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Fatigue behaviour and BS7608 fatigue classes of steels with thermally cut holes

S. Cicero [a,*], T. García [a], J.A. Álvarez [a], A. Klimpel [b], A. Bannister [c], A. Martín-Meizoso [d]

[a] LADICIM (Laboratory of Materials Science and Engineering), University of Cantabria. E.T.S. de Ingenieros de Caminos, Canales y Puertos, Av/Los Castros 44, 39005 Santander, Spain
[b] Politechnika Slaska - Sutil, Akademica 2ª, 44-100 Gliwice, Poland
[c] Tata Steel, Swinden Technology Centre, Moorgate, Rotherham S60 3AR, UK
[d] Centro de Estudios e Investigaciones Técnicas de Guipúzcoa (CEIT), c/ Manuel de Lardizábal 15, 20018 San Sebastián, Spain

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ABSTRACT

Thermal cutting includes oxy-fuel, plasma and laser cut technologies. These cutting methods generate cut surfaces and material transformations that determine the final fatigue behaviour of cut structural components. The BS7608, like most of the standards, does not provide fatigue design curves for thermally cut holes, restricting its scope to drilled or reamed holes. This limits the use of oxy-fuel, plasma and laser technologies in numerous engineering applications. This research analyses the effect of the three thermal cutting methods on the fatigue behaviour of cut holes performed on a wide range of structural steels (S355M, S460M, S690Q and S890Q). The experimental fatigue results obtained have been used to generate the corresponding BS7608 design classes, which have also been validated by comparing them to experimental data found in the literature.

1. Introduction

Numerous steel structural components are cut during their manufacture, fabrication and construction. To do this, a range of cutting processes can be used depending on physical determinants, such as thickness, or technological and economic factors (e.g., number of components, structural detail, final application…). The main alternatives used by the industry are normally referred to as thermal cutting processes, and include oxy-fuel cutting, plasma cutting and laser cutting. The most important difference between these thermal cutting processes is the methodology used to melt the metal: oxy-fuel cutting uses a torch to heat metal to its kindling temperature; then, a stream of oxygen is 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 and, simultaneously, an electrical arc is formed through the gas from the nozzle to the surface being cut, turning some of that gas to plasma. This plasma is sufficiently hot (in the range of 25.000 °C) to melt the metal being cut and moves sufficiently fast to blow molten metal; finally, laser cutting works by directing the output of a high power laser at the material to be cut. Then, the material either melts, burns, vaporizes away, or is blown away by a jet of gas, leaving an edge with a high quality surface finish.

When subjected to static loading, the mechanical properties of structural steels do not depend significantly on the quality of the cut surface. However, when sustaining dynamic loading, the quality of the surface has a considerable influence on the material fatigue strength [1]. The topography of the cut surface and the material microstructure are modified as a result of thermal cutting processes, which also introduce residual stresses in the adjacent material [2,3].

There are numerous examples of the increasing use of laser and plasma-arc cutting in the bridge [4,5], ship [6,7], yellow goods [3] and defence equipment [8] sectors, driven by the numerous advantages of these cutting techniques. However, fatigue standards such as BS7608 [9], Eurocode 3 [10] or AASHTO LRFD Bridge-Design Specifications [11] do not cover thermal cutting methods in many applications.

For example, if it was necessary to evaluate the fatigue performance of a steel component with straight thermally cut-edges, the fatigue class corresponding to oxy-fuel cut edges would be the only option when using BS7608 [9]. The authors have recently published a paper [12] with the intention of covering this gap by proposing BS7608 fatigue classes for plasma and laser cut straight edges.

Likewise, when dealing with the production of bolt holes, it is common that standards only cover holes made by drilling or punching (e.g., [9–11]). More precisely, if it was necessary to evaluate the fatigue performance of a component with thermally cut holes, this would not be possible when following BS7608 [9], because it does not include this fatigue detail. This standard only refers to:

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

* Corresponding author.
E-mail address: ciceros@unican.es (S. Cicero).

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Table 1
Chemical composition of steels S355M, S460M, S690Q and S890Q (wt%). CE: carbon equivalent.

	S355M	S460M	S690Q	S890Q
C	0.14	0.12	0.15	0.16
Si	0.35	0.45	0.40	0.34
Mn	1.35	1.49	1.42	1.26
P	0.015	0.012	0.005	0.012
S	0.008	0.001	0.001	0.002
Cr	0.021	0.062	0.02	0.26
Mo	0.002	0.001	0.002	0.470
Ni	0.021	0.016	0.16	0.03
Al	0.03	0.048	0.056	0.081
Cu	0.015	0.011	0.01	0.02
Nb	0.025	0.036	0.029	0.025
N	0.004	0.005	0.006	0.002
Sn	0.002	0.002	0.002	0.006
Ti	0.002	0.003	0.003	0.003
V	0.004	0.066	0.058	0.29
CE	0.37	0.39	0.43	0.52

Others, such as the Specification for Structural Joints Using High-Strength Bolts [13], permit thermally cut holes when this is approved by the Engineer of Record. However, in practice, this clause is generally not applied because there are no data to show how these holes perform under fatigue loading. Furthermore, some fabrication standards, (e.g., Alberta Specification for Bridge Construction [14]), define noticeably conservative hardness limitations which cannot generally be reached by thermal cutting processes.

With all this, the main objective of this work is to analyse the fatigue behaviour of thermally cut holes performed in structural steels, providing the corresponding BS7608 fatigue classes.

2. Materials

The fatigue classes of structural details refer to particular geometries (e.g., straight cut edges, cut holes, rolled plates, butt welds, etc.), independently of the specific structural steel being used. Thus, the corresponding S-N design curves must generate accurate, safe predictions for the whole range of structural steels. Hence, the experimental programme gathered here comprises four different steels covering a wide range of mechanical properties. These steels are the same as those used by the authors in [12] in the analysis of thermally cut straight edges:

- S355M [15]: thermomechanical rolled fine grain structural steel that presents a ferritic-pearlitic microstructure. It has a minimum yield stress of 355 MPa, something that corresponds to low-medium strength. The steel was supplied in a 15 mm thick steel plate.
- S460M [15]: thermomechanical rolled fine grain structural steel that presents a ferritic-pearlitic microstructure. Its minimum guaranteed yield stress of 460 MPa corresponds to medium strength. The steel was supplied in plates of two different thicknesses (15 mm and 25 mm) with the same chemical composition.
- 690Q [16]: this is a high strength steel in quenched and tempered conditions. Its minimum yield stress is 690 MPa and it presents a microstructure with bainite and tempered martensite. This steel was supplied in a 15 mm thick steel plate.
- S890Q [16]: this is also a high strength steel in quenched and tempered conditions. In this case, the minimum yield stress is 890 MPa and it also presents a microstructure with bainite and tempered martensite. This steel was also supplied in a 15 mm thick steel plate.

Table 2
Mechanical properties of the steels being analysed. YS = yield stress (R_{eH} for steels S355M and S460M, and $R_{p0.2}$ for steels S690Q and S890Q); R_m = ultimate tensile strength; ε_{max} = strain under maximum load.

Steel	YS (MPa)	R_m (MPa)	R_e/R_m	ε_{max} (%)
S355M	426.6	559.2	0.76	15.8
S460M – 15 mm	484.1	594.4	0.81	14.4
S460M – 25 mm	465.5	596.3	0.78	14.5
S690Q	776.2	833.7	0.93	7.0
S890Q	940.2	999.0	0.94	6.0

Table 3
Cutting parameters.

Oxy-fuel cutting			
		15 mm	25 mm
Cutting speed (mm/min)		400–450	350–400
Torch diameter (mm)		1	1.5
Propane flux (l/min)		6	8
Oxygen flux (l/min)			
	Preheating	20	25
	Cutting	35–40	65–70
Plasma cutting			
		15 mm	25 mm
Arc current (A)		200	200
Arc voltage (V)		131	143
Cutting speed (mm/min)		2200	1100
Torch standoff (mm)		4.1	5.1
Oxygen flow rate (l/min)			
	Arc initiation	24	24
	Cutting	69	69
Air flow rate (l/min) (shielding gas)			
	Arc initiation	65	65
	Cutting	28	28
Piercing time (s)		0.6	1
Piercing standoff (mm)		8.2	10.2
Laser cutting			
		15 mm	25 mm
Beam power (W)		3600	5600
Cutting speed (mm/min)		1000	900
Nozzle diameter (mm)		1.7	1.7
Nozzle distance (mm)		0.5–0.8	1.0
Focus diameter (mm)		0.2	0.63
Focus position		Plate surface	
Assist gas (oxygen) pressure (bar)		0.6	0.6

Table 1 gathers the chemical composition of the four steels, while Table 2 shows the corresponding tensile properties at room temperature [17].

3. Experimental programme

The aim of the experimental programme is to show the influence of thermal cutting methods (oxy-fuel, plasma and laser) on the fatigue behaviour of structural steels containing cut holes obtained when using the cutting parameters used by industry. At the same time, there is no intention to provide the optimum cutting parameters for each thermal cutting method. In practice, these cutting parameters do not vary very much and depend more on the economics of the cutting process than on the final quality of the cuts (provided a minimum quality of such

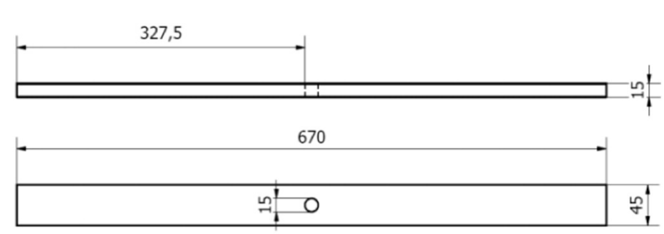

Fig. 1. Drawing of the 15 mm thick specimens (dimensions in mm).