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Fatigue behavior of high strength steel S890Q containing thermally cut straight edges

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Abstract

This paper evaluates the effect of different thermal cutting methods on the fatigue life of high strength steel S890Q. The investigation covers flame, plasma and laser cutting methodologies, and specimens with rectangular sections and cut straight edges. The experimental program is composed of 30 specimens that were conducted to failure by applying fatigue cycles with a stress ratio (R) of 0.1 in a high frequency testing machine. The resultant best-fit S-N curves have been compared, revealing a better performance for laser cut straight edges. Moreover, the corresponding Eurocode 3 FAT class has been derived for each of the three cutting methods, resulting in FAT160 in all cases. This suggests that the use Eurocode 3 FAT125, which is the fatigue class currently provided for flame cut straight edges, is an overconservative assumption for thermally cut straight edges in steel S890Q, regardless of the thermal cutting technique being used (flame, laser or plasma).

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Keywords: fatigue; S890Q; flame; plasma; laser.

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1. Introduction

Most of the steel components used in different sectors (e.g., bridge construction, naval industry, etc) require specific shapes to allow their final assembly. Thus, steels need to be cut during the construction or fabrication. In this sense, some of the main alternatives used by the industry, which are analyzed in this paper, are normally referred to as thermal cutting processes, and include flame (oxy-fuel) cutting, plasma cutting and laser cutting.

These cutting techniques are based on melting the metal, and the most important difference between them is, precisely, the methodology to melt the metal. In flame cutting, a torch is used to heat metal to its kindling temperature; after that, a stream of oxygen is then trained on the metal, burning it into metal oxide that flows out of the kerf as slag. In plasma cutting, an inert gas is blown at high speed out of a nozzle; at the same time an electrical arc is formed through that gas from the nozzle to the surface being cut, turning some of that gas to plasma, which is sufficiently hot (in the range of 25.000ºC) to melt the metal being cut and moves sufficiently fast to blow molten metal. Laser cutting works by directing the output of a high power laser at the material to be cut; the material then either melts, burns, vaporizes away, or is blown away by a jet of gas, leaving an edge with a high quality surface finish.

After thermal cutting, the cut-edges of steel sheet components show a characteristic surface topography and a heat affected zone (HAZ) similar to that produced by welding processes. Durability requirements for safety-critical structures are significantly influenced by the conditions of the cut-edges produced during component manufacture [1]. Particularly, when investigating dynamic loading and fatigue failure, the quality of the surface has a considerable influence on the fatigue strength [2].

Flame cutting is the traditional thermal cutting process. However, this technology is in the process of being significantly replaced by plasma and laser cutting. These two modern cutting techniques allow manufacturers to increase productivity (and consequently reduce production costs) and to cut sheet components with very intricate geometries with high precision. These advantages are not normally reflected by current standards or design codes, which only take into account flame cutting process. This concern is particularly important for the fatigue codes that standardize the fatigue performance of components with straight cut-edges.

With all this, the main objective of this work is to analyze the fatigue behavior of thermally cut straight edges performed in structural steel S890Q, providing the corresponding Eurocode 3 [3] FAT classes (thus, S-N design curves) for plasma and laser cut edges.

Nomenclature

N	Number of cycles related to a constant stress range
$\Delta\sigma$	Nominal stress range
$\Delta\sigma_{limit}$	Fatigue strength
$\Delta\sigma_{run\ out}$	Stress range value below which no failure will occur in tests under constant
m	Slope of fatigue strength curve
logA	Intercept of the mean S-N curve

2. Material

The material chosen for this research is structural steel S890Q, supplied in rolled plates of 2000 mm x 2500 mm and 15 mm thickness. The selection criterion of this steel grade and thickness is its use in heavy loaded yellow goods and the manufacturing industry. It is a high strength steel in quenched and tempered conditions. The minimum yield stress is 890 MPa and it presents a microstructure with bainite and tempered martensite. Its chemical composition and some of the main mechanical properties are summarized in Table 1, while its microstructure is shown in Figure 1.

Table 1. Chemical composition and mechanical properties of steel S890Q.

