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*Dedicated to Professor Dr. rer. nat. Dr.-Ing. e. h. Winfried Dahl on the occasion of his $70^{th}$ birthday*

# Flame straightening of thermomechanically rolled structural steel

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Shape control by local heating is often used in processing of structural steels. Experience has proven that normalised steels are suitable for this operation if it is carried out properly. During the last years thermomechanically controlled rolled (TM) steels have been developed. For their application it was necessary to investigate the response of this steel type to flame straightening. Two essential processing conditions must be considered: heating limited to the surface and heating of the full material thickness. The temperatures were varied from 650 to 950 °C by different heat inputs. Tensile and Charpy impact tests have proven that within this temperature range the investigated steels (S355ML -EN10113) were not affected. For conditions of wedge heating a drop in the mechanical properties was observed if the temperatures exceeded 650 °C. Both limits 950 °C in line heating and 650 °C in wedge heating allow an effective shaping of steel constructions. Experienced operators can easily respect these limitations. Hence the TM rolled heavy plates are suitable for flame straightening.

**Flammrichten thermomechanisch gewalzter Baustähle.** Flammrichten ist ein Verfahren, das beim Herstellen von Stahlkonstruktionen häufig angewendet wird. Für die normalgeglühten Stähle hat es sich seit langem bewährt. Für die in den letzten Jahren entwickelten thermomechanisch gewalzten Stähle mußte die Eignung erst nachgewiesen werden. Die Wirkung unterschiedlicher Flammrichtbedingungen auf Gefüge, Kerbschlagarbeit und Festigkeitseigenschaften wurde für TM-Bleche (S355ML nach EN10113) untersucht. Abhängig von der Vorschubgeschwindigkeit des Brenners wurden Oberflächentemperaturen von 650 bis 950 °C eingestellt. Beschränkte sich die Wärmewirkung auf die Blechoberfläche (Wärmestrich), so blieben die Eigenschaften im Rahmen dieser Versuchsbedingungen praktisch erhalten. Wurde der Blechquerschnitt durchgreifend über 650 °C erwärmt (Wärmekeil), was zu einem langsameren Abkühlen führt, so wurde die Streckgrenze vermindert. Für beide Verfahrensvarianten lassen diese werkstoffbedingten Grenzen ein effektives Richten zu. Sie können von geschultem Flammrichtpersonal sicher eingehalten werden. Die Eignung TM-gewalzter Grobbleche für das Flammrichten konnte somit nachgewiesen werden.

In the fabrication of steel structures flame straightening is often used in order to adjust the geometry to the dimensional tolerances. Flame straightening (or forming) has proven its value in many areas of steel processing [1]. Skilled operators can reach extremely close tolerances [2]. The process can be used without heavy mechanical equipment which is an important advantage especially for on site operation. Many practical hints are given by Pfeiffer [3].

Normalized structural steels have not shown particular problems after flame straightening, so that the process was generally accepted for structural steel work, ship building and for other applications. In the last years TM steels have become increasingly used for the same purposes thanks to their improved weldability [4; 5]. However, softening was expected for heating TM steels to temperatures exceeding 580 °C, this temperature was set for all fabrication process including flame straightening [6].

So low temperatures hardly allow an effective shaping. Therefore it was of industrial importance for the use of TM steels, that higher temperatures are acceptable as well. The investigation reported hereafter was carried out in order to prove this.

## Experimental procedure

The investigation was carried out on plates of 355 MPa nominal yield strength (corresponding to API 2W Grd 50 and EN10113 S355ML). 3 plates 15, 50 and 75 mm thick were taken from the plate production of Dillinger Hütte GTS, The parent plate tensile properties given in **tabe 1** confirm that with TM rolling very lean chemical compositions, **table 2**, are sufficient to meet the requirements even for important plate thickness. The 15 mm plate represents a typical S355ML, rolled for structur steelwork. For such plates a simple TM rolling is sufficient to achieve the requirements. For thicker plates accelerated cooling after final rolling pass is beneficial to ensure an optimised grain re-

