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Fatigue performance of thermally cut bolt holes in structural steel S460M

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Abstract

Current fatigue codes only consider the fatigue performance of drilled and punched holes, limiting the use of thermal cutting processes to produce bolt holes. This paper studies the fatigue performance of structural steel S460M plates containing thermally cut bolt holes. The research covers three thermal cutting methods: the traditional one (oxy-fuel cutting) and two more modern processes (plasma and laser cutting). Specimen geometry is defined by a rectangular cross section with a cut hole in the middle. All the specimens were conducted to failure by applying fatigue cycles, the stress ratio (R) being 0.1. The corresponding S-N curve and fatigue limit were obtained for each cutting method. Fatigue results have been compared with previous researches on fatigue performance of drilled and punched holes, and with the predictions provided by current fatigue standards, analyzing the possibility to extrapolate their S-N curves, focused on drilled and punched holes, to thermally cut holes.

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Keywords: Oxy-fuel cutting; Plasma cutting; Laser cutting; Fatigue; S-N curve.

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1. Introduction

The majority of steel components used in different sectors such as construction, the naval industry or the manufacturing industry require specific shapes to enable their final assembly. In this case, thermal cutting processes are the most widely used manufacturing techniques for obtaining specific geometries from rolled steel plates.

Within thermal cutting processes, the main alternatives used by the industry are named flame cutting (or oxy-fuel cutting), plasma cutting and laser cutting. They are based on melting the metal to cut it, but the most important difference between them is the methodology to melt the metal. In oxy-fuel 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].

Oxy-fuel 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.

Regarding the production of bolt holes, current manufacture codes often state that holes shall only be made by drilling or punching. For example, the Specification for Structural Joints Using High-Strength Bolts [3] defines that thermally cut holes produced by mechanically guided means are permitted in statically loaded joints and, for cyclically loaded joints, thermally cut holes may be permitted if approved by the Engineer of Record. However, many constructors do not choose to exercise this clause because there are no data to show how these holes perform under fatigue loading. So far, steel structure fabricators have had to perform multiple material-handling steps to accommodate standard drilling and punching operations. The validation of thermally cut holes for cyclically loaded joints would allow multiple processes to be performed at one time, reducing the amount of handling, thus leading to reduced fabrication costs. Furthermore, some fabrication standards, particularly North American codes (i.e., Alberta Specification for Bridge Construction [4]), define some extremely conservative limitations of cut-edge hardness, which cannot be reached by the two alternatives of cutting process or even (in many occasions) by oxy-fuel cutting.

The aim of this research is, on the one hand, to compare the fatigue performance of the three thermal cutting methods concerning cut holes; and, on the other hand, to evaluate the possibility of extrapolating the standards S-N curves to thermally cut holes.

Nomenclature

N	Number of cycles related to a constant stress range
$\Delta\sigma$	Nominal stress range
$\Delta\sigma_{run\ out}$	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 S460M, 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 parts of bridges, in the building sector, yellow goods and manufacturing industry. The S460M steel is a thermomechanical rolled steel with a low carbon equivalent value. Its chemical composition and some of the main mechanical properties are summarized in Table 1. It presents a hypoeutectic microstructure which is shown in Figure 1 (a). It is typically formed by polygonal ferrite (white grains in the optical micrograph) and perlite blocks. A banded microstructure is observed, which is very frequent in rolled plates. It should be noted that central segregations are clearly visible.

Table 1. Chemical composition and mechanical properties of S460M.

Chemical composition (%)							
C	Si	Mn	P	S	Cr	Mo	Ni
0.12	0.45	1.49	0.012	0.001	0.062	0.001	0.016
Al	Cu	Nb	N	Sn	Ti	V	CEV
0.048	0.011	0.036	0.005	0.002	0.003	0.066	0.39

Mechanical properties		
Young modulus (GPa)	Yield Strength (Mpa)	Tensile Strength (MPa)
205	484.1	594.4

a) b)

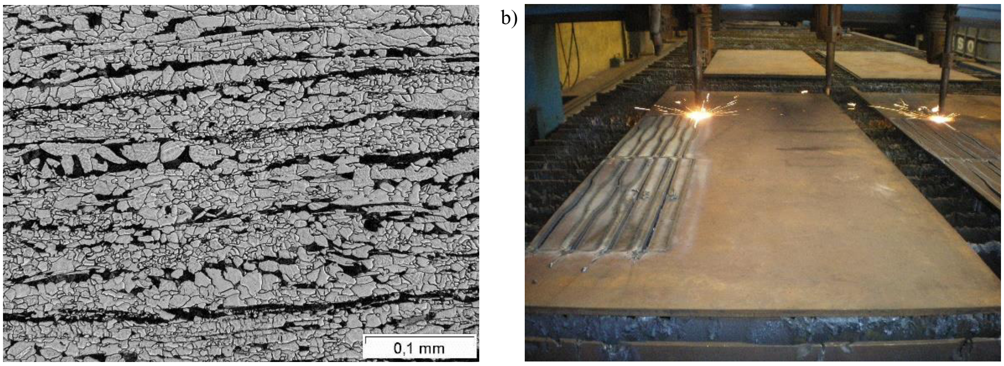

Fig. 1. (a) Ferritic-perlitic microstructure of S460M; (b) Fabrication of the specimens flame cut.

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 fabrication process of the flame cut specimens can be observed in Figure 1 (b). 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 to the cutting speed, it is straightforward to notice 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 oxy-fuel cutting (0.5 m/min).

Table 2. Cutting parameters.

OXY-FUEL 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 program

In order to achieve the conditions stated by ASTM E739-10 [5] 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
Oxy-fuel cutting	10
Plasma cutting	10
Laser cutting	10

The specimen with a centered hole and machined straight edges has been designed to simulate the presence of a bolt hole in a real component. The geometry, shown in Figure 2, is defined by a rectangular cross section and a cut hole in the middle of the specimen, the hole diameter being equal to the plate thickness and the width being three times the hole diameter [6]. Further, the piercing point is located at the end of the hole diameter parallel to the load direction, given that this is a singular point in which the material disturbance is significantly higher.

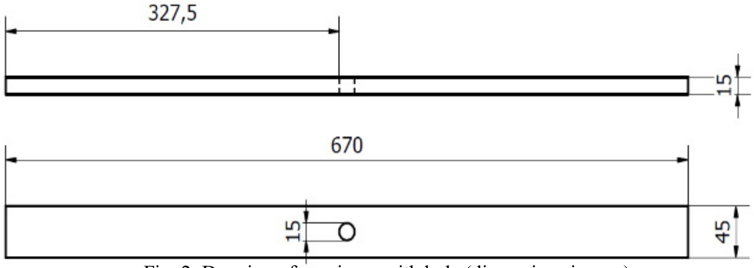

Fig. 2. Drawing of specimen with hole (dimensions in mm).

Both the S-N curves and the fatigue limit are the parameters selected to evaluate the fatigue behavior. Fatigue tests were conducted using a high frequency testing machine with a 400KN capacity, which can carry out fatigue tests at the specimen resonance frequency. This frequency oscillates between 77 and 79 Hz for the specimens selected. Referring to the definition of the rest of the fatigue test parameters, the stress ratio (R) selected is equal to 0.1, which is adopted by most of the references found in the bibliography (i.e., [2]). The stress ranges have been defined taking into account that the maximum stress of the sinusoidal cycle cannot be higher than the steel yield stress. Finally, a number of cycles equal to 10^7 has been adopted to define the fatigue strength in the infinite fatigue life [7].

5. Cut-hole characterization

In order to evaluate the quality of thermally cut holes, the surfaces affected have been analyzed. Figure 3 shows a general view of the thermally cut holes.

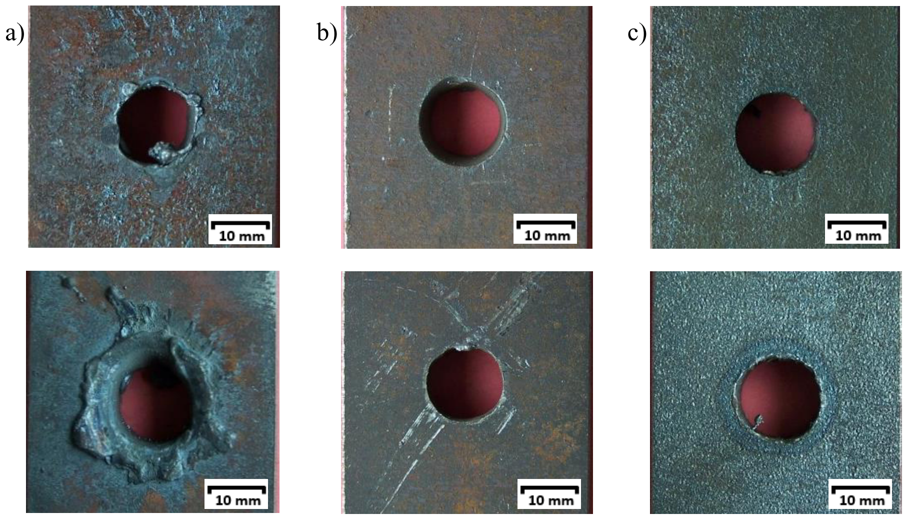

Fig. 3. Appearance of thermally cut holes: (a) Oxy-fuel; (b) Plasma; (c) Laser.

The top images belong to the top surface of each specimen, while the bottom images are from the bottom surface of each specimen. During the cutting processes melted material is ejected from the specimen through bottom surface. The oxy-fuel cut hole is characterized by the adherence of some dross at the bottom.

The main characteristic of the plasma and laser cut hole is that they do not show dross adherence and the geometry is somewhat better than that provided by oxy-fuel cutting. On the other hand, according to the standard EN 1090 [8] thermally cut holes should meet the same quality requirements (roughness) as straight edges. Due to the fact that the rugosimeter can only be used in straight planes, and in this case draglines are vertical and located in the edge of the hole, the surface roughness cannot be measured. Despite this inconvenient, a qualitative evaluation of the surface quality has also been done.

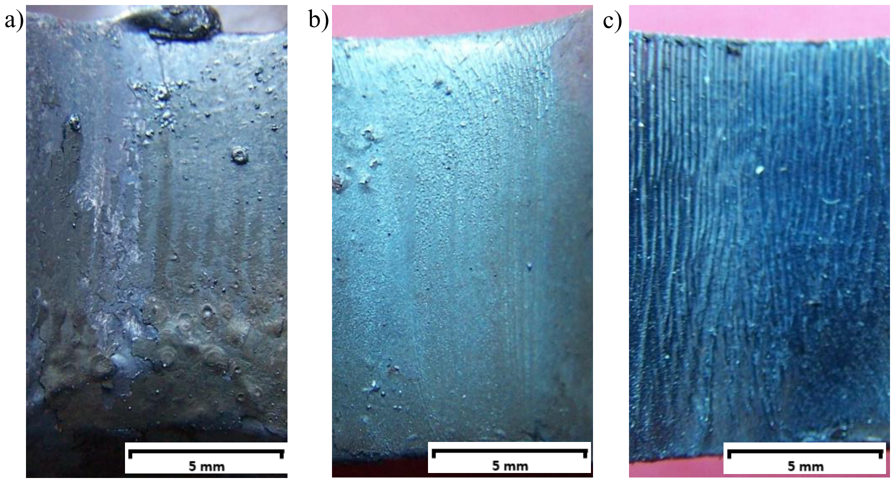

Fig. 4. Appearance of surfaces of thermally cut holes: (a) Oxy-fuel; (b) Plasma; (c) Laser.

The physical appearance of the surfaces of thermally cut holes is shown in Figure 4. The oxy-fuel cut holes displays a smooth surface. The formation of surface dross at the bottom of the cut edge is clearly visible and the bottom edge has also been rounded. It can be observed that the plasma cut-surface has the best quality, with the absence of defects and very shallow draglines. Finally, the quality of the laser cut surface is the worst and it is characterized by the presence of predominant surface draglines, particularly near the top of the cut edge.

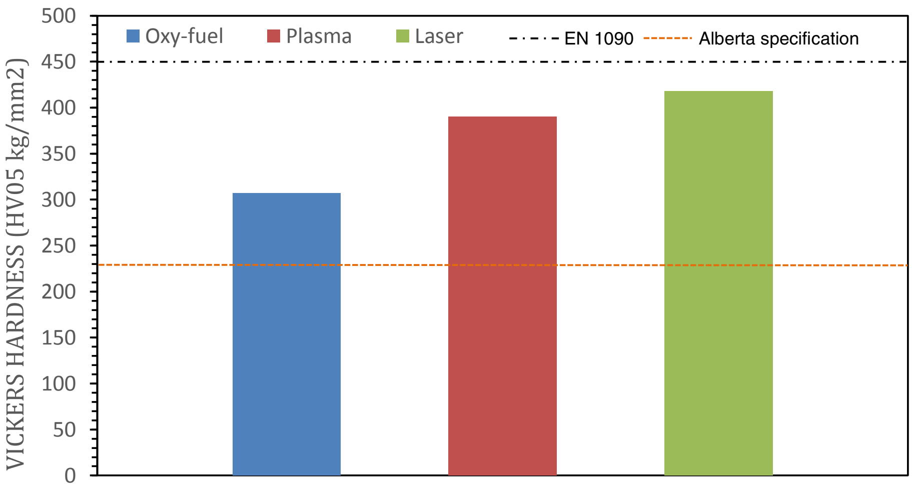

Fig. 5. Maximum hardness.

In order to complete the cut edge characterization, Figure 5 compares the maximum hardness measured in the three thermally cut-edges with the hardness limit defined by two representative standards of USA (Alberta Specification for Bridge Construction [4]) and EU (EN 1090 [8]). The results show a similar value for plasma and laser cutting methods, which is higher than the result obtained by oxy-fuel cutting. The maximum hardness in all cases do not exceed the limit value defined by [8]. However, none of them meet the requirement of maximum hardness proposed by [4], which seems to be extremely conservative.

6. Results and analysis

6.1. Comparison between the different cutting methods

To study the fatigue performance of thermally cut bolt holes, it is necessary to evaluate the influence of the different thermal cut processes. The corresponding S-N curve and fatigue limit were obtained for each cutting method, the results being shown in Figure 6.

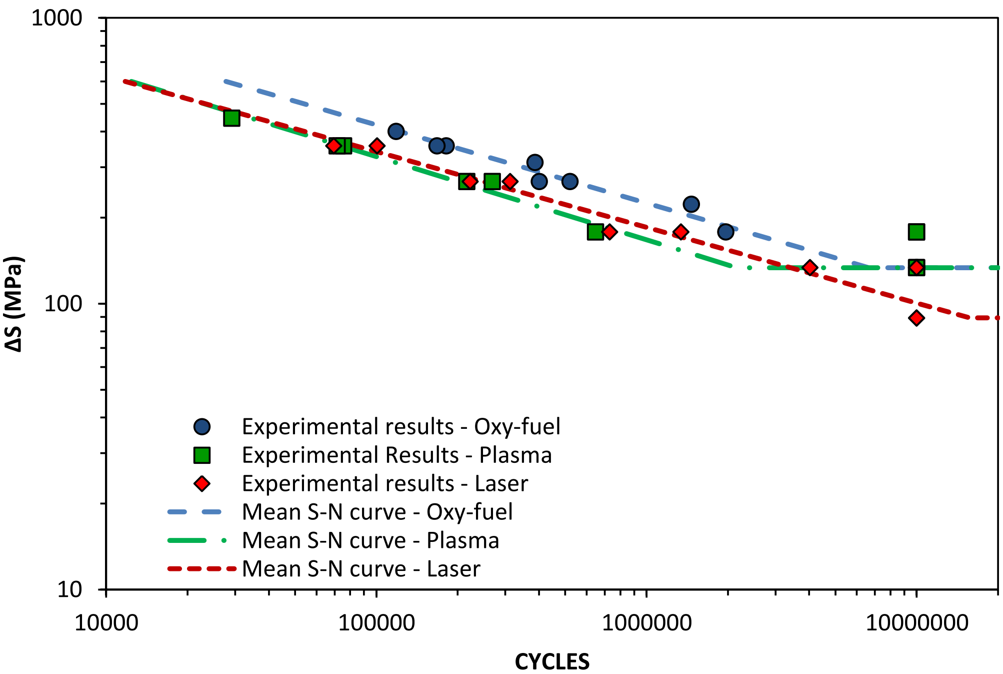

Fig. 6.Experimental results and mean S-N curve corresponding to the three thermal cutting processes.

It can be observed that the fatigue performance in the finite fatigue range of oxy-fuel cutting holes is slightly higher than those observed for plasma or laser processes, which present a similar fatigue behavior.

On the other hand, the fatigue strength at the run out level is quite similar for oxy-fuel and plasma, 134MPa, and higher than the fatigue limit measured for laser, 90 MPa. It should also be added that the best fit S-N curves have approximately the same value of the slope, between 3.5 and 4.0.

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

$$\log N = \log A_{mean} - m \cdot \log \Delta\sigma \quad (1)$$

Table 4. S-N curve fitting parameters.

Cutting method	$logA_{mean}$	m	$\Delta\sigma_{limit}$
Oxy-fuel	14.59	3.65	134 MPa
Plasma	13.64	3.51	134 MPa
Laser	14.56	3.78	90 MPa

Regarding the locating crack initiation, fatigue cracks for laser cut holes start in the cut surface, favored by their roughened surfaces. Nevertheless, holes cut by oxy-fuel and plasma processes have a high quality surface with a limited number of defects and presents initiation points not only at the cut surface but also at the top or bottom edges. Figure 7 shows the crack surface in an oxy-fuel cut hole, with the initiation point in the point edge.

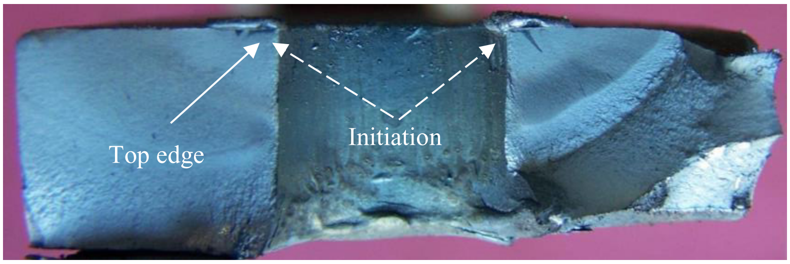

Fig. 7. Fatigue crack due to superficial dross on top edge of an oxy-fuel cut hole.

6.2. Comparison between thermal methods and traditional methods

Up to now, bolt holes are generally manufactured by traditional processes such as drilling or punching. In order to compare these methods with thermal methods, the experimental results that were obtained in the European project COLDFOSS [6] were considered, in which the fatigue performance of drilled and punched holes was evaluated. Steel grade (S460M), plate thickness, specimen geometry and stress ratio (R=0.1) were exactly the same as those selected in this research, so the fatigue results can be compared. Figure 8 compares the S-N curves that have been obtained before for thermally cut holes with the experimental results corresponding to drilled and punched holes.

If Figure 8 is analyzed, the experimental results reflect that the fatigue resistance of the specimens containing a punched hole is lower than any other result obtained for specimens with a thermally cut hole. In addition, punched holes are observed to show a similar value as Laser cut holes in the fatigue strength at the run out level. However, this value displays a significant drop in comparison with the other thermally cut holes: punched holes lower the plasma and oxy-fuel cut hole fatigue limit by 50%, 44 MPa. Comparing thermally cut holes S-N curves with drilled holes fatigue results, it is straightforward to see that the plasma and laser cut hole have a similar fatigue resistance than the drilled hole within the fatigue life. The oxy-fuel cut holes results show a better fatigue performance than the drilled holes in this range. Finally, comparing the values obtained for the fatigue strength at the run out level of thermally processes with drilled holes, the laser cut holes exhibit a drop by nearly 100 MPa at the run out level in comparison with the drilled holes. Oxy-fuel and plasma cutting methods have a slightly lower result at the run out level than drilled holes.

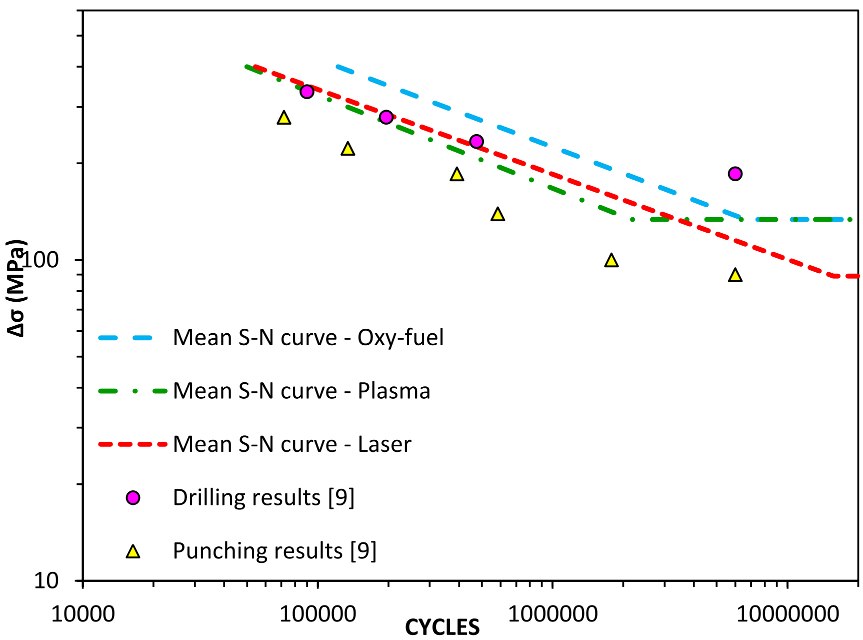

Fig. 8. Comparison between thermally cut holes and drilled and punched holes.

6.3. Comparison with standards

The nominal stress approach is the established approach for fatigue design and assessment of steel components adopted by most standards. The nominal stress approach is based on S-N curves. Structural details are designed based on the nominal stress range in the connecting members rather than on the local concentrated stress. The fatigue design procedure is based on associating the detail under consideration with a specific category.

The most important fatigue standards that are used in Europe are Eurocode 3 [9], BS 7608:1993 [10], IIW [11] and DNV-RP-C203 [12]. With the aim of validating the present research, the standards selected are Eurocode 3 [9], a reference standard in all Europe, and BS 7608:1993 [10], the probably most updated fatigue code which is used in many industrial applications. Besides, both standards cover the steel grade (S460M) and plate thickness (15mm) studied in the present paper.

One of the main advantages of BS 7608:1993 [10] is that each design class is characterized by a mean and a design S-N curve corresponding to the nominal probability of failure selected. The expression proposed to define both S-N curves is shown in equation (2):

$$\log N = \log A_{mean-Class} - d \cdot \sigma_{Class} - m \cdot \log \Delta\sigma \quad (2)$$

where:

- $\log A_{mean\text{-}Class}$ is the intercept of the mean S-N curve of the design class adopted.
- σ_{Class} is the standard deviation of the design class selected.
- m_{Class} is the slope of the design class adopted.
- d is the coefficient which considers the nominal probability of failure based upon an assumed normal distribution. d=0 corresponds to 50% nominal probability of failure (mean S-N curve), and d=2 is the typical value to define standard design S-N curves and corresponds to 2.3% nominal probability of failure.

In order to evaluate the fatigue performance of a component with thermally cut bolt holes, the situation represented here by the specimens with the hole would not be possible, because BS7608 [10] does not include this fatigue detail. For this reason, the fatigue category used to evaluate drilled holes is adopted to be compared with the experimental results:

- Class D: "Small hole: (may contain bolt for minor fixtures). Hole drilled or reamed. Minimum distance between center of hole and plate edge: 1.5 x hole diameter".

BS7608 [10] includes a procedure to validate a design S-N curve based on a new experimental programme. Initially the assumption is made that the new test results form part of the same population as that used to determine the design S-N curve (this is called the null hypothesis). Then, the hypothesis is used to show that, under this assumption, it is very unlikely (at a specified significance level) that the new results would be as high as they are. This is the basis for regarding the null hypothesis as implausible, and for accepting the alternative hypothesis that the new results actually belong to a population having longer fatigue lives than the main database. Thus, the use of the selected class would be valid.

Assuming a 5% significance level, the condition for accepting the alternative hypothesis is:

$$\log A_{mean-test} \geq \log A_{\lim it} \tag{3}$$

$$\log A_{\lim it} = \log A_{mean-Class} + \frac{1.645 \cdot \sigma_{Class}}{\sqrt{n}} \tag{4}$$

where $\log A_{mean-test}$ is the intercept of the mean S-N curve fitted from the experimental results (assuming the same slope m of the design class that is validated), and n is the number of tests.

Consequently, the mean curve fitted to the test results is expected to be on or above the following S-N curve:

$$\log N = \log A_{mean-Class} + \frac{1.645 \cdot \sigma_{Class}}{\sqrt{n}} - m_{class} \cdot \log \Delta\sigma \tag{5}$$

In terms of required endurance, this corresponds to achieving a mean S-N curve that is at least 1.3 times higher than the mean class curve, or 3.42 times higher than the class design curve, which lies $2\sigma_{Class}$ below the mean.

The standard BS7608 [10] proposes design class D for drilled or reamed holes. The aim is to determine whether or not it is possible to apply this design class to steel components with thermally cut holes. According to this Standard, the slope of the best fit S-N curves is 3. So as to validate the application of the design Class D to thermally cut holes, $\log A_{mean\text{-}test}$ values have been checked against $\log A_{limit}$ values. As shown on Table 5, class D is only applicable for oxy-fuel cut holes. Nevertheless, this class could not be extrapolated to plasma and laser cut holes. In these cases, class F and E could be used respectively.

Table 5. Intercepts to compare.

Cutting method	$\log A_{mean\text{-}test}$	$\log A_{mean\text{-}Class}$	$\log A_{limit}$	Class
Oxy-fuel	12.987	12.601	12.722	D
Plasma	12.559	12.237	12.383	F
Laser	12.722	12.517	12.673	E

Finally, Figure 9 compares the S-N curves provided by design classes D, E and F of BS7608 [10] with the experimental results obtained in specimens on S460M with a thermally cut hole. For the classes chosen, it can be stated that the fatigue design values are safe enough in the finite life region and the fatigue limit is highly conservative, comparing with the fatigue strength at the run out level.

