Fatigue strength assessment of cut edges considering material strength and cutting quality

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A B S T R A C T

In the present study, statistical analysis for previously reported cut edge fatigue test results is performed. Experimental fatigue tests are conducted for machined, plasma, and fiber laser-cut S960 edges to verify the effect of yield strength and cut edge quality, and to study the effect of the cutting method on fatigue performance. Experimental fatigue tests were complemented with hardness and residual stress measurements and metallurgical analyses with electron backscatter diffraction (EBSD) to characterize cut edge fatigue properties and to verify statistical analysis findings. The results show that cut edges can be divided into high- and low-quality categories. On the basis of these high- and low-quality categories, material strength, and applied cutting methods, FAT classes and recommended fatigue design practices are proposed.

1. Introduction

Cutting is an important manufacturing method that has recently been developed to incorporate fiber laser technology. Local approaches have been adopted for welded joints [1] whereas cut edges are only covered with treatment-based [1,2] or surface roughness effects-based nominal FAT classes [3]. To design and manufacture lightweight and energy-efficient structures, accurate fatigue properties of cut edges should be obtained. For the welded and high-frequency mechanical impact (HFMI-treated) joints, the effective notch stress (ENS) method has increased the accuracy of fatigue strength assessments [4].

Hultgren et al. [5] introduced a probabilistic fatigue model for waterjet cut edges that takes into account material properties, surface quality and residual stresses at the cut edges. Barthsch and Feldmann [6] re-evaluated the EC3 cut edges fatigue performance by using fatigue test results from 1950s and 1960s. The previous studies and fatigue strength assessment guidelines did not cover comprehensively fiber laser fusion cutting and ultra-high-strength steels (UHSSs) that are in the focus of this study. Additionally, the current study includes also other traditional cutting methods and materials. Instead of re-analyzing previously gathered data, a new dataset from recent experimental studies [7–16] (from 2005 to 2020) was extracted to cover the current cutting methods, their technological development, and materials. Detailed differences between the cutting methods are highlighted using the data, and a statistical analysis on the data is carried out.

The experimental part of the study extends and verifies the findings of the statistical analysis. The experiments are carried out to obtain the presence of initial defects and local geometries, residual stresses, and material properties that are needed to establish a parametric model that adapts local material properties and initial defects in association with different base materials. Initial defect-based fatigue strength assessment method is introduced to enable increase in the fatigue performance resulting from recently developed steel materials and manufacturing methods, but to also increase the safety of fatigue critical components. The fatigue test data (S-N data points) was gathered using nominal stress method since the geometrical notch stress concentrations of cut edge specimens are negligible small compared to welded joints. However, the study aims to enable the utilization of the presented results beyond the nominal stress method. Cut parts typically includes geometrical shapes, and the most reliable fatigue strength assessment is performed by evaluating stress concentrations with finite element analysis (FEA). In the proposed fatigue strength assessment model, the local stresses are compared to the actual fatigue capacity of characterized cut edges in respect to cut edges quality and base material potential.

The fatigue strength and failure mechanisms of as-cut and burr ground S690 and S1100 laser-cut edges have been studied previously [13]. The development of fiber laser technology has increased the use of fusion cutting with nitrogen (N2) instead of oxygen (O2) as an assistant...
gas. With this fusion cutting approach, cutting speed increases along with usable laser power and the focus of development has chiefly been on cutting efficiency rather than fatigue performance. The fatigue strength of thermally-cut edges has been tested in several studies [7–16] and low-quality cut edges have been found as highly comparable to welded joints in as-welded conditions (ASW) whereas HR surface has been critical over high quality thermally cut edges or longitudinal welds in beam structures [17,18]. Prior research tended to focus on welded joints fatigue, increasing the knowledge gap between the fatigue behavior of welded joints and cut edges. Nevertheless, particularly in high-quality weldments, such as post-weld-treated joints made of UHSSs, the fatigue strength of cut edges becomes more important to design criteria. The fatigue strength of cut edges has been defined by FAT classes with a nominal stress method. EN13001 [3] defines FAT classes by \( R_2 \) value and material strength for cut edges, whereas the FAT classes for cut holes are specified as per the cutting method and material strength. One fatigue strength study [13] suggested that cut edge defects, hardness, and residual stresses have a more significant influence on fatigue capacity than the \( R_2 \) value. The FAT classes – defined by the EN13001 standard – have been found as more suitable for fatigue strength assessments than those recommended in previous studies by the IIW Recommendations or Eurocode 3 [1,2]. All these design standards, however, have been found to provide conservative FAT classes, particularly for reactive fusion-cut edges with high surface roughness and cut edges with burr attachment. The most typical discontinuity point of the cut edge is the burr at the bottom. The burr attachment depends on the cutting method, the parameters, and the steel’s chemical composition [19].

UHSSs are commonly manufactured by quenching & tempering (Q&T) or direct quenching (DQ) [20]. The manufacturing method and chemical composition also affect material hardening and softening, as well as residual stresses [21]. Moreover, surface quality is influenced by plate thickness, and DQ grades are limited to thinner sheets than QT grades. UHSSs with a thickness of \( t = 16 \) mm were fatigue tested in [16] and included in statistical analysis, whereas up to 20 mm thick HSSs were tested in [9]. Results from [13] were used to evaluate the effects of the steel manufacturing method on cut edge fatigue properties.

In the present study, fatigue test results from previous studies are extracted and divided into high- and low-quality (HQ and LQ) categories based on fatigue performance, which is defined by FAT class related to material potential. The experimental study concentrates to fiber laser fusion cutting since a lack of fatigue test results was found in the literature review and is performed to verify the statistical analysis findings and to establish knowledge of the combined effects of metallurgy, residual stresses, and surface quality on the fatigue performance of cut edges.

2. Statistical analysis

2.1. Data collection and statistical methods

The fatigue test data for statistical analysis was collected from previous studies conducted between 2005 and 2020 (see Appendix A1), which incorporated numerical-controlled (NC) cut component size structural steel dog-bone specimens (\( t = 4–20 \) mm) [6–17]. Specimens that resulted in failure between 1-10⁷ and 2-10⁸ cycles were included. Some of the previous studies did not specify the exact crack initiation locations or laser sources. In the statistical evaluation, laser cutting was considered as one group. This was instead of division to different laser sources or the applied assistant gases, although they can affect fatigue performance and laser technology has progressed from CO₂ lasers towards fiber lasers during the study period. This approach takes conservative estimates of fatigue performance characteristics, for example, due to the low performance of thick high-strength fiber laser fusion cut edges tested in [13].

