ABSTRACT

In designing, dimensioning of welded structures, also selecting the welding technology we strive to minimize the deformations of structures during manufacturing. Even with the maximum observance of technological discipline, in many cases, the deformation of our products beyond the margin of tolerance is often unavoidable. Therefore, we need to straighten our structures with a mechanical or thermal source of heat.

Nowadays, steel construction and machine manufacturing companies prefer to use flame, (or other hot) levelling technologies to recover and ensure the shape and dimensional stability of parts, welded structures. There was a need for exact specification of the technology parameters before, but due to the introduction of the EN 1090 standard series, it is becoming more and more important to follow and document the steps of flame straightening.

The warm straightening is an important part of the production life cycle of the structure, therefore, the operation of the physical phenomena of the technology must be known must be experienced in the process, as well as the mechanical and micro-structure changes of the materials which used. Regarding to the new developed advanced materials (e. g. Q+T and TM high strength steels) in many cases there is not enough experience of the possible behaviour of the material. At the moment there is very little scale of literature on flame straightening of steels, especially for high strength steels. For this reason, it is advisable to prove the applicability of flame straightening with preliminary technological tests. The following summary shows how different materials are affected in different ways by flame straightening technology through a series of experiments on several material qualities.

1. INTRODUCTION

In this paper we examined mainly welded I-beams from two kind of high strength Q+T steels (S690QL, S960QL) in different thicknesses, regarding to the different flame straightened work pieces, what structural and hardness changes have occurred. It is noted that we have also performed our research in comparison with normalized steels (S355J2+N, S460N), but the results are not described in this case due to quantitative constraints. The full results of our studies are described in [1] literature.

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In the case of Q+T high-strength steels, which application of technologies involving heat input (e.g. thermal cutting, welding, flame-straightening) should be carried out very carefully. The need for caution in relation with the more brittle behaviour, than conventional steels.

2. THE PRINCIPAL OF FLAME STRAIGHTENING

The welding and related technologies, which are accompanied by heat, leaving stresses in the material, which try to decompose in the form of deformation or deflection during cooling. Flame straightening is based on the physical principle that metals expand as a result of heating and shrinks as a result of cooling.

Figure 1. shows the principle of flame straightening. If a non-clamping rod is heated, it expands and then shrinks to its original length after cooling. However, if you do this on a clamped rod, blocking free deformation, it will not be able to expand in the longitudinal direction, resulting pressure stresses. If more heat transferred into the material, in higher temperature, it is cause high stresses, which eventually reaches the yield strength of the material. Than plastic deformation occurred, causing „swelling” of the rod. After cooling, the plastic deformation is retained and the rod shrinks longitudinally. [2][3][4]

![Fig. 1 The heating of rod without blocking (left) and inhibited in deformation (right) and their consequences [2]](image)

3. EFFECT OF FLAME STRAIGHTENING ON MATERIAL PROPERTIES

Based on the rate of heat input to the flame straightening can be divided into two cases. According to the first case, only the surface layer of the structure is heated. Thus amount of heat input is low compared to the material thickness of the work piece, with rapid cooling of the material. However, when the entire cross-section of the work piece is heated locally, a high heat input and a low cooling rate can be expected.[5]
The most important aspect of the mechanical properties of the materials is the temperature and cooling conditions of the flame straightening. For steels structural changes resulting from the straightening can be divided into two types, depending on the straightening temperature: [5]
- straightening below eutectic temperature (T ≤ 700 °C)
- straightening over eutectic temperature (T > 700 °C)

### 3.1. Allowed heating temperatures

CEN/TR 10347: 2006 "Guidelines for the processing of structural steels" technical report sets out recommendations for the maximum temperature of each type of steel in the case of flame straightening with different techniques.

<table>
<thead>
<tr>
<th>Delivery condition</th>
<th>Short term, surface heating</th>
<th>Short term, full cross section heating</th>
<th>Long term, full cross section heating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized, unalloyed steels to 355 MPa strength</td>
<td>≤ 900 °C</td>
<td>≤ 700 °C</td>
<td>≤ 650 °C</td>
</tr>
<tr>
<td>TMCP steels to 460 MPa strength</td>
<td>≤ 900 °C</td>
<td>≤ 700 °C</td>
<td>≤ 650 °C</td>
</tr>
<tr>
<td>TMCP steels between 500-700 MPa strength</td>
<td>≤ 900 °C</td>
<td>≤ 600 °C</td>
<td>≤ 550 °C</td>
</tr>
<tr>
<td>Q+T high strength steels (eg S690QL, S960QL)</td>
<td>≤ generally at 20 °C under the tempering temperature of the selected material (around 530 °C)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Recommendation for maximum flame straightening temperatures [4]

### 4. DETAILS OF FLAME STRAIGHTENING EXPERIMENT

Our experiment is illustrated by examining a further thought-out version of a classic flame straightening exercise. The task is to correct distortions of welded I-beams from different material qualities by flame straightening. In our experiment, we investigated how flame straightening affects the properties of each raw material, depending on the thickness of the plate.

During the experiment, the following materials and the following plate thicknesses (t-mm) was used for the given material (welded I-beams):
- S355J2+N t8 and t20
- S460N t10 and t30
- S690QL t12 and t20
- S960QL t8 and t25

The main dimensions of the I-beams are shown in Figure 2.
4.1 Flame Straightening of I-beams

The efficiency of flame straightening depends on, that the material how high temperature be heated (the previously described thermal expansion is significantly depending on the temperature). It is important to avoid overheating of the material, thereby change its properties and the risk of local surface melting due to the high excessive temperatures. During the experiments the significance of the effect of excessive heat intake was examined as well. In addition, the effects of cooling modes (compressed air, water spray) used in many industrial applications have been investigated, which are used to reduce the cooling time of the structures and increase the levelling efficiency. This may affect the heated areas negatively (as a surface hardening technology) with particular attention to overheating of the material. The effects of the above-mentioned events are not well known, however, in the manufacture of welded structures, the structural changes of the parts affected by local heating may be important to the mechanical properties of the structure.

To determine these changes, the following flame straightening temperatures and cooling modes were determined for the welded I-beams identified during the experiment:

- A: normal heating (750-800 °C), spontaneous air cooling,
- B: overheating (1000-1200 °C), spontaneous air cooling,
- C: normal heating (750-800 °C), continuously cooled with compressed air,
- D: normal heating (750-800 °C) cooled by water jet (Fig. 3).

To determine the straightening temperature, we have used CEN/TR 10347:2006 technical report. In case of Q+T high strength steels we deviated slightly from the recommended value due to the fact that, on the basis of practical experience, the structures can be better straightened. To the heating of thin plates (under t=12mm) we have used a specially designed 3-head acetylene-oxygen burner with 1:1 flame ratio per burner (Fig. 4). For thick plates we have used a high performance one headed, multi-flame acetylene-oxygen burner (Fig. 5).
5. EFFECT OF FLAME STRAIGHTENING METHODS ON THE HARDNESS OF MATERIALS

The hardness measurements of metallographic sections were made from the straightened work pieces, which plan based on Fig. 6. for each piece, 5 measurements were made in the following places:

- heated area (HAZ) close to the surface and far away from that (HAZ 1, HAZ2),
- in the weld metal, in the HAZ of welding, and in the base metal.
Based on the measurement results of Q+T high strength steels, there were observed great differences between the different straightened samples. Differences occurred especially with S960QL samples.

Regarding to the hardness measurements, the following general statements can be made:

**S690QL samples (Fig. 7):**
- between t=12mm and t=20mm samples, there were significantly different hardness values,
- regarding to t=12mm sample, higher hardness values could be measured in the heated zone compared to the base material, but there was no significant difference between each mode,
- in the case of t=20mm, only the water-cooled method showed a slight increase in hardness between the HAZ and base metal.

**S960QL samples (Fig. 8):**
- in case of t=8mm sample, the hardening methods showed a hardness increase compared to the base material, especially after water cooling, where an increase of ~ 25% was achieved,
- regarding to t=25mm thickness sample, there was a softening compared to the hardness of the base material, except for the water cooling after straightening, where also a ~ 25% increase occurred.

Based on our experience, due to overheating the specimens, there was no significant changes in hardness.
6. EVALUATION OF MEASURED HARDNESS VALUES FOR COMPLIANCE

Flame straightening is considered to be related to welding technology, therefore the results obtained for hardness measurement were evaluated according to MSZ EN ISO 15614-1, Table 7.4.5., which giving the maximum HV10 hardness values for steel groups according to ISO / TR 15608 (Table 2.).

<table>
<thead>
<tr>
<th>Steel groups acc. to ISO/TR 15608</th>
<th>Without heat treatment</th>
<th>With heat treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;a&lt;/sup&gt;, 2&lt;sup&gt;b&lt;/sup&gt;</td>
<td>380HV</td>
<td>320HV</td>
</tr>
<tr>
<td>3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>450HV</td>
<td>380HV</td>
</tr>
</tbody>
</table>

<sup>a</sup> – if hardness measurement needed
<sup>b</sup> - \( R_{eb} > 890 \) N/ \( \text{mm}^2 \) In the case of steels with the minimum required flow limits, the values must be set separately

Table 2. Maximum allowed HV10 Vickers hardness values [6]

Taking into account the conditions in the table above, for S960QL 8 and 25 mm steels in Figure 8, the hardness values of "D" samples (water-cooled) are higher than the value of 450 HV which is allowed for main group 3.
Using this standard, due to hardness variations, water cooling after flame straightening causes the non-compliance of the technology. Our measurements clearly demonstrate that the use of water cooling is by no means recommended and it may be extremely dangerous due to the integrity of the structure.

7. EFFECT OF FLAME STRAIGHTENING ON MATERIAL MICROSTRUCTURE

Below the limitations of the content we presented only the typical results of microstructures „B” (overheated with normal cooling) and „D” (normal heating with water cooling) straightening modes. Based on the test results of each straightening methods, it concluded that between "A" and "C" mode there is no large differences can be observed in the case of microstructure and hardness.

7.1 Comparison of S690QL t=12mm straightening modes

7.1.1 Straightening with overheating („B”)

Fig. 9. shows the microstructure of base metal, which contains homogeneous, uniformly distributed ferrite and bainite. Similarly, in the "b" part of the same figure (part of HAZ far from the surface). In the "c" part of this figure (near-surface HAZ) affecting by the flame, growing of the primary grains is perceptible, within which the fine distribution of the bainite grains is formed.

Fig.9. Microstructure pictures of overheated S690QL t=12mm sample base metal (a), HAZ of heating far from the surface (b) and in the surface (c)

7.1.2 Water cooling after normal heating („D”)

The „a” part of Figure 10 shows the microstructure of base metal which is also ferritic-bainitic structure. In the "b" part of the same figure it can be observed that the heating causes approx. 10% ferrite appears in the microstructure and refinement of the base material occurred.
The image "c" shows that the microstructure of HAZ, which close to the surface differs from the other flame-straightening methods. Based on the results of the hardness measures, the microstructure is probably being bainite and/or martensitic.

7.2 Comparison of S960QL $t=8\text{mm}$ straightening modes

7.2.1 Straightening with overheating (,,B’’)

The „a” part of Figure 11 shows a fine and homogeneous distribution of martensite-bainite structure. Image „b” shows the ferrite transformation of base metal structure (about 70% ferrite), where softening is occurred, which is supported by the HV10 hardness measurement (283HV). The „c” part of the figure, which was made close to the surface of the heating, shows that the primary grain sizes is extremely increased. In addition, the high temperature causes a reduction in ferrite content (20%). After cooling, the microstructure may consist of ferrite and bainite and/or martensite.
7.2.2 Water cooling after normal heating ("D")

The "a" part of Fig. 12 shows same structure likewise regarding to Fig 11. On the "b" image a small amount of ferrit can be seen (~8%), in addition, there is some grain refinement compared to the base material. It is noticeable on the image "c" that after flame straightening the water cooling caused significant grain refinement and restructuring compared to the base material. The formed microstructure can be bainite or martensite, which is also confirmed by hardness measurement.

![Fig. 12. Microstructure pictures of water-cooled S690QL t=12mm sample](image)

Fig. 12. Microstructure pictures of water-cooled S690QL t=12mm sample base metal (a), HAZ of heating far from the surface (b) and in the surface (c)

7.3 Comparison of S960QL t=25 mm straightening modes

On the basis of the hardness measurements of the samples of each straightening method, it can be concluded that a significant difference occurred only in the water cooled sample. Fig 13. "b" and "c" part can be seen in the HAZ of heating a different microstructure compared to the base material, which can be granular bainite.

![Fig. 13. Microstructure pictures of water-cooled S690QL t=25mm sample](image)

Fig. 13. Microstructure pictures of water-cooled S690QL t=25mm sample
base material (a), HAZ of heating far from the surface (b), and in the surface (c)

8. SUMMARY

As our experiments have confirmed, flame straightening can have a significant impact on the properties of the materials, so its implementation needs more attention. Using improper technology can cause critical changes in the material structure that can already cause problems with less high-strength steels.

Intensive cooling applied during flame straightening (often used to improve the effect of time saving and straightening) can cause hardness increasing and microstructure changes that may be critical to the integrity of the structure.

On this basis, it is strongly recommended to avoid rapid cooling. In contrast, air cooling has not been shown to have a significant effect on the material structure, so its use in industrial practice is conceivable. Similarly, to cooling, the temperature is also an important parameter. Although the superheated samples didn’t achieve a significant increase in hardness, their grain structure was too coarse-grained, which obviously impaired the toughness properties of the material. This can be particularly critical for high strength steels.

Another source of troubles in high-strength steels is that, during heating, the carefully tempered martensitic / bainite microstructure, due to the rapid cooling after the austenitic transformation, the material also leads to a rigid / hard structure.

The rigid, hard micro structure in the heating zone of heating affects the structures unfavourably in terms of the formation and spread of cracks. In brittle microstructure the cracks can start and spread easily. From the point of view of the fatigue destruction of the structures, the heat zone of flame straightening is also unfavourable due to the surface position.

REFERENCES: