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Definition and validation of Eurocode 3 FAT classes for structural steels containing oxy-fuel, plasma and laser cut holes

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ABSTRACT

When the fatigue behaviour of structural components containing holes is analysed, Eurocode 3 only considers the fatigue performance of drilled holes, limiting the use of thermal cutting processes to produce, for example, bolt holes. This paper studies the fatigue performance of structural steel plates containing thermally cut holes. The research covers three thermal cutting methods: the traditional one (oxy-fuel cutting) and two more modern processes (plasma and laser cutting). An experimental program composed of 150 fatigue specimens has been completed, combining four steels (S355M, S460M, S690Q and S890Q), the three thermal cutting methods and two different thicknesses (15 mm and 25 mm). The S–N results obtained have been used to estimate the corresponding Eurocode 3 FAT classes, which have finally been validated by comparing them to additional experimental data found in the literature.

1. Introduction

On many occasions, the standardised geometries (e.g., plates) in which the steel products are provided by the mills need to be modified in order to obtain the final geometry of the specific structural component. Some of the main alternatives used by the industry, which are analysed in this paper, are normally referred to as thermal cutting processes, and include oxy-fuel cutting, plasma cutting and laser cutting. Oxy-fuel cutting is the traditional thermal cutting process. However, this technology is in the process of being replaced by plasma and laser cutting. These two modern cutting techniques allow manufacturers to increase productivity (and consequently reduce production costs) and to cut structural components with very intricate geometries with high precision. 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 that 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 surface. However, when sustaining dynamic loading, the quality of the surface has a considerable influence on the material fatigue strength [1]. The cut surface topography and the material microstructure are modified as a result of thermal cutting processes, which also introduce residual stresses in the material adjacent to the cut surface [2–7].

When dealing with the production of bolt holes, it is frequent that codes and standards just cover holes made by drilling or punching (e.g., [8–10]). Others offer additional possibilities with few practical applications. For example, the Specification for Structural Joints Using High-Strength Bolts [11] establishes 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, in practice, this clause is generally not applied because there are no data to show how these holes perform under fatigue loading. Moreover, some fabrication standards, principally North American codes (e.g., Alberta Specification for Bridge Construction [12]), define noticeably conservative hardness

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limitations which cannot generally be reached by thermal cutting processes.

Additionally, until now, steel structure manufacturers have had to perform multiple material-handling steps to adapt standard drilling and punching operations. The knowledge and definition of the fatigue behaviour of thermally cut holes would allow these techniques to be used, reducing the amount of handling, thus leading to reduced fabrication costs.

With all this, the main aim of this research is to analyse the fatigue performance of the three thermal cutting methods concerning cut holes, defining the corresponding FAT classes of Eurocode 3 [9], and analysing the possibility of using the S–N curves defined by Eurocode for drilled holes.

2. Materials and methods

2.1. Materials

The definition of the different FAT classes for structural steels depends on the particular geometry of the structural detail being analysed (e.g., straight edge, cut holes, butt welds, etc.), but it does not generally depend on the particular steel being used. Consequently, design S–N curves (FAT classes) must provide accurate safe predictions for the whole range of structural steels. Hence, the experimental program gathered here comprises four different steels:

- S355M (EN 10025-4 [13]): this is a thermomechanical rolled fine grain structural steel that presents a ferritic-pearlitic microstructure. It presents a minimum guaranteed yield stress of 355 MPa, corresponding to low-medium resistance (TGS8: Technical Group Steel: Steel products and applications for building, construction and industry. Internal report. Research Fund for Coal and Steel Unit (RFCS). European Commission). The steel was supplied in a 15 mm thick steel plate.
- S460M (EN 10025-4 [13]): this is also a thermomechanical rolled fine grain structural steel that presents a ferritic-pearlitic microstructure (Fig. 1). Its minimum guaranteed yield stress of 460 MPa corresponds to medium–high resistance (TGS8: Technical Group Steel: Steel products and applications for building, construction and industry. Internal report. Research Fund for Coal and Steel Unit (RFCS). European Commission). The steel was supplied in plates of two different thicknesses (15 mm and 25 mm) with the same chemical composition.
- 690Q (EN 10025-6 [14]): 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 (EN 10025-6 [14]): 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 (Fig. 1). This steel was also supplied in a 15 mm thick steel plate.