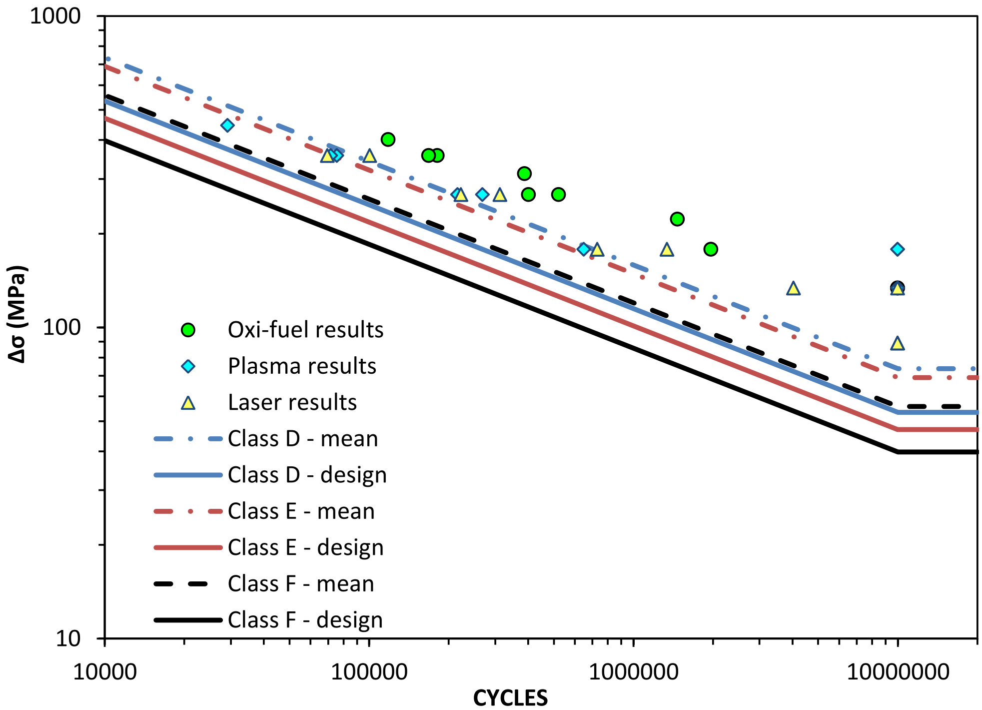

Fig. 9. Comparison between experimental results and BS7608 [7] S-N curves.

On the other hand, Eurocode 3 [9] has been used as well to complete the present research. This standard does not evaluate the fatigue performance of a component with thermal cut-holes, the situation represented here by the specimens with the hole. For this reason, the fatigue category used to evaluate drilled and punched holes is adopted to be compared with the experimental results:

- Eurocode 3 - FAT 90 [9]: "Structural element with holes subject to bending and axial forces". The industrial process is not specified again, but it can be deduced that the fatigue category is applied to drilled holes. Eurocode 3 - FAT 90 [9] corresponds with BS 7608:1993 – Class D [10], which states "Hole drilled or reamed".

The aim is to verify if this curve can be extrapolated to thermal cut-holes. The S-N design curves have taken into account the following considerations of Eurocode 3 [9]: slope with m=3 and calculation for a 75% confidence level of 95% probability of survival for log N. The expression proposed to define S-N curves is shown in equation (6):

$$\log N = \log A_{design,test} - 3 \cdot \log \Delta\sigma \tag{6}$$

where:

$$\log A_{design,test} = \log A_{mean,test} - k \cdot Stv \tag{7}$$

k value corresponds to the confidence level and the probability of survival included in Eurocode 3 [9]. However, the value of the standard deviation (Stv) for each FAT class is not given by this European standard. For the calculations it has been taken the value from BS7608 [10] for drilled holes, Class D (0.2095).

Once $\log A_{design,test}$ has been calculated for each cutting method, the FAT design class is calculated with the equation 8:

$$FAT_{design,test} = 10^{\frac{(\log A_{design,testt}) - (2 \cdot 10^6)}{3}} \tag{8}$$

In order to estimate the standardized FAT for each cutting method, it has been chosen the immediately lower class proposed by Eurocode 3 [9]. Regarding the results in Table 6, the only method on which FAT 90 would be adequate is laser process. In addition, for oxy-fuel cut holes, class FAT 90 would be conservative, being class FAT 112 more compliant for this cutting method. The plasma cut holes fatigue result is under FAT 90, so class FAT 80 has been proposed for that kind of cut holes.

