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# Characterization of heat affected zones produced by thermal cutting processes by means of Small Punch tests

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ABSTRACT

Thermal cutting processes introduce changes in the heat affected zone (HAZ), which can lead to a significant reduction of the service life of components. In order to assess their influence, different cutting processes have been analysed on a structural steel. The characterization of the reduced volumes of HAZ posed a major challenge, since conventional techniques require greater pieces of material. Alternative miniature techniques had to be applied, such as Small Punch tests and microhardness measurements, from which the material tensile properties and fracture toughness values have been obtained. Results show that oxyfuel HAZ exhibit minor alterations of the material, while plasma cutting seems to improve the material tensile properties and fracture toughness. Besides, the suitability and accuracy of the Small Punch technique for similar applications can be derived from this work, turning it into a promising candidate to perform integrity assessments of actual components.



## 1. Introduction

Cutting processes constitute an essential part of the manufacturing process of steel components. They enable the transformation of the metal pieces provided by steel mills (with standard dimensions) into other pieces with specific geometries for each kind of component.

Among the different cutting techniques that are currently available, thermal cutting processes play an outstanding role. They are widely employed in the shipbuilding industry, boiler making industry, etc., or even in the building trade. Their main advantages are their versatility and the high production rate that can be reached by means of their use. However, they also have some drawbacks, since they introduce changes in the heat affected material, due to the high temperatures needed to achieve the cutting process. These modifications turn the material in these areas into a new one, with a different microstructure and different properties to the ones of the base material.

Generally, under static loads, these changes do not have any influence on the behaviour of the components. However, under dynamic loads, the heat affected zone can reduce in a significant way their service life [1], due to the resulting surface topography, the generated residual stresses and the microstructural changes produced by the cutting process. The effects of thermal cutting methods in both straight edges and cut holes may be found in literature (e.g., [2,3]).

The aim of this work is to assess the influence of three different thermal cutting processes on the properties of the resulting heat affected zone (HAZ). In order to achieve this, three cutting methods have been chosen: oxyfuel, plasma cutting and laser cutting. The first one, traditionally employed by the industry, is based on the formation of iron oxides, with lower melting points than the base material, which are removed by the high pressure oxygen cutting jet as they start to flow. Plasma cutting achieves the material melting by reaching temperatures up to 30.000 °C by means of an electric arch, in a point between the component and the cutting torch. Lastly, laser cutting reaches the melting temperature of the material by directing the output of a high power laser to the material to be cut.

Even if plasma and laser cutting methods can attain higher productive capacities and better quality cut-edges than oxyfuel, it is common that these improvements are not reflected by the current standards. On the other side, when these advantages are taken into account, excessively conservative design parameters are usually applied, since these are only based in the cutting qualities obtained by the oxyfuel method [4–7]. Therefore, an accurate characterization of these cutting methods is critical, in order to reduce the current conservatism.

In this work, in order to evaluate the influence of the cutting methods in the HAZ properties, the following points have been

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analysed: microstructure, hardness, tensile properties and fracture toughness. The latter pose a major challenge, since their evaluation cannot be performed by means of conventional methodologies, which require a large volume of material in order to perform the characterization. In this case, it was impossible due to the limited thickness of the HAZ. Consequently, the use of the Small Punch technique, firstly introduced in the 80s at the MIT to characterize irradiated materials [8], is proposed to achieve this goal. Basically, the Small Punch test is a miniature test, which consists on applying a mechanical load to a 0.5 mm-thickness test piece by means of a punch. On account of the small size of the specimens, it can be regarded as a non-destructive test, and it is able of evaluating the material properties in local zones of the components. Furthermore, this technique has been in continuous development since its beginnings for various applications [9–11], and it has already been accepted in the nuclear and aerospace industry [12]. As a result, these characteristics turn this technique into an effective solution in order to achieve the targets of this work.

Briefly, the influence of three different cutting methods on a structural steel has been analysed, evaluating changes in the tensile properties, obtained by means of Small Punch tests and hardness tests, and the modification of fracture toughness values, obtained by means of Small Punch tests, as well as microstructural and hardness changes.

## 2. Materials and procedures

### 2.1. Material

In this paper, a S640M steel has been analysed, supplied in rolled plates of 15 mm thickness. It is a structural steel widely employed in bridge construction, building trade, boiler making industry or industrial machinery. With a low carbon equivalent value, it is a hot rolled steel, whose chemical composition and mechanical properties are summarized in Table 1 [13], and whose banded microstructure, formed by polygonal ferrite (white grains in the optical micrograph) and perlite blocks, is shown in Fig. 1.

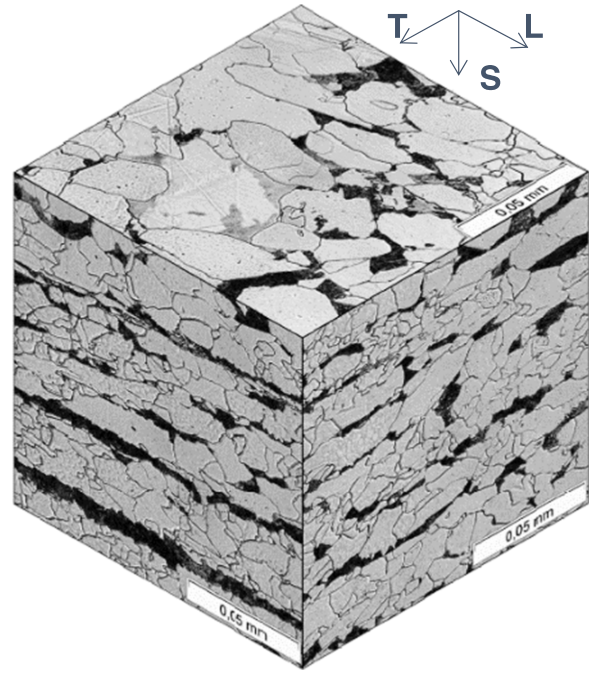


**Fig. 1.** Microstructure of S460M Steel, which is hypoeutectoid and formed by polygonal ferrite (in light grey) and perlite blocks with a grains size of 6.18 μm, according to ASTM E112 [14].

### 2.2. Thermal cutting processes

In order to accurately simulate the actual conditions, the cutting processes have been performed with the parameter settings that are widely employed in the steel industry for the given steel grade and plate thickness [4–7]. These are summarized in Tables 2, 3 and 4 for the three regarded cutting methods.

### 2.3. Hardness assessment

To evaluate hardness changes of the material, Vickers HV05 microhardness tests have been performed according to the recommendations of ASTM E384 [15], given the reduced thickness of the heat affected zones. Hardness profiles have been obtained at the middle of the plate thickness, always taking into account the minimum 3-diametre distance to the cutting surface.

Regarding the laser cutting process, its hardness profile has been obtained at the lower part of the cutting area in order to achieve a better characterization, given the small size of the HAZ in this case, which is slightly wider a the former position.

### 2.4. Tensile properties evaluation

Tensile properties have been obtained from Small Punch tests, according to the recommendations of CWA 15627 [16], and also from the hardness values, by applying the proposed formulation in BS7910 for the parent metal [17].

In this case, the major challenge was posed by the attainment of Small Punch specimens. These have to be obtained as close as possible to the cutting surface, always taking into account that a final 0.5 mm homogeneous thickness had to be achieved, as can be seen in Fig. 2. In order to guarantee such conditions, 10 × 10 mm square samples have been cut at the centre of the HAZ surface, parallel to this same surface, 1 mm-thick, with a precision cut-off machine. The samples have then been polished on the HAZ surface side until guaranteeing a flat surface, removing the minimum amount of material, and then ground on the other side to achieve the final thickness required for the Small Punch test. By using this procedure, an accurate assessment of the HAZ can be achieved, given that the SP samples have been obtained as closed as possible to the cutting edge.

Once the samples were prepared, they have been tested according to the Code of Practice [16] and the results have been evaluated by applying the methods proposed in [18–20].

**Table 1**
Chemical composition and mechanical properties of the S460 M Steel.

| 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 moudulus (GPa) | | Yield strength (MPa) | | | Tensile strength (MPa) | | |
| 205.35 | | 484.1 | | | 594.4 | | |

**Table 2**
Oxyfuel parameters.

| Parameter | Value | |
|---|---|---|
| Cutting speed | 0.45–0.5 m/min | |
| Propane pressure | 0.4 bar | |
| Oxygen pressure | Pre | 1.2 bar |
| | Working | 6 bar |