Chemical composition (%)							
C	Si	Mn	P	S	Cr	Mo	Ni
0.16	0.34	1.26	0.012	0.002	0.26	0.47	0.03
Al	Cu	Nb	N	Sn	Ti	V	CEV
0.081	0.02	0.025	0.002	0.006	0.003	0.29	0.52

Mechanical properties

Young modulus (GPa)	Yield Strength (Mpa)	Tensile Strength (MPa)
205	940.2	999.0

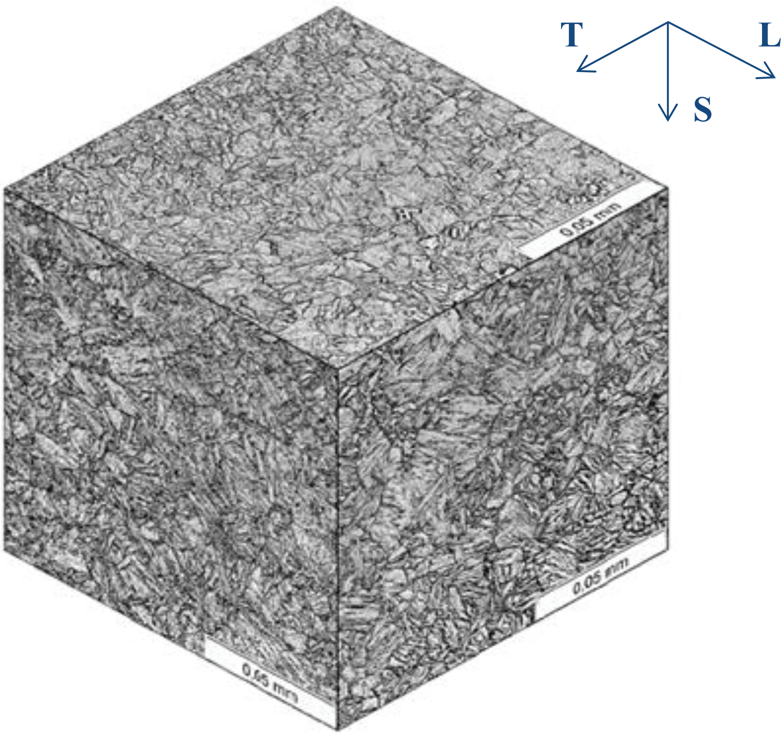

Fig. 1. Microstructure of steel S890Q. The sample was polished and etched with Nital 2%.

3. Thermal cutting processes

To perform a complete comparative study, the three thermal cutting processes have been analyzed. It was intended that the cut-edge quality was as much representative of real quality as possible, so the selected cutting parameters selected are the ones used by industry to cut the steel grade and thickness considered. The cutting parameters of each cutting processes are summarized in Table 2.

It should be noted that plasma cutting has used oxygen and air as plasma and as shielding gas, respectively, and laser cutting has used oxygen as assist gas. This election is very common in carbon steels given that the heat of the oxidizing exothermic reaction allows the cutting speed to be increased by 25%.

Concerning the cutting speed, it should be pointed out that the cutting speed provided by both plasma cutting (2.2 m/min) and laser cutting (1 m/min) is considerably higher than that provided by flame cutting (0.5 m/min).

Table 2. Cutting parameters.

FLAME CUTTING		
Parameter	Value	
Cutting speed	0.45-0.5 m/min	
Propane Pressure	0.4 bar	
Oxygen pressure	pre	1.2 bar
	working	6 bar
PLASMA CUTTING		
Parameter	Value	
Plasma arc current	200 A	
Plasma arc voltage	131 V	
Cutting speed	2.2 m/min	
Torch standoff	4.1 mm	
Plasma gas: Oxygen flow rate	pre	24 l/min
	working	69 l/min
Shielding gas: Air flow rate	pre	65 l/min
	working	28 l/min
Piercing time	0.6 s	
Piercing standoff	8.2 mm	
LASER CUTTING		
Parameter	Value	
Beam power	3600 W	
Cutting speed	1 m/min	
Nozzle diameter	1.7 mm	
Nozzle distance	0.5-0.8 mm	
Focus diameter	0.2 mm	
Focus position	On the top surface	
Assist gas	Oxygen	
Assist gas pressure	0.6 bar	

4. Experimental programme

In order to achieve the conditions specified by ASTM E739-10 [4] 10 specimens have been used to define the S-N curve for each cutting method. As a summary, 30 fatigue tests have been carried out. The specimen distribution is shown in Table 3.

Table 3. Specimen distribution.

Cutting method	No. of specimens
Flame cutting	10
Plasma cutting	10
Laser cutting	10

The specimens were thermally cut (flame, plasma or laser) parallel to the rolling direction, presenting the cut edges all along their length. The geometry of the specimens followed the specifications of [5] and it is shown in Figure 2. Here, it should be noted that the flame cut edges were not subsequently machined or ground, so they would be classified as FAT125 when following Eurocode 3.

Finally, the specimens were subjected to fatigue loading following the recommendations of ASTM E739 [4] and ASTM E466 [5]. All of them were subjected to constant amplitude loading until the final failure, the run-out level being established at 10^7 cycles. The tests were performed in a high frequency testing (resonance) machine with 400 kN of load capacity, the R ratio ($\sigma_{min}/\sigma_{max}$) being 0.1, which is adopted by many of the references found in the bibliography (e.g., [2,6,7]). The frequency varied between 77 and 79 Hz for the different specimens.

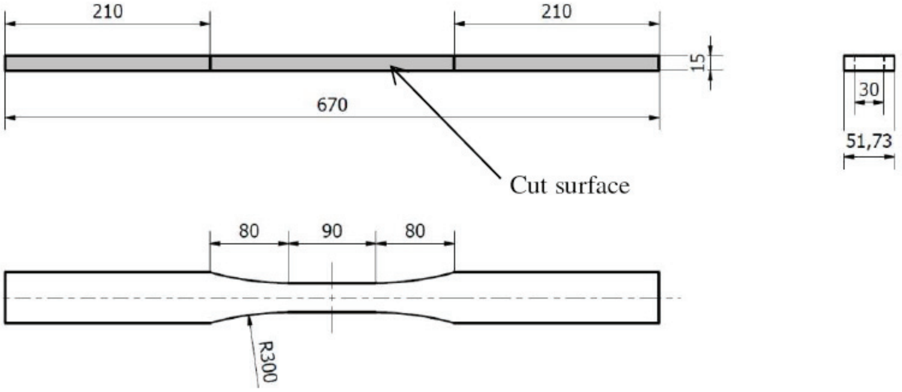

Fig. 2. Geometry of the specimens. Dimensions in mm.

5. Results and analysis

The S-N curve and the corresponding fatigue limit were obtained for each cutting method, the results being shown in Figure 3.

It can be observed that the fatigue performance in the finite fatigue range, and over $2\cdot10^5$ cycles of laser cutting straight edges is noticeably higher than those observed for flame or plasma processes, which present a similar fatigue behavior.

On the other hand, the resulting fatigue strength at the run out level is also higher for laser cuts, with flame cutting presenting the lowest performance.

The fatigue fitting parameters (least squares) are summarized in Table 4, assuming the following fitting equation:

$$\log N = \log A_{mean} - m \cdot \log \Delta\sigma \tag{1}$$

Regarding the location of the crack initiation sites, fatigue cracks in flame cut straight edges generally started in the lower edge of the cut, associated to the presence of dross adherence. In the case of plasma cuts, cracks initiated indistinctly from the upper or the bottom edge. Finally, in the case of laser cuts, all cracks initiated from the bottom edge of the cut.

Table 4. S-N curve fitting parameters.

Cutting method	$\log A_{mean}$	m	$\Delta\sigma_{limit}$
Oxy-fuel	16.67	4.09	324 MPa
Plasma	14.88	3.43	374 MPa
Laser	32.60	9.79	449 MPa

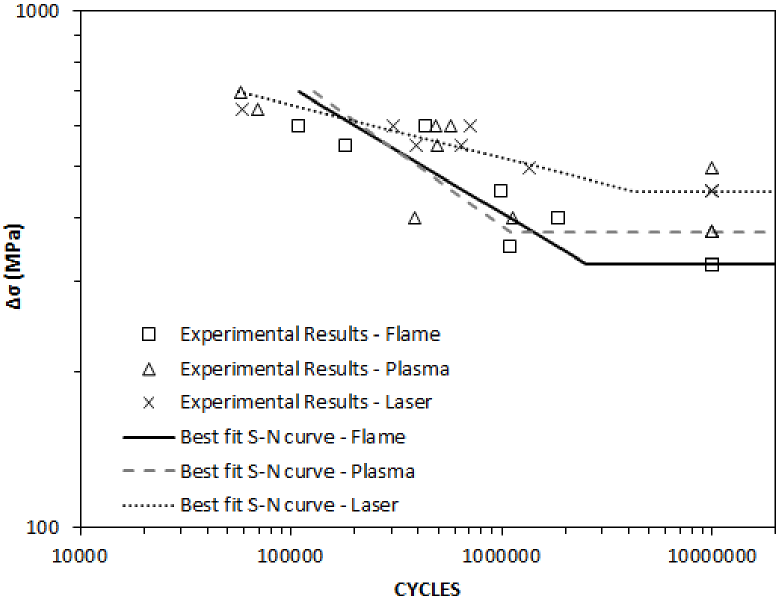

Fig. 3. Experimental results and resulting S-N curves (least squares)

The results obtained in the fatigue experimental programme were used to define the corresponding Eurocode 3 FAT classes. In this sense, the S-N curves provided by this standard present the following main characteristics:

- Each detail category is associated to a FAT class (e.g., FAT125 for flame cut straight edges), which represents the fatigue strength at $2\cdot10^6$ cycles.
- The curves have a slope (m) of 3 up to $5\cdot10^6$ cycles, whereas the slope is 5 from $5\cdot10^6$ cycles up to 10^8 cycles.
- For constant amplitude loading conditions, such $5\cdot10^6$ cycles correspond to the fatigue limit (CAFL, Constant Amplitude Fatigue Limit).
- For non-constant amplitude loading conditions, the curves present a cut-off at 10^8 cycles.