The data included specimens in both as-cut [8–10,13,16] and corners chamfered [7,11–16] conditions. IIW recommendations [1] gives FAT 100 \( m = 3 \) for manually-cut edges and a higher class, and FAT 125 with \( m = 3 \) for mechanized cut edges with chamfered corners. Deming regression has been found to minimize the scatter of large fatigue test data analysis in [22] compared to the standard statistical approach and was, therefore, used in this study as a statistical method. The slope parameter of S-N curves was calculated by finding the mass center of data points and then minimizing scatter with Eq. (1). FAT classes were also estimated for fixed slopes \( m = 3 \) and \( m = 5 \).

\[
\begin{align*}
\sum_{i=1}^{n} v_i = \sum_{i=1}^{n} w_i \pm \sqrt{\left( \sum_{i=1}^{n} v_i - \sum_{i=1}^{n} w_i \right)^2 + 4 \left( \sum_{i=1}^{n} u_i v_i \right)^2} \\
2 \left( \sum_{i=1}^{n} u_i v_i \right)
\end{align*}
\] (1)

where \( u_i = \log \Delta \sigma_i - \frac{\sum_{j=1}^{n} \log \Delta \sigma_j}{n} \) and \( v_i = \log \Delta N_i - \frac{\sum_{j=1}^{n} \log N_j}{n} \) is the stress range, and \( N_i \) is the fatigue life. The mean and characteristic fatigue strength, corresponding to 50% and 97.7% survival probabilities, respectively, were calculated using Eqs. (2)–(4).

\[
\begin{align*}
\log C_{\text{mean}} &= -m \log \Delta \sigma \sum_{j=1}^{n} N_j - m \log \Delta \sigma n \\
\log C_{\text{char}} &= \log C_{\text{mean}} - k \cdot \text{Stdv}
\end{align*}
\] (2) (3)

where \( k = 1.645 \cdot 1 + \frac{1}{n} \cdot \text{Stdv} \)

\[
FAT_{\text{mean/char}} = \sqrt{\frac{\log C_{\text{mean/char}}}{2 \cdot 10^6}}
\] (4)

In the case of a calculated characteristic FAT class gave lower fatigue strength than the worst data point of experimental results, the worst point fatigue class was used as characteristic FAT values to minimize the effects of high scatter.

2.2. Cut edges fatigue performance analysis

Cutting methods and steel grade have been found to have the most significant influence on fatigue performance [13,15] resulting in their selection as the main features for categorizing this study’s test series. Gathered fatigue test data is presented in Fig. 1 and classified according to yield strengths and cutting methods. Scatter index \( T_N \) was determined from FAT classes based on the survival probabilities of 10% and 90%. The high surface roughness and compressive residual stresses in waterjet cut edges lead to high free slope parameter \( m \) value due to compressive residual stresses that are more beneficial when fatigue life increases. The mean fatigue strength of waterjet cut specimens with a fixed slope of \( m = 5 \) seems to be higher than that of machined specimens.

Each cutting method combined with the steel grade and thickness has different properties. A categorization of high quality (HQ) and low quality (LQ) cut edges based on initial defects was suggested in [13]. In [12,15,23], fatigue capacity was found to strongly depend on the steel grade in the case of high-quality laser cut and machined edges. Both of these aspects should be considered when developing an advanced fatigue strength assessment approach.

The reported test series were divided into low- and high-quality categories based on assumed initial defects, reported treatments, fatigue performance, and run-out levels. The categorization was performed for each test series and all selected test series data points were included in this study, even though yield strength was only exceeded in a few low-strength steel fatigue tests, which reduced fatigue performance and increased scatter. To evaluate the effect of burr attachment, the FAT category was further divided into as-cut and edges chamfered classes. Both LQ and HQ classes included test results from the laser, plasma, and oxy-fuel cut edges, whereas all waterjet cut edges were classified to HQ class despite the high \( R_2 \) values reported in [10,13]. The principal
The difference between HQ and LQ classes is found in the crack initiation. In HQ edges, only small or non-existing initial cracks are present, resulting in a long crack initiation period, whereas the crack growth phase determines fatigue life with LQ edges. This study only considered machined edges as a reference.

Cut edge fatigue test results are shown in Fig. 2 with the proposed quality classification. The division to LQ and HQ is highlighted in class $590 \leq f_y \leq 700$ (Fig. 2b), in which a high amount of fatigue tests was available for both examples. Only a limited number of LQ specimens with chamfered edges were found in the literature, but it should be

![Fig. 1. Fatigue test results, number of test specimens and scatter ranges of (a) all cut (excl. machined) b) machined, c) laser, d) plasma, e) oxy-fuel and f) waterjet cut edges. Data from [7–16].](image1)

![Fig. 2. Fatigue test results of (a) $350 \leq f_y \leq 500$, (b) $590 \leq f_y \leq 700$, and (c) $890 \leq f_y \leq 1100$ cut edges with quality classification by the quality and yield strength. Data from [7–16].](image2)
noted that as-cut edges may have a high fatigue performance, whereas the chamfering of edges does not necessarily guarantee a HQ classification.

Fig. 3 illustrates the quality-based fatigue performance of studies cut edges with the suggested slope parameters of $\leq 590$ MPa $\leq f_y$ for HQ cut edges. It can be identified that yield strength has a significant effect on fatigue performance when $350 \leq f_y \leq 500$ MPa. However, the fatigue performance is similar in $350 \leq f_y \leq 700$ and $890 \leq f_y \leq 1100$ classes. Scatter index $T_n$ decreases to acceptable level after quality classification when compared to original data (Fig. 1a). The results suggest that for computer-aided cutting in as-cut conditions, the FAT 150 class with $m = 3$ is valid but conservative and the full potential of high strength, quality, or post-treatments are not enabled. The results indicate that, for LC cut edges, the slope parameter of $m = 3$ is more suitable, especially for as-cut edges because burr attachment has the most detrimental effects on fatigue performance. Moreover, defects have a smaller effect on fatigue performance at the low cycle when compared to the high cycle regime, instead of $m = 5$ which is given in EN13001 for all cut edges.

The correlation of fatigue strength to yield strength was identified from HQ cut edges. LC cut edges, however, had a similar fatigue capacity in the regime of $350 \leq f_y \leq 700$ MPa, and slightly higher in

Table 1
Mean fatigue strength based on test results. Data from [7–16].

| Class          | As-cut - LQ | Chamfered - LQ | HQ (cut) | All (cut) |
|----------------|-------------|----------------|----------|-----------|
|                | MSSPD FAT   | MSSPD FAT      | MSSPD FAT| MSSPD FAT|
|                | [MPa] m = 5 | [MPa] m = 5    | [MPa] m = 5| [MPa] m = 5|
| $350 \leq f_y \leq 500$ | 238 5.74 229 | 233 5.43 227 | 233 5.43 227 | 237 13.85 277 | 284 8.33 252 |
| $590 \leq f_y \leq 700$ | 235 4.8 244 | 269 4.8 273 | 329 8.09 351 | 414 3.9 292 |
| $890 \leq f_y \leq 1100$ | 293 5.92 277 | 331 7.81 283 | 406 6.34 370 | 406 5.39 341 |
| $350 \leq f_y \leq 1100$ | 240 4.81 243 | 239 4.05 261 | 346 5.56 332 | 270 4.25 288 |

1 Value determined as a worst point analysis.

Table 2
Characteristic fatigue strength based on test results. Data from [7–16].

| Material | FAT As-cut | FAT Chamfered | All LC | HQ | Machined | FAT & HQ cut |
|----------|------------|---------------|--------|----|----------|--------------|
|          | FAT m = 3  | FAT m = 5     | FAT m = 3 | FAT m = 5 | FAT m = 3 | FAT m = 5 |
| $350 \leq f_y \leq 500$ | 141 194 | 141 194 | 142 195 | 142 195 | 207 207 | 202 266 |
| $590 \leq f_y \leq 700$ | 152 199 | 185 195 | 153 195 | 200 179 | 272 272 | 192 251 |
| $890 \leq f_y \leq 1100$ | 164 224 | 163 256 | 163 224 | 194 295 | 217 249 | 349 170 |
| $350 \leq f_y \leq 1100$ | 147 195 | 157 207 | 145 198 | 170 240 | 201 281 | 216 149 |

The 890 MPa $\leq f_y \leq 1100$ MPa class. The FAT classes are presented in Table 1 with the classification made according to cut quality and yield strength. LC cut edges have a strong correlation to yield strength and low scatter even when thermal and mechanical cutting methods are combined. The fatigue strengths of LC cut edges are comparable to the fatigue strength of welded structures. Consequently, the importance of quality increases along with yield strength due to increased notch sensitivity, higher stress range, and the effect of the crack initiation stage.