**Table 1.** Mechanical properties of the parent plates

| plate thickness, mm | 15 | 50 | 75 |
|---|---|---|---|
| yield strength, MPa | 440 | 420 | 390 |
| tensile strength, MPa | 540 | 500 | 490 |
| elongation $A_5$, % | 33 | 33 | 31 |
| CVN (-40°C), J | 280 | 300 | 300 |

Table 2. Chemical composition of the investigated TM-steels

| plate | chemical composition | | | | | carbon equivalent | |
|---|---|---|---|---|---|---|---|
| thickness | C | Si | Mn | Ni | Nb | CE(IIW) | Pcm |
| 15 mm | 0.10 | 0.35 | 1.42 | - | 0.02 | 0.36 | 0.19 |
| 50 mm | 0.07 | 0.30 | 1.38 | 0.23 | 0.02 | 0.33 | 0.16 |
| 75 mm | 0.07 | 0.30 | 1.38 | 0.23 | 0.02 | 0.33 | 0.16 |
| S355ML | ≤0.14 | ≤0.5 | ≤1.6 | ≤0.3 | ≤0.05 | ≤0.40 | |
| S355ML – EN10113-3 | | | | | | | |
| CE(IIW) | C + Mn/6 + (Cr+Mo+V)/5 + (Cu+Ni)/15 | | | | | | |
| Pcm | C + Si/30 + (Mn+Cu+Cr)/20 + Ni/60 + Mo/15 + V/10 + 5*B | | | | | | |

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finement. Plates of relatively high tensile properties were selected for the test program as it was expected that such plates would react most sensitively to softening.

**Line heating of test panels.** By line heating of thick plates the thermal field is mostly concentrated close to the plate surface as schematically shown in **figure 1.**

As direct measurements of the temperature at the surface exposed to the flame are not possible, an indirect measurement technique had to be adopted. The test arrangement is shown in **figure 2.** Temperatures were measured by thermocouples that were introduced from the bottom side and fixed by TIG-welding at about 2 mm subsurface. It became obvious from the microstructure that the temperature was 50-150 °C higher at the very plate surface. However, in the paper the measured values are referenced as flame straightening temperatures $T_{max}$.

Line heating was applied to a number of test panels cut from 15 and 50 mm thick plates. A multiflame oxyacetylene torch was used. At first a correlation between travel speed and maximum temperature ($T_{max}$) was established for constant gas flows [7]. The travel of the torch was mechanised to ensure constant heat inputs. The travelling speed of the torch was then adapted to produce maximum temperatures of 650, 750, 850 and 950 °C.

For a special set of tests the flame straightening was repeated, affecting the material three times with the same $T_{max}$. For the standard single cycles and the triple cycles the heated areas cooled by free heat flow. In practice sometimes water cooling is also applied to force the straightening effect and to accelerate the operation. Such conditions were therefore included in the test program as well. The water shower followed the torch at such a distance, that the temperature at the point of water cooling was below 600 °C.

Tensile and impact specimens were machined from the panels and polished and etched surfaces prepared for metallographic examination. Full thickness flat tensile specimens were tested to look for the integral behaviour of the shaped plates. More localised effects of flame straightening on the mechanical properties were characterised in testing subsized specimens extracted at the surfaces. These flat tensile specimens were 3 mm thick for 15 mm plate, 5 mm for 50 mm plate, respectively. The parent plate properties were tested parallel on specimens of the same type to allow a direct comparison. For impact tests standard Charpy specimens were used located subsurface.

**Thermal simulation tests.** Tests on specimens subjected to time-temperature-cycles corresponding to flame straightening were tested in order to measure more local properties. The heat treatment was performed using conductive heating in a Gleeble equipment. The full cross-section of the simulated specimens consisted homogeneously of a microstructure corresponding to a particular area of the heat affected zone.

The following thermal cycles were applied. Heating in 60 s to maximum temperature, holding time 60 s, cooling according to $t_{8/5}$ cooling time of 20 s. Peak temperatures of 650, 750, 850 and 950 °C were chosen for the thermal cycles.

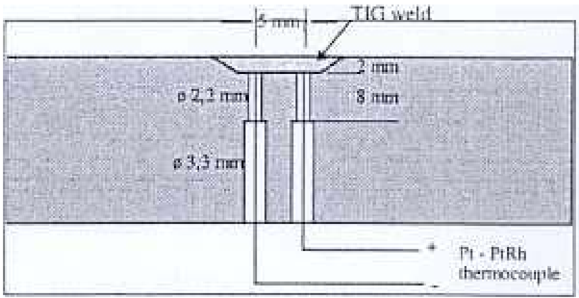

Figure 1. Arrangement to measure the subsurface temperature by thermocouples introduced from the bottom side of the panel

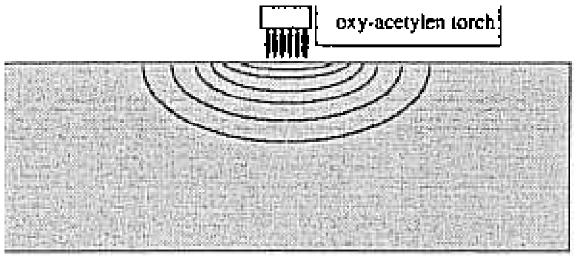

Figure 2. Typical distribution of temperatues achieved in line heating

Single cycle and triple cycles repeating the same thermal conditions were used. From the simulated bars Charpy impact and small size tensile specimens were prepared.

**Wedge heating.** The third part of the investigation dealt with the conditions of shape control where approximately the same temperature is reached through the full plate thickness. Such conditions are typical for wedge heating to straighten girders or point heating for the flattening of buckles. These procedures generally use softer flames or waving. The heat spreads in a larger area, heating and cooling are much slower compared to line heating and the steel is exposed longer to peak temperature.

Full thickness heating was simulated by simple furnace heat treatments. Panels of 15, 50 and 75 mm thickness were exposed to different temperatures. The holding times were adapted to the thickness of the plates. 2 min holding time per mm plate thickness should represent worst case of

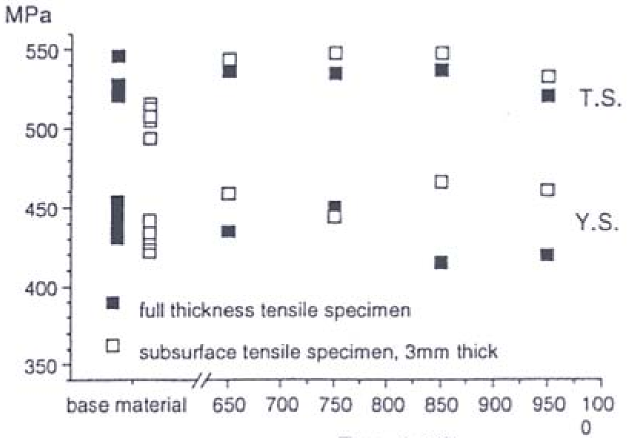

Figure 3. Tensile properties of 15 mm thick panels after line heating

Table 3. Impact transition temperatures after line heating

| $T_{max}$ °C | cooling | cycles | 15 mm plate $T_{T50J}$ | 15 mm plate $T_{T100J}$ | 50 mm plate $T_{T50J}$ | 50 mm plate $T_{T100J}$ |
|---|---|---|---|---|---|---|
| 650 | free | 1 | -114 | -110 | - 90 | -80 |
| 750 | | | -115 | -106 | - 79 | -65 |
| 850 | | | -113 | -100 | - 85 | -76 |
| 950 | | | -118 | -112 | - 86 | -78 |
| 850 | water | | - 98 | - 94 | - 80 | -68 |
| 950 | | | - 99 | - 95 | - 81 | -72 |
| 850 | free | 3 | -116 | -110 | - 94 | -86 |
| | water | | - 92 | - 95 | -112 | -99 |

straightening operations. After removal from the furnace the panels cooled in still air.

## Test results

**Tensile properties.** The influence of different flame straightening conditions on tensile properties are shown in **figure 3** for the 15 mm plate, respectively in **figure 4** for 50 mm panels. Each symbol in the figures represents one individual test result, so that an inherent scatter has to be accepted. No clear trend can be seen as a function of maximum temperature from 650 to 950 °C and the level remained unchanged as the parent plate properties. The slight differences can rather be attributed to inherent scatter than to metallurgical effects.