Eurocode proposes 14 detail categories, from FAT160 to FAT36.

Now, in order to define new Eurocode 3 FAT classes for a particular type of structural detail (here, thermally cut straight edges), a statistical procedure based on the one proposed by such a standard [3] will be followed in this research. The S-N curves follow equation (2):

$$\log N = \log A_{design,test} - 3\cdot\log\Delta\sigma \qquad (2)$$

where:

$$\log A_{design,test} = \log A_{mean,test} - k \cdot Stv \tag{3}$$

k value corresponds to the confidence level and the probability of survival included in Eurocode 3. It should be noted that the slope of the curves is fixed at 3.0, whereas the slope of the curves obtained above (through best fitting) may be very different (9.79 in the case of laser cutting).

Once $\log A_{design,test}$ has been calculated for each cutting method, the FAT design class is calculated with the equation (4):

$$FAT_{design,test} = 10^{\frac{(\log A_{design,testt})-(2\cdot 10^{6})}{3}} \tag{4}$$

In order to estimate the standardized FAT for each cutting method, the next lowest class proposed by Eurocode 3 [3] has been chosen. Regarding the results in Table 5, the three methods provide results well above the maximum fatigue class included in Eurocode 3 (FAT160). Therefore, although laser cuts have provided better fatigue performance than flame cuts and plasma cuts, the Eurocode 3 is not sensitive to such differential behavior.

Table 5. FAT classes.

Cutting method	$\log A_{mean\text{-}test}$	$\log A_{design,test}$	$FAT_{design,test}$	$FAT_{Eurocode}$
Oxy-fuel	13.751	13.309	217	160
Plasma	13.691	13.303	215	160
Laser	13.879	13.437	239	160

Finally, both the experimental results and the resulting fatigue design curves are shown in Figure 4. As mentioned above, it can be observed that the three thermal cutting methods are finally associated to FAT160. It can also be observed that FAT125 (the fatigue class provided by Eurocode 3 for flame cut straight edges) is overconservative for the experimental results obtained here. Even FAT160, the highest fatigue class provided by Eurocode 3, provides highly conservative results for high strength steel S890Q containing thermally cut edges, regardless of the cutting technique being used.

6. Conclusions

The experimental results obtained in this paper, showing the fatigue performance of thermally cut straight edges in steel S890Q, reveal that laser cuts generate better fatigue performance than that observed with flame cuts and plasma cuts. Particularly, the fatigue limit is noticeably higher for laser cuts.

The Eurocode 3 FAT125 curve, which is used in the design of flame (oxy-fuel) cut straight edges, is highly conservative for this particular high strength steel. This conservatism is still present if the maximum Eurocode fatigue class (FAT160) is considered.

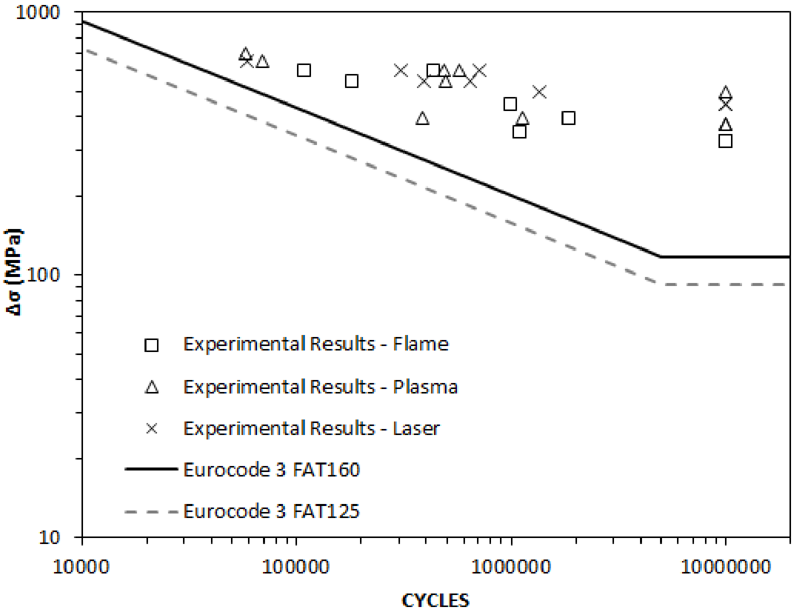

Fig. 4. Experimental results and comparison to Eurocode 3 S-N curves.

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