To enable a comparison with design rules, FAT values were estimated from classified data as a characteristic value and also with 97.7% survival probability (Table 2). The classification of cut edges decreases the scatter inside the categories. LC cut edges have an almost similar fatigue performance to machined edges and a high correlation to EN13001 given that yield strength-based FAT classes with Range 1 cut quality was observed with slightly modified material strength classes. The finding supports that cut edge fatigue EN13001 performance has good agreement with fatigue test results when defects are considered instead of surface quality measured with $R_z$ value. In a statistical analysis performed in [24], it was also found that high fatigue performance despite high surface roughness specimens and $R_z$ of 75 μm was proposed as a cut edge requirement for an increased FAT class.
The traditional approach to estimating characteristic FAT class from all fatigue tests can be used, suggesting FAT 150 \( m = 3 \) for cut edge fatigue performance. A conducted statistical analysis suggests a 20% better fatigue performance than current IIW recommended FAT 125 \( m = 3 \) for thermal cut and chamfered edges, or 50% improvement compared to FAT 100 recommended for manually-cut edges in as-cut conditions. In comparison to EN13001, the found FAT 200 \( m = 3 \) for cut edge suggests a 40% higher fatigue strength than the suggested FAT 140 \( m = 5 \) for as cut edges, including for burrs at cut edges.

### 3. Experimental tests

#### 3.1. Materials and measurements

Experimental fatigue test series were performed to verify the statistical analysis results, with the study focused on fiber laser cutting with oxygen and nitrogen as assistant gases. In addition to laser cutting, fatigue tests were conducted for plasma, oxy-fuel, waterjet, and guillotine cut edges. Machined specimens were used to provide a comparison to cut edges. Structural steels manufactured by SSAB with 6 mm thickness and nominal yield strengths of 420 MPa, 700 MPa, and 960 MPa (Table 3) were used for the experimental tests. Materials were in the hot-rolled (HR) condition and specimens were cleaned with 10% citric acid before residual stress measurements to remove mill scale and possible oxide layers. Sharp corners were chamfered with grinding parallel to loading to ensure separately stated as-cut specimens.

Two different industrial fiber laser cutting systems were used to manufacture the specimens. The study's main focus was on a standard industrial fiber laser fusion cutting with a 10 kW laser system. S690 \( t = 12 \text{ mm} \) and S1100 \( t = 8 \text{ mm} \) specimens cut and tested in [13] were cut with the same 10 kW fiber laser system as S960 \( t = 6 \text{ mm} \) in this study. Fiber laser fusion-cut edges were tested in as-cut, burr ground, and shot-peened conditions. Shot peened specimens were treated for two minutes in a drum-type machine. In addition to the industrial 10 kW laser cutting parameters, a custom high pressure (HP) parameter set was used to evaluate the effects of focal point position and assistant gas pressure on fatigue performance. The most important parameters of laser cutting, which have been varied in this study, are presented in Table 4. The cutting with a custom parameter set significantly increases costs due to a slower cutting speed and also increased the assistant gas consumption. The available parameters for plasma, oxy-fuel, guillotine, and waterjet cutting are presented in Table 5. Machined specimens were manufactured from fiber-cut billets with 2 mm machining clearance on each side. NC milling was performed clockwise with the parameters presented in Table 6. A 3 kW laser setup was also used for additional fatigue tests to study the effects of lower surface quality on fatigue performance.

### Table 3

Nominal material properties and chemical composition.

| Material | Yield strength [MPa] | Tensile strength [MPa] | Chemical composition [wt %] |
|----------|---------------------|------------------------|----------------------------|
|          | \( \sigma_{ymin} \) | \( \sigma_{ymax} \) | \( C_{\text{mass}} \) | \( S_{\text{mass}} \) | \( M_{\text{mass}} \) | \( P_{\text{mass}} \) | \( S_{\text{max}} \) | \( A_{\text{mass}} \) |
| S420     | 420                 | 480–620                | 0.10                      | 0.3                      | 1.50                  | 0.025                  | 0.01                  | 0.015                  |
| S700     | 700                 | 750–950                | 0.12                      | 0.25                     | 2.1                   | 0.020                  | 0.01                  | 0.015                  |
| S960     | 960                 | 980–1250               | 0.12                      | 0.25                     | 1.3                   | 0.020                  | 0.01                  | 0.015                  |

### Table 4

Laser cutting parameters.

| Cutting method | Assistant gas | Power [kW] | Cutting speed [mm/min] | Assistant gas pressure [bar] | Nozzle diameter [mm] | Focal point [mm] | Specimen type |
|----------------|---------------|------------|------------------------|-------------------------------|----------------------|----------------|---------------|
| FL             | \( N_2 \)     | 10         | 10,500                 | 6.5                           | 4                    | –3            | Fatigue & metallurgy |
| FL HP          | \( N_2 \)     | 10         | 8000                   | 20                            | 4                    | –6            | Additional fatigue tests |
| FL             | \( O_2 \)     | 4.2        | 3000                   | 0.65                          | 1.25                 | 6             | Fatigue & metallurgy |
| FL             | \( O_2 \)     | 3          | 2600                   | 0.5                           | 1.20                 | 0             | Fatigue & temperature |

### Table 5

Plasma, oxy-fuel, guillotine, and waterjet cutting parameters.

| Plasma         | Oxy fuel  | Guillotine | Waterjet |
|----------------|-----------|------------|----------|
| Current Speed  | 130A      | Speed      | Clearance| 0.6 mm   |
| Shielding gas  | 3800 mm/min | Gas       | Angle    | 1.3 degree |
| Cutting gas    | Air       |            | Speed    | 300 mm/min |

### Table 6

Machining parameters.

| Operation       | Roughing | Finishing |
|-----------------|----------|----------|
| Tool type       | Shoulder | Solid carbide end |
| Tool diameter [mm] | 25  | 20 |
| Feed rate [mm/min] | 300 | 900 |
| Rotation speed [RPM] | 1200 | 2000 |
| Repetitions     | 3        | 1        |
specimens. Stress concentrations obtained with FEA were below 1.02 of nominally applied loading and are not considered in the results. The failures in fatigue tests were initiated and propagated from both the constant width area and tapered sections, with no difference in fatigue strength between 20 mm and 50 mm specimen sizes being found.

Visual surface qualities are illustrated in Fig. 5. Surface quality was measured with an optical profilometer (Keyence VR-3200), with the results presented in Table 7 together with the FAT classes given as function of plate thickness in EN9013 [25] and further restricted with maximal $R_{\text{z5}}$ values in EN13001 [3]. It should be noted that the fiber laser-cut S420 edges surface quality was classified as Range 4, being outside of EN13001 requirements for fatigue-loaded structures. The use of custom parameters (see Table 4) and shot peening was found to improve the surface quality of fiber laser fusion-cut edges. Cut edges were classified to perpendicularity classes according to EN9013, although this is not considered as a fatigue parameter. Laser cutting

![Fig. 4. Test specimen geometries and rig attachments for (a) 50 mm and (b) 20 mm wide specimens.](image)

![Fig. 5. Visual surface quality of investigated cut edges.](image)

### Table 7
Surface quality and EN13001 classifications.

| Specimen          | $R_a$ [μm] | $R_z$ [μm] | $R_z$ Max [μm] | EN9013 and EN13001 classifications |
|-------------------|------------|------------|----------------|-----------------------------------|
|                   |            |            |                | Surface quality | FAT $m = 5$ [MPa] | Perpendicularity |
| HR                | 2          | 7          | 10             | –                   | 315               | –                |
| HR SP             | 4          | 17         | 25             | –                   | 280               | –                |
| Machined S960     | 1          | 4          | 7              | –                   | 315               | –                |
| Machined S700     | 2          | 4          | 8              | –                   | 280               | –                |
| Machined S420     | 2          | 5          | 10             | –                   | 225               | –                |
| Fiber laser O$_2$ S960 | 1    | 7          | 11             | Range 1             | 280               | 1                |
| Fiber laser O$_2$ S420 | 29  | 89         | 109            | Range 4             | –                 | 1                |
| Fiber laser N$_2$ | 8          | 42         | 60             | Range 3             | 180               | 1                |
| Fiber laser N$_2$ SP | 8    | 35         | 56             | Range 2             | 200               | 1                |
| Fiber laser N$_2$ HP | 5   | 31         | 44             | Range 2             | 200               | 1                |
| Plasma            | 3          | 10         | 14             | Range 1             | 280               | 2                |
| Oxy-fuel          | 10         | 25         | 51             | Range 2             | 200               | 2                |
| Waterjet          | 25         | 82         | 141            | Range 4             | –                 | 3                |
produces highly perpendicular edges and decreases machining, i.e. in weld preparations.

Residual stresses parallel to the loading direction, as well as full width half maximum (FWHM) values, were measured with a Stresstech Xstress G3 X-ray diffractometer. Residual stresses were measured from the middle of cut edges and from the HR surface as close to the upper corner of the specimens as possible with a 1 mm collimator spot size.

Tensile residual stresses were measured from laser-cut S960 specimen cut edges. The assist gas only minorly affected the results in both S960 and S1100 specimens, whereas both manufacturing method and chemical composition had significant influences on residual stresses, according to the measurements presented in Table 8.

Compressive residual stresses were measured from oxy-fuel and waterjet cut edges that compensate for material softening close to the cut edge and low surface quality. Guillotine cutting induced high tensile residual stresses equal to yield strength on the fracture section.

| Specimen type | Material | Cut edge | HR surface |
|---------------|----------|----------|------------|
|               |          | Avg. residual stress (MPa) | Avg. FWHM [°] | Avg. residual stress (MPa) | Avg. FWHM [°] |
| Machined edge | S960     | 42       | 3.3        | 31         | 2.4          |
| Machined edge | S700     | 242      | 2.5        | 69         | 2.0          |
| Machined edge | S420     | 275      | 2.1        | 33         | 1.7          |
| Fiber laser O2 | S420    | 358      | 4.4        | 171        | 1.9          |
| Fiber laser O2 | S960    | 269      | 4.0        | 104        | 2.5          |
| Fiber laser N2 | S960    | 236      | 4.3        | 99         | 2.4          |
| Fiber laser N2 SP | S960 | –573    | 4.4        | –340       | 3.4          |
| Fiber laser N2 [13] | S1100 | –6    | 4.4        | –153       | 2.4          |
| Fiber laser O2 [13] | S1100 | –4    | 4.9        | –          | –            |
| Plasma | S960     | 226      | 4.1        | 174        | 2.5          |
| Oxy-fuel | S960     | –114     | 2.6        | 248        | 2.6          |
| Waterjet | S960     | –397     | 3.2        | 15         | 2.4          |
| Shear cut – Shear section | S960 | 308     | 4.5        | –          | –            |
| Shear cut – fracture section | S960 | 948     | 4.6        | –          | –            |

Residual stress measurements reveal a trend that residual stresses are low on machined specimen HR surfaces. With both cutting surfaces, laser cutting results in a similar residual stress state in both cut edges and HR surfaces, although cutting speed distinguishes. The results suggest that plasma cutting induces higher tensile residual stresses to HR surfaces when compared to laser cutting. Tensile residual stresses were induced to S960 DQ laser-cut edges in contrast to the negligible small residual stress state of S1100 Q&T cut edges. Only minor residual stress relaxation was found when an average 211 MPa tensile residual stresses from the S960 fiber laser fusion-cut edge were measured after 5∙10⁶ cycles run-out test.

3.2. Metallurgical characterisation

Electron backscatter diffraction (EBSD) measurements and analysis were performed using an Oxford-HKL acquisition and analysis software. A field emission scanning electron microscope (FESEM) (Ultra plus, Zeiss) for the EBSD measurements was operated at 15 kV and the step size was 0.2 μm. EBSD mapping was conducted from the middle section of specimens to categorize grain morphology. The analyses were conducted for S960 specimens that have been fatigue tested in this study and S1100 cut edges that were fatigue tested in [13] to study the effects of chemical composition and manufacturing method. The results are shown in Figs. 6 and 7 with a classification of coarse-grained and fine-grained material.

![Fig. 6. EBSD mapping of (a) fiber laser reactive fusion cut and (b) fiber laser fusion cut S960 edges.](image)

![Fig. 7. EBSD mapping of (a) fiber laser reactive fusion cut and (b) fiber laser fusion cut S1100 edges tested in [13].](image)

![Fig. 8. Microhardness profile of S420, S960 DQ, and S1100 Q&T thermally-cut edges. S1100 data from [13].](image)
grained heat-affected zones (CGHAZ and FGHAZ), as well as the base material.

The differences in microstructures under a 100 μm distance from a cut edge can be explained by different cutting processes and the presence of oxygen. At a further distance, the differences are due to heat input and heat diffusion time, resulting in narrower HAZ in fusion-cut specimens. A crack-like defect is visible in fiber laser fusion-cut edge Fig. 6b. The defect is minor in size compared to the 200 μm long defects at the same distance from the edge in the examined fracture surfaces. Similar defects were found to influence S1100 fiber laser fusion-cut specimens’ fatigue performance in [13]. Grain size in the vicinity of a reactive fusion-cut S960 cut edge is larger and more constant when compared to an S960 fusion-cut edge. The cut edges of an S1100 microstructure can be distinguished from S960 edges with a smaller grain size in both CGHAZ and FGHAZ. Edge perpendicularity varies between oxygen and nitrogen assistant gases. Reactive fusion-cut edges are highly perpendicular at high magnification levels, whereas fusion-cut edges have more variation.

Hardness of laser and plasma cut edges were measured from polished cross sections. Hardness distribution was measured with the HV0.05 method for the first point at the 35 μm distance from cut edge, and with the HV0.2 method for following points up to 0.5 mm distance. Micro hardness profiles are presented in Fig. 8. A softened zone was found in the S960 hardness measurements. With slower cutting speed, the softened zone was more significant than with fast fiber laser fusion cutting. Fiber laser cut edge hardness in vicinity of cut edge distinguished significantly when compared to S1100 in [13], where similar measurements were conducted and hard layer close to cut edge but without softened zone was found. It can be noticed that oxy-fuel cut S960 and fiber laser cut S420 hardness are intersecting close to cut edge and the local fatigue capacity of oxy-fuel cut edge has decreased.

3.3. Fatigue test results

The fatigue test results performed in this study, together with the results from [13] in as-cut conditions and R = 0.1 stress ratio tested fiber laser fusion-cut specimens, are illustrated in Fig. 9 to highlight the effects of edge condition, cutting method, and plate thickness on fatigue performance. The EN13001 S-N curves for machined UHSSs and thermal-cut Range 3 surface quality FAT 180 MPa m = 5 can be found in [5] and is considered conservative for fiber laser fusion-cut edges even when they include the initial cut-edge defects. The statistical analysis resulted in FAT 150 MPa m = 3 for base value in as-cut conditions, FAT 200 MPa m = 5 for edges chamfered, and FAT 225 MPa m = 5 for edges chamfered plasma or fiber laser fusion-cut UHSS edges, which are shown as a statistical analysis comparison and also found as valid for this study’s experimental fatigue tests. A machined and reactive fusion-cut run-out level is high compared to FAT values. Reactive fusion-cut S960 t = 6 mm specimens were also tested in as-cut conditions, with no benefit from chamfering edges being found.

Although a thicker plate resulted in lower surface quality, the fatigue performance in the Burr ground-condition of S690 specimens t = 12 mm matched S960 specimens, whereas the S1100 t = 8 mm specimens had a significantly higher fatigue performance despite similar cutting parameters recommended by manufacturers. This difference could be explained by the different chemical compositions of Q&T and DQ steel grades and by the differences in residual stresses measured at cut edges.

The fatigue performances of reactive fusion-cut specimens and machined specimens were similar and at the highest level of tested specimens. The effects of stress ratio on fatigue performance were studied with the S960 specimens, and a slightly lower fatigue strength was observed when R = 0.4 and test with higher mean stress is included in FAT values shown in Table 9. Fatigue test results are presented as mean FAT classes due to a limited number of performed fatigue tests by manufacturers. This difference could be explained by the different chemical compositions of Q&T and DQ steel grades and by the differences in residual stresses measured at cut edges.

| Specimen       | Material | Experimental FAT 50% [MPa] m = 3 | Number of test specimens with failure |
|----------------|----------|----------------------------------|-------------------------------------|
| Machined       | S960     | 279 383 3                        | 3                                   |
| Machined       | S700     | 265 358 2                        | 2                                   |
| FL O2         | S960     | 279 392 4                        | 3                                   |
| FL O2         | S420     | 220 279 2                        | 2                                   |
| FL N2 AC      | S960     | 235 287 2                        | 2                                   |
| FL N2 EC      | S960     | 205 298 7                        | 7                                   |
| FL N2 HP      | S960     | 232 333 3                        | 3                                   |
| FL N2 Comb.   | S960     | 216 305 12                       | 12                                  |
| FL N2 SP      | S960     | 303 392 3                        | 3                                   |
| Oxy-fuel      | S960     | 205 296 3                        | 3                                   |
| Waterjet      | S960     | 234 340 3                        | 3                                   |
| Guillotine    | S960     | 159 164 2                        | 2                                   |

Fig. 9. Fatigue test results for (a) conventional cutting methods and (b) fiber laser fusion cutting. S690 and S1100 data from [13].
fatigue performance – defined as FAT class – close to machined and reactive fusion-cut specimens.

The typical fracture surfaces of fiber laser-cut specimens are shown in Fig. 10 a and b with crack initiation locations marked. The fatigue test results are explained by crack initiation locations. The fracture initiated a cut edge from pores and crack-like defects under the recast layer in fusion-cut specimens. A fusion-cut edge detail is illustrated in Fig. 10c to highlight the difficulty of material removal from the kerf. An increase in assistant gas pressure and lowering the focal point had a positive influence on fatigue performance, but a fatigue crack was still initiated from the cut edge. A crack initiation from the HR surface in a reactive fusion cut (Fig. 10 a) and machined specimens explains the similar fatigue performance obtained in these series.

From a visual inspection of a reactive fusion-cut S420 specimen, the crack initiation was assumed to be influenced by a very rough surface quality. However, further SEM analysis revealed crack initiation from a relatively large nonmetallic inclusion (NMI), shown in Fig. 11a. The inclusion was identified, via energy-dispersive X-ray spectroscopy (EDS), to consist of mainly sulfur and calcium. NMIs close to a cut edge, especially when close to high-tensile residual stress fields at HAZ and BM transition, are detrimental to fatigue performance. However, only the largest NMI was found to be critical over all the HR surface defects. Fig. 11b–d illustrate the crack initiation from fiber laser fusion-cut S960 edges in various conditions. The HP assistant gas flow was found to form a significantly thinner recast layer than standard industrial settings but, similarly, the crack initiation occurred from the cut edge due to pore-like and crack-like defects. Shot peening induces compressive residual stresses to the cut edge and improves fatigue performance, whereas fatigue crack was still initiated from cut-edge defects. In Fig. 11c, the individual shots attached to the cut surface are still visible. It remains unclear, however, whether these defects are formed in cutting or during shot peening. The burr in the bottom of the fusion-cut edge was found to be detrimental to fatigue performance, but with 6 mm thick specimens (Fig. 11d) a major crack-like defect was not found, unlike in 8 mm and 12 mm thick specimens in [13], while the fatigue performance of as-cut $t = 6$ mm specimens was also higher.

Waterjet, oxy-fuel, and guillotine cut edge fracture surfaces are shown in Fig. 11e–g. It can be seen that cracks have propagated from the bottom of the striations in Fig. 11e and f. In addition to the surface quality measured by $R_z$ value (Table 7), waterjet cutting produces a locally rough surface similar to fiber laser fusion cutting, whereas where oxygen is present the cut surface is smooth in oxy-fuel and reactive fusion laser cutting. Guillotine cutting induces the initial cracks to the cut edge before the fatigue crack propagates from these initial defects, resulting in a worse fatigue performance being found in this study.

4. A design proposal for the fatigue strength assessments of cut edges

The fatigue strength classes for machine-controlled cut edges, based
on the characteristic FAT values obtained in statistical evaluation and experimental fatigue test of this study, are presented in Table 10. The lowest point of each tested experimental fatigue test series of cut edges (excl. guillotine cutting) exceeded characteristic FAT classes obtained in statistical analysis. It should be noted that fatigue strength assessments should consider stress concentrations, preferably with FEA. The use of FEA in the determination of stress concentration diminished the need for an additional safety margin in the structures with cut geometrical shapes when compared to the nominal stress method.