It must be noted that the depth of the heat affected zones was small in relation to the specimen thickness. Therefore a strong softening would have been necessary to show a remarkable global softening in testing the full thickness specimens.

In order to get information about more local properties flat tensile specimens of reduced thickness were tested. This part of the investigation may be more relevant for metallurgists than for designers or users of the steels. Considering the parent plate the properties determined subsurface were identical to the full thickness specimens. Yield strength between 420 and 450 MPa were measured for the 15 mm plate, 390 to 420 MPa for the 50 mm plate. This shows that the TM-rolling created a homogeneous fine grained microstructure across the plate thickness and no surface hardening was produced by the accelerated cooling of the 50 mm plate.

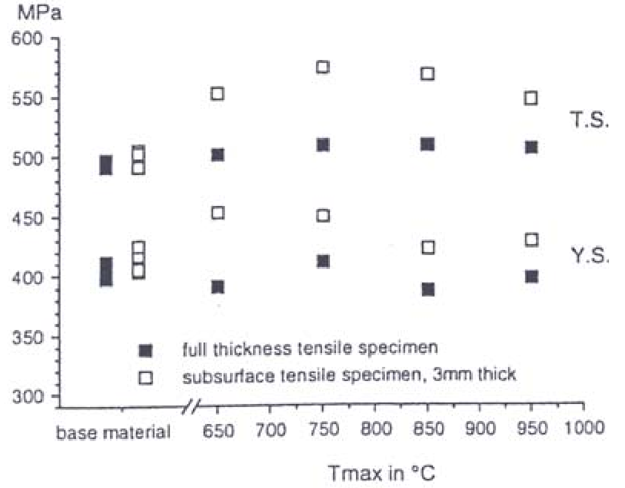

Figure 4. Tensile properties after line heating of the 50 mm thick panel

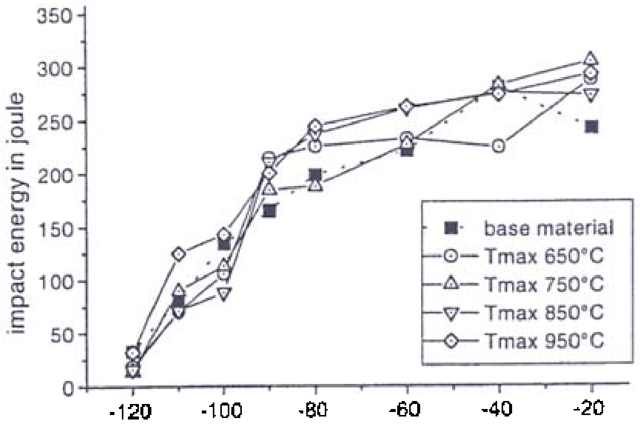

**Figure 5.** Impact transition curves for subsurface specimens machined from 15 mm panels line heated to different temperatures

After flame straightening the subsurface yield strength was slightly raised reaching an average of 450 MPa for all test conditions. The ultimate tensile strength was also increased by some 40 MPa compared to the values determined on the full thickness specimens.

**Impact toughness.** The toughness within the different zones was characterised by Charpy impact tests. The specimens were machined from subsurface and orientated transverse to the plate rolling direction. They were fractured at different temperatures, so that full transition curves could be established. The curves of the 15 mm panels in the parent condition and after flame straightening to different maximum temperatures are shown in **figure 5**. The lines within the graph connect the average values each representing a set of 3 individual tests per series. No systematic influence of the flame straightening on the impact toughness could be observed. Further results from triple cycle and water cooling are summarised in **table 3** along with the corresponding results of the 50 mm panels. In order to characterise the transition behaviour the temperatures, for which an impact energy of 50 or 100 J were

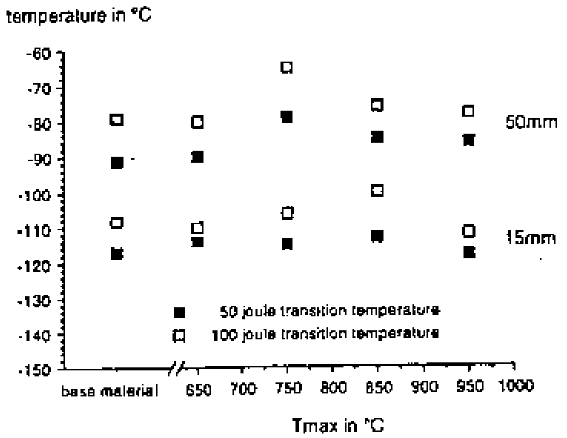

**Figure 6.** Impact transition temperatures as a function of maximum temperature in line heating

determined. This was done by using an eye fit average curve. The transition temperatures ($T_{T50J}$ and $T_{T100J}$) confirm that excellent impact toughness was obtained for all test conditions. This is true not only for the single cycles but also includes multiple treatments and accelerated cooling by water shower. A slight shift of the brittle fracture transition curve may be interpreted for some of the curves for specimens which have been subjected to intercritical heating (max. temperatures 750-850 °C). If any the difference was below 15 °C. The most brittle impact series reached 50 J as low as -79 °C.

One can therefore conclude that for the thermal conditions of line heating, the low carbon TM-steels were not susceptible to embrittlement, **figure 6.**

**Impact test on simulated microstructures.** So far only impact results were reported where in the specimen HAZ areas heated to different temperatures were sampled so that an integral fracture behaviour of different microstructures was determined. Information about the toughness of individual microstructures of the heat affected zone was assessed on thermally simulated specimens.

The impact transition temperatures, hardness results and tensile properties from this investigation are summarised in **table** 4. The following trends were observed.

The hardness was not significantly changed for any of the test conditions. The tensile strength was also not altered and the results were within a close range between 533 and 550 MPa. For the 0.2 % yield strength a minimum was obtained. Due to partial transformation carbon was locally enriched during the intercritical heating with a peak temperature of 850 °C and some ferrite grains were observed for which the grain size (ASTM) had increased from 10-11 (parent plate) to 9-10. Compared to single cycles the specimens subjected to triple cycles led to about 30 MPa lower yield strength for all cycles again as a result of more pronounced carbon segregation.

Impact transition temperatures were at an excellent level for any of the thermal cycles with the worst $T_{T50J}$ at -76 °C (triple cycle) and exceeded by far the requirements for the parent material. As for the yield strength the slightly reduced toughness can be explained by increased ferrite grain size and carbon concentration in the areas of the microstructure that were transformed to austenite at peak temperature.

**Tensile properties/mechanical properties for the conditions of wedge heating.** For temperatures commonly used for PWHT and up to 625 °C no change of properties was remarked for any of the tested plates. In order to separate more distinctively the effects caused by tempering from those caused by a partial transformation also temperatures of 700 and 720 °C were tested, which is just below the transformation temperature. It was observed that this treatment effected a globularisation of cementite particles so that the yield strength was reduced by approximately 30 MPa.

**Figure 7** shows that the yield strength was again lowered when higher temperatures were applied. Slower cooling and hence slower transformation led to a remarkable increase in ferrite grain size compared to parent material. As the cooling rate for air cooling decreased with increasing plate thickness the 75 mm plate had the lowest cooling rate, the biggest grains and consequently the lowest yield strength. For conditions of partial austenization a softening was obtained, which could be attributed to the formation of selective larger ferrite grains and carbon segregation. The drop, in Y.S. compared to parent plate reached about 50 MPa, so that after 750 °C heat treatment the requirements were hardly fulfilled. Higher temperatures leading to complete transformation again led to somewhat higher properties, but still below the initial values. Compared to the behaviour after $T_{max}$ in the intercritical range carbon distribution was more homogeneous, carbon distribution and absence of individual ferrite grains of excessive size was obtained.

**Table 4.** Mechanical properties of simulated microstructures

| temperature °C | cycles | hardness HV 10 | yield strength MPa | tensile