Table 1 presents the chemical composition of the four steels, whilst Table 2 shows the tensile properties at room temperature of the different steels, obtained experimentally following EN ISO 6892-1 [15]. It can be observed that the minimum required yield stress is satisfied in all cases.

2.2. Experimental methods

This aim of this work is not to provide the optimum cutting parameters for each thermal cutting method, but rather to determine the fatigue performance of thermally cut holes obtained when using the cutting parameters used by industry. In practice, these 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 cuts is guaranteed) (see Table 3).

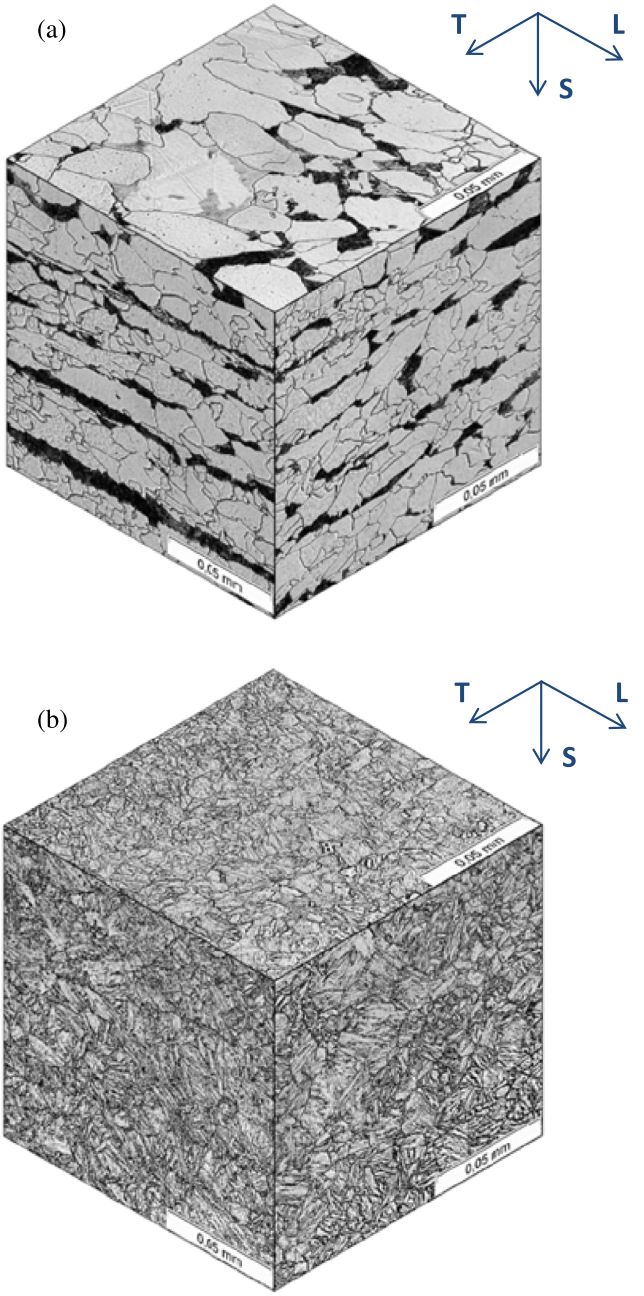

Fig. 1. Microstructure of steels S460M (a) and S890Q (b). The samples were polished and etched with Nital 2%.

150 fatigue specimens were cut from the 5 steel plates, 10 for each combination of material (5, considering that steel S460M presents two different thicknesses) and cutting method (oxy-fuel, plasma and laser). The specimens were designed to simulate the presence of a bolt hole in a real component. They all present a centred hole and machined straight edges. The geometry, shown in Fig. 2, is defined by a rectangular cross section and a cut hole in the middle of the specimen, the diameter of the hole being equal to the plate thickness and the width being three times the