The proposed FAT classes 150 MPa with a slope parameter of \( m = 3 \), and 200 MPa or higher with a slope parameter of \( m = 5 \), intersects at the low-cycle regime. According to the experimental findings, FAT 150 MPa (\( m = 3 \)) should be used when beneficial. Proposals for the FAT classes are established by modifying those given in the current EN13001 based on this study’s findings. The most significant differences between the current proposal and the EN13001 standard are the inclusion of the cutting method effect and typical defects, together with an increased fatigue strength capacity at the low-cycle regime, i.e. FAT 150 (\( m = 3 \)) is applicable at high-stress ranges. When proposed FAT classes are compared to the EC3 standard and IIW recommendations [1,2] for cut edges, it can be noted that the additional capacity of UHSSs or cut edges quality improvement from 1960 s and 1970 s, where mainly oxy-fuel cutting was used, can be enabled using the proposed model. Final draft of upcoming Eurocode 3 [26] recommends the use of slope parameter \( m = 5 \) with the FAT value of 125 MPa for the cut edges for EN9013 Range 2 surface quality edges in the corners chamfered-condition, and 160 MPa for ground edges.

Shot peening has been found to be a highly effective post-treatment that could be used to increase lower FAT classes up to 200 or 250 MPa \( m = 5 \), depending on BM yield strength. The effects of shot peening should be studied with machined specimens to ensure beneficial effects gained with machined and reactive fusion-cut edges, in which the fatigue performance was high without treatments. After further fatigue testing, the FAT classes for shot-peened cut edges could be increased. The statistical analysis included thick HSSs and UHSSs cut edges with plasma and reactive fusion-cut edges but reported studies with fiber laser fusion cutting are limited to \( t = 12 \) mm sheet thickness. Thick HSSs fiber laser fusion-cut edges should be fatigue tested to verify findings or to introduce thickness reduction for FAT classes.

5. Discussion

IIW recommendations for cut edge FAT classes were found to be conservative in this study, although it should be noted that only numerically-controlled cut edges were included in the statistical analyses. EN13001 provides a good estimation for fatigue strength for the characteristic machined-cut edges, which is due to the low scatter of reported fatigue test results. The high scatter of previously reported cut edge fatigue test results is the main factor for conservative FAT classes with \( m = 5 \) or high requirements for cut edge quality in EN13001. A slope parameter of \( m = 3 \) should be used for LQ cut edges to improve accuracy. FAT class 140 MPa (\( m = 3 \)) and the possibility of improving fatigue strength by chamfering edges is recommended in [27] for guillotine-cut edges. Based on this study’s findings, the FAT 125 MPa class (\( m = 3 \)) should be used and the FAT class cannot be increased with corners chamfering due to crack propagation from a cut surface.

Sperle [15] and Laitinen et al. [12] have suggested that fatigue classes should be determined based on the material strength and cutting method. The machined and reactive fusion-cut specimens tested in this study showed high agreement with Sperle’s conclusions. Supplementing the statistical analysis with more results of various cutting methods, however, indicated that the material strength-based approach for FAT classes could not be used without considering defects and cut edge hardness due to the fatigue performance of LQ cut edges being found as material independent.

A previous fatigue test results classification to LQ and HQ categories was performed without a detailed fractography due to the lack of data. In this study, fiber laser fusion and oxy-fuel cut S960 edges were considered as LQ edges based on crack initiation to the cut edge. Moreover, the characteristic fatigue strengths of these test series showed good agreement with FAT 150 MPa (\( m = 3 \)), and FAT 200 and 225 MPa (\( m = 5 \)), which were found in the statistical analysis and proposed as design FAT classes.

Jokialo et al. [28] found cracking in oxy-fuel cut edges, which could explain the high scatter in fatigue test results. In this study, oxy-fuel cutting resulted in relatively high fatigue performance, but it should be considered as an LQ cutting method due to possible initial cracks and also due to high tensile residual stresses that are highly detrimental to fatigue performance. Crack initiation also occurred from a waterjet cut edge but, based on this and previous studies [8,14], waterjet cutting should be considered as a HQ cutting due to small initial defects and compressive residual stresses parallel to the loading direction. As a slow cutting method, waterjet cutting is beneficial only with wear-resistant steel grades. Classification based on steel grade and its chemical composition, cutting method, local hardness, and initial defects should be studied to introduce parametric fatigue strength assessment.

Fiber laser fusion-cut S960 specimens were also tested in as-cut conditions. It was identified that the effect of burr attachment on

| Cutting method | Condition | Requirements | Material [MPa] | FAT class |
|----------------|-----------|--------------|---------------|-----------|
| Guillotine cutting | As-cut or edges chamfered | Visually acceptable quality | \( 350 \leq f_y \leq 1100 \) | 125 MPa \( m = 3 \) |
| All thermal cutting methods and waterjet cutting | As-cut | Visually acceptable quality | \( 350 \leq f_y \leq 1100 \) | 150 MPa \( m = 3 \) |
| Laser (O\& N & t \leq 12 mm), plasma and waterjet cutting | Edges chamfered | Visually acceptable quality | \( 350 \leq f_y \leq 700 \) | 200 MPa \( m = 5 \) |
| All thermal cutting methods | Shot peened after cutting | Visually acceptable quality | \( 890 \leq f_y \leq 1100 \) | 225 MPa \( m = 5 \) |
| Reactive fusion laser cutting | No burr attachment or edges chamfered | Cut edge \( R_{3s} < 60 \mu m \) | \( 890 \leq f_y \leq 500 \) | 225 MPa \( m = 5 \) |
| Machining | Sharp corners deburred | Cut edge \( R_{3s} < 20 \mu m \) | \( 900 \leq f_y \leq 700 \) | 280 MPa \( m = 5 \) |

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fatigue performance in the S960 \( t = 6 \) mm specimens was minor compared to the S1100 \( t = 8 \) mm specimens tested in [11]. Based on this study’s findings, fiber laser fusion cutting is the most suitable for \( t \leq 6 \) mm fatigue-load components, with its use also being economically profitable with thicker sheets when 10–20 kW laser power cutting systems are available. Studying the effects of burr attachment with statistical analysis is challenging due to the different characteristics (shape and size) of burr with cutting methods. Shot peening significantly improved the fatigue performance of fiber laser fusion-cut specimens by inducing compressive residual stresses and modifying recast layers by mechanical impact. A fatigue performance increase after shot peening was also found in [10] with oxy-fuel cut edges. However, fatigue performance increases are not considered in current design codes.

Stress concentrations from geometrical shapes should be considered carefully with a nominal stress method. It should be noted that the notch factor varies according to specimen dimensions and is higher when the hole is small compared to full width. The notch factor of small fatigue test specimens is lower than in a full-scale structure when the evaluation is conducted on the basis of a net cross-section. No separate FAT classes for cut holes are needed if maximum stress at the stress concentration is obtained with FEA and compared to the proposed FAT classes. Thermally-cut holes are a special stress concentration case, which is conducted on the basis of a net cross-section. No separate FAT classes factor varies according to specimen dimensions and is higher when the hole is small compared to full width. The notch factor of small fatigue test specimens is lower than in a full-scale structure when the evaluation is conducted on the basis of a net cross-section. No separate FAT classes for cut holes are needed if maximum stress at the stress concentration is obtained with FEA and compared to the proposed FAT classes. Thermally-cut holes are a special stress concentration case, which is covered in EN13001 with a maximal nominal FAT class 160 MPa \( m = 5 \) for net cross-section and materials with \( f_y > 650 \) MPa whereas Final draft of EC3 [26] proposes FAT 90 MPa \( m = 5 \) for drilled and FAT 50 MPa \( m = 3 \) for thermally cut or punched holes. This study’s results suggest that the EN13001 recommended class is suitable for reactive fusion-cut holes similarly than CO2 laser reactive fusion cut UHSS holes in [29], but optimistic for fiber laser fusion-cut holes when a linear stress concentration factor of \( 2 < k_t < 3 \) for a hole is considered. Upcoming EC3 recommended FAT class for thermally cut edges has good agreement with LQ cut edges FAT class recommended in this study. In modern fiber laser systems, the cutting process can be changed during cutting by automated nozzle change. For instance, a global shape can be cut using fusion cutting and with fatigue-critical holes as reactive fusion cutting to optimize the structure’s efficiency and performance.

Run-out tests were not considered in this study’s statistical analysis even though a high number of run-outs has been reported in previous studies [7–16]. Leonetti et al. [30] proposed a smooth transition for S-N curve knee points. Initial defects have a major influence on the run-out level and the categorization of a test series with the characteristic initial defects is challenging. However, the results in this study indicate that an S-N curve knee point should be considered, especially with high quality cut or machined edges.

An ENS method is used for a welded joints fatigue strength assessment and could also be used for cut edges based on the results presented in this study. IIW recommends FAT classes for HFMI-treated weld joints from FAT320 to FAT500 with \( m = 5 \) in accordance with the material strength, and FAT225 \( m = 3 \) is used for all steel grades in the ASW condition. The recommended values could be used for cut edges with a statistically determined fatigue notch factor instead of a geometric notch factor. The fatigue notch factor \( K_t \) is usually determined based on the fatigue limit difference between a cut edge and smooth specimen in fatigue testing, similar to [31]. Based on this study’s findings, the stress concentration factor should be estimated from the relationship between the EN5 FAT class and the statistically determined FAT classes for each cutting method and yield strength classes.

Low-strength steels have a lower defect and notch sensitivity and, thus, a lower potential for quality improvement. When using low-strength steels, the quality of the cut edge does not become critical in structures and the focus should be on the productivity of cutting processes. Fatigue tests were performed at an elastic stress region and low-strength specimens have a significantly longer fatigue life at stress ranges equal to nominal yield strength than HSS/UHSS specimens. Based on the results, nominal yield strength was found to be a valid limitation to FAT classes. When UHSSs are used, straight-cut edges should be cut with a method that produced a defect-free cut surface if a structure or components are otherwise optimized, and welded joints are HFMI-treated or TIG-dressed to meet the full potential in regard to the weldments found in [18].

The results suggest that a laser source has no effect on the cut edge fatigue performance when oxygen is used as an assistant gas. When nitrogen is used as an assistant gas with a fiber laser, fatigue performance significantly decreases. Fiber laser fusion cutting is beneficial for the productivity viewpoints and its fatigue performance is sufficient for free-cut edges with ASW-joints.

6. Conclusions

The conducted study highlights the importance of cutting quality consideration in fatigue-loaded structures. The classification system according to cut edge quality was found to be necessary for efficient utilization of fatigue capacity. For LQ cut edges, a slope parameter of \( m = 3 \) was found to estimate fatigue performance the most accurately, whereas HQ cut edges benefit from the use of a slope parameter of \( m = 5 \). The analysis was carried out separately for three yield strength classes \((350 \leq f_y \leq 500, 590 \leq f_y \leq 700, 890 \leq f_y \leq 1100)\). LQ cut edges had a similar fatigue performance regardless of the material strength, and the low-cycle regime had limited yield strength. In contrast with LQ cut edges, HQ cut edges had a correlation with material strength from low- to high-cycle regimes.

The previous statistically re-analyzed experimental fatigue test studies indicated that FAT 150 \( m = 3 \) should be used as a minimum level for fatigue performance and for LQ thermally-cut edges in as-cut condition. Respectively, FAT 200 \( m = 5 \) for edges chamfered LQ cut edges and FAT \( m = 5 \) classes from 200 MPa to 315 MPa according to material strength for HQ cut and machined edges are suggested. According to the present results, reactive fusion laser cutting produces the best quality in terms of fatigue performance even when \( R_k \) value defined surface quality is low. The typical defects and heat input of the applied cutting method should be considered to achieve high cutting quality.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Tables A1 and A2.
### Table A1
Statistically analyzed test series.

| Ref. | Cutting method | Material | t [mm] | Surface quality Rₐ [µm] | Cutting speed [mm/min] | Quality classification |
|------|----------------|----------|--------|--------------------------|------------------------|------------------------|
| [7]  | Plasma         | S355     | 16     | 60                       | –                      | H                      |
| [7]  | Oxy-fuel       | S355     | 16     | 55                       | –                      | H                      |
| [8]  | Plasma         | S355     | 15     | 10                       | 2200                   | L                      |
| [8]  | Plasma         | S460     | 15     | 10                       | 2200                   | H                      |
| [8]  | Plasma         | S690     | 15     | 10                       | 2200                   | L                      |
| [8]  | Plasma         | S890     | 15     | 10                       | 2200                   | L                      |
| [8]  | Oxy-fuel       | S355     | 15     | 35                       | 400-450                | L                      |
| [8]  | Oxy-fuel       | S460     | 15     | 25                       | 400-450                | H                      |
| [8]  | Plasma         | S690     | 15     | 10                       | 400-450                | L                      |
| [8]  | Oxy-fuel       | S890     | 15     | 10                       | 400-450                | L                      |
| [8]  | Laser 3.6 kW O₂| S355     | 15     | 15                       | 1000                   | L                      |
| [8]  | Laser 3.6 kW O₂| S460     | 15     | 40                       | 1000                   | H                      |
| [8]  | Laser 3.6 kW O₂| S690     | 15     | 35                       | 1000                   | L                      |
| [8]  | Laser 3.6 kW O₂| S890     | 15     | 15                       | 1000                   | H                      |
| [9]  | Oxy-fuel       | S355     | 8      | 30-50                    | 600                    | L                      |
| [9]  | Oxy-fuel       | S355     | 20     | 40-80                    | 390-420                | L                      |
| [9]  | Oxy-fuel       | S690     | 8      | 25-45                    | 600                    | L                      |
| [9]  | Oxy-fuel       | S690     | 20     | 25-45                    | 390-420                | L                      |
| [9]  | Oxy-fuel       | S960     | 8      | 40-50                    | 600                    | L                      |
| [9]  | Plasma         | S355     | 8      | 15-30                    | 3420                   | L                      |
| [9]  | Plasma         | S355     | 20     | 10                       | 1300-1430              | L                      |
| [9]  | Plasma         | S690     | 8      | 15-30                    | 3420                   | L                      |
| [9]  | Plasma         | S690     | 20     | 15-30                    | 1300-1430              | L                      |
| [9]  | Laser          | S355     | 8      | 35-70                    | 900-1100               | H                      |
| [9]  | Laser          | S690     | 8      | 30-60                    | 900-1100               | L                      |
| [10] | Waterjet       | S355     | 8      | 29-97                    | 70-220                 | H                      |
| [10] | Waterjet       | S690     | 8      | 28-73                    | 70-220                 | H                      |
| [10] | Laser          | S650     | 4      | –                       | –                      | H                      |
| [11] | Laser          | S900     | 4      | –                       | –                      | H                      |
| [12] | Laser          | S900     | 6      | 8-20                     | –                      | H                      |
| [13] | Plasma         | S690     | 12     | 40-70                    | 2200                   | L                      |
| [13] | CO₂ Laser 5.7 kW O₂| S690 | 12   | 50-80                   | 1700                   | L                      |
| [13] | FL 10 kW N₂    | S690     | 12     | 15-25                    | 3150                   | L                      |
| [13] | FL 10 kW N₂    | S1100    | 8      | 40-70                    | 6000                   | L                      |
| [14] | Plasma         | S460     | 15     | 8-20                     | –                      | H                      |
| [14] | Plasma         | S690     | 15     | 8-20                     | –                      | H                      |
| [15] | Oxy-fuel       | S350     | 12     | 36                       | –                      | L                      |
| [15] | Plasma         | S350     | 12     | 30                       | 3500                   | H                      |
| [15] | Plasma         | S350     | 12     | 30                       | 3500                   | H                      |
| [15] | Plasma         | S350     | 12     | 25                       | 2500                   | H                      |
| [15] | CO₂ Laser 2.6 kW O₂| S350 | 12 | 25 | 2500 | H |
| [15] | CO₂ Laser 2.6 kW O₂| S590 | 12 | 25 | 2500 | H |
| [15] | CO₂ Laser 1 kW O₂| S700 | 6 | 13 | 1100 | H |
| [15] | CO₂ Laser 1 kW O₂| S900 | 6 | 10 | 1100 | H |
| [16] | Oxy-fuel       | S700     | 16     | 100-130                  | 900                    | H                      |
| [16] | Oxy-fuel       | S960     | 16     | 100-130                  | 900                    | H                      |
| [16] | Plasma         | S700     | 16     | 50-100                   | 1060                   | H                      |
| [16] | Plasma         | S960     | 16     | 50-100                   | 1060                   | L                      |
| [16] | Laser 5.7 kW O₂| S700     | 16     | 90-120                   | 1600                   | L                      |
| [16] | Laser 5.7 kW O₂| S960     | 16     | 90-120                   | 1600                   | H                      |
| [16] | Waterjet       | S700     | 6      | 25-35                    | 750                    | H                      |
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Table A2
Fatigue test results performed in this study.

| Cutting method | Condition | Material | R [-] | Stress range [MPa] | Fatigue life [cycles] | Note |
|----------------|-----------|----------|-------|--------------------|-----------------------|------|
| Machining      | EC        | S960     | 0.1   | 700                | 102,554               |      |
| Machining      | EC        | S960     | 0.1   | 575                | 347,020               |      |
| Machining      | EC        | S960     | 0.4   | 575                | 187,912               |      |
| Machining      | EC        | S960     | 0.1   | 500                | 2,000,000             | RO   |
| Machining      | EC        | S960     | 0.1   | 550                | 1,277,253             | FR   |
| Machining      | EC        | S700     | 0.1   | 600                | 162,103               |      |
| Machining      | EC        | S700     | 0.1   | 525                | 273,247               |      |
| Machining      | EC        | S420     | 0.1   | 400                | 482,800               |      |
| Machining      | EC        | S420     | 0.35  | 850                | 47,208                |      |
| Machining      | EC        | S420     | 0.35  | 2,000,000          | FR                   |      |
| Machining      | EC        | S960     | 0.1   | 550                | 5,000,000             | RO   |
| Machining      | EC        | S960     | 0.4   | 550                | 184,766               |      |
| Machining      | EC        | S420     | 0.1   | 405                | 238,820               |      |
| Machining      | EC        | S420     | 0.1   | 395                | 459,782               |      |
| Machining      | EC        | S420     | 0.1   | 385                | 5,000,000             | RO   |
| Machining      | EC        | S960     | 0.1   | 675                | 40,416                |      |
| Machining      | EC        | S960     | 0.1   | 600                | 57,746                |      |
| Machining      | EC        | S960     | 0.1   | 500                | 119,946               |      |
| Machining      | EC        | S960     | 0.1   | 425                | 195,187               |      |
| Machining      | EC        | S960     | 0.1   | 400                | 439,447               |      |
| Machining      | EC        | S960     | 0.1   | 375                | 688,105               |      |
| Machining      | EC        | S960     | 0.1   | 350                | 5,000,000             | RO   |
| Machining      | AC        | S960     | 0.1   | 400                | 436,289               |      |
| Machining      | AC        | S960     | 0.1   | 375                | 455,103               |      |
| Machining      | SP        | S960     | 0.1   | 675                | 110,138               |      |
| Machining      | SP        | S960     | 0.1   | 575                | 371,624               |      |
| Machining      | SP        | S960     | 0.1   | 500                | 569,034               |      |
| Machining      | HP        | S960     | 0.1   | 675                | 52,883                |      |
| Machining      | HP        | S960     | 0.1   | 500                | 148,652               |      |
| Machining      | HP        | S960     | 0.1   | 425                | 195,187               |      |
| Machining      | HP        | S960     | 0.1   | 400                | 439,447               |      |
| Machining      | HP        | S960     | 0.1   | 375                | 688,105               |      |
| Machining      | HP        | S960     | 0.1   | 350                | 5,000,000             | RO   |
| Plasma         | EC        | S960     | 0.1   | 375                | 124,730               |      |
| Plasma         | EC        | S960     | 0.1   | 550                | 979,709               | FR   |
| Oxy-fuel       | EC        | S960     | 0.1   | 600                | 61,361                |      |
| Oxy-fuel       | EC        | S960     | 0.1   | 500                | 118,550               |      |
| Oxy-fuel       | EC        | S960     | 0.1   | 450                | 285,638               |      |
| Waterjet       | EC        | S960     | 0.1   | 675                | 56,633                |      |
| Waterjet       | EC        | S960     | 0.1   | 575                | 186,933               |      |
| Waterjet       | EC        | S960     | 0.1   | 500                | 162,629               |      |
| Guillotine     | AC        | S960     | 0.1   | 500                | 51,968                |      |
| Guillotine     | AC        | S960     | 0.1   | 275                | 476,838               |      |

Note: Table A2 shows the fatigue test results performed in this study. The cutting method includes Machining, Plasma, Oxy-fuel, Waterjet, and Guillotine. The condition includes EDGES Chamfered (EC), As-Cut (AC), Shot Peened (SP), High Pressure custom parameters (HP), Run Out (RO) and Fretting failure (FR).
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