Table 6. FAT classes.

Cutting method	$\log A_{mean\text{-}test}$	$\log A_{design,test}$	$FAT_{design,test}$	$FAT_{Eurocode}$
Oxy-fuel	12.987	12.549	121	112
Plasma	12.559	12.103	86	80
Laser	12.722	12.276	98	90

Finally, both the experimental results and the fatigue design curves are shown in Figure 10. For the classes chosen, it can be analyzed in the same way as it was stated for BS standard: the fatigue design values are safe in the finite life region and the fatigue limit is highly conservative, comparing with the fatigue strength at the run out level.

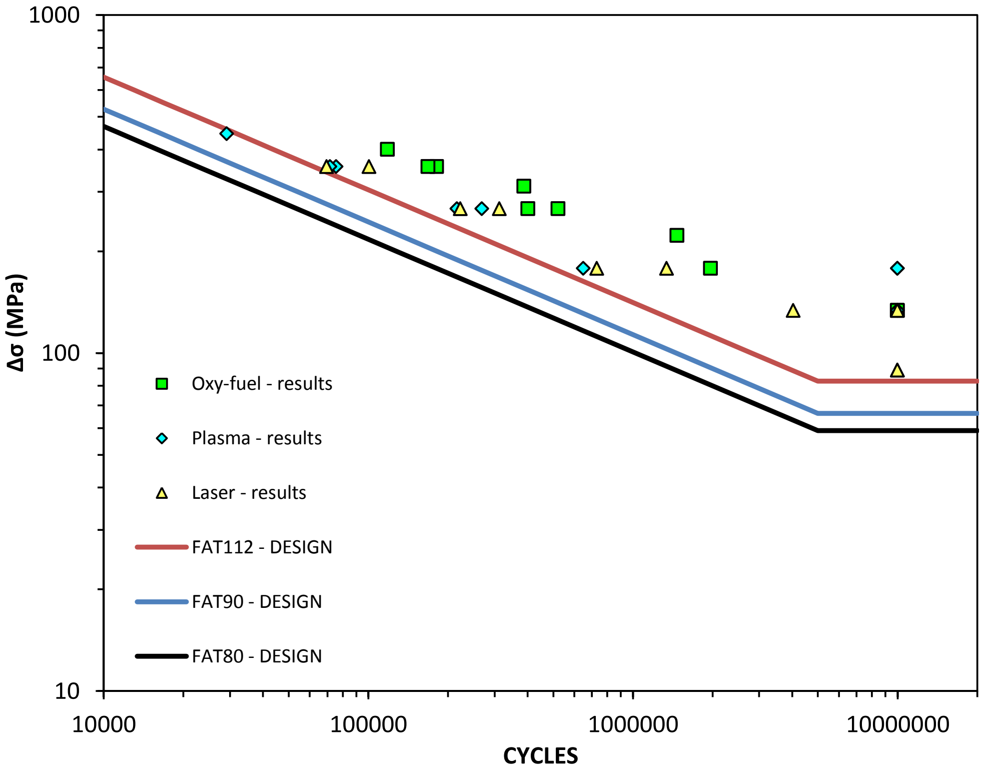

Fig. 10. Comparison between experimental results and Eurocode 3 [6] S-N curves.

7. Conclusions

Analyzing specimens from structural steel S460M plate that have thermally cut bolt holes, it can be concluded that oxy-fuel cut holes display a better fatigue performance in the finite fatigue life region than those with a plasma or a laser cut hole. Particularly, this latter one reduces considerably the fatigue limit.

Moreover, the fatigue performance of thermally cut holes has also been compared with the behavior of drilled and punched holes. It has been observed that thermally cut holes improve the fatigue performance of the punched holes and displays a quite similar fatigue performance to that observed in drilled holes. At the run out level, the highest fatigue strength has been obtained for drilled holes, and the lowest for laser and punched holes, which present a similar results.

The BS7608 – design class D curve, which is used in the design of drilled and reamed components, could be adequate for oxy-fuel cut holes. According to this standard procedure, plasma and laser cut holes require using more conservative classes, F and E respectively.

Finally, it has also been demonstrated that the fatigue category proposed by Eurocode 3 for drilled holes, FAT 90 (corresponding with BS7608 – Class D), is adequate for laser cut holes. Regarding oxy-fuel results, FAT 112 may be used for this method. Plasma cut holes do not meet FAT 90 requirements, so it has been proposed to be analyzed as FAT 80.

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