue design of welded joints and components WRC*, Welding Research Council Bulletin, WRC 520, 2009.
- [10] European Standard: Eurocode 3: Design of steel structures – Part 1-9: Fatigue, EN 1003-1-9, Brussels, Belgium, 2005.
- [11] European Standard: EN 13001 Cranes – General Design – Part3-1: Limit states and proof competence of steel structures, second edition EN 13001-3-1:2012+A1:2013, Brussels, Belgium, 2013.
- [12] M. Khurshid, Z. Barsoum, G. Marquis, *Behavior of Compressive Residual Stresses in High Strength Steel Welds Induced by High Frequency Mechanical Impact Treatment*, J Pressure Vessel Technology, vol. 136, no.4, 2014.
- [13] D. Thomas, *The influence of the laser and plasma traverse cutting speed process parameter on the cut-edge characteristics and durability of Yellow Goods vehicle applications*, J Manufacturing Processes, vol. 13, no. 2, pp. 120-132, 2011.
- [14] American Standard: Standard Practice for Statistical Analysis of Linearized Stress-Life and Strain-Life Fatigue Data, ASTM E 739-91, Conshohocken, US., 2004.
- [15] C. M. Sonsino, T. Bruder, J. Baumgartner, *SN-curves for welded thin joints – suggested slopes and FAT-values for applying the notch stress concept with various reference radii*, International Institute of Welding, Doc. XIII-2280-09, 2009.
- [16] European Standard: EN 1090 Execution of steel structures and aluminum structures – Part 2: Technical requirements for steel structures, first edition EN 1090-2:2008+A1:2011, Brussels, Belgium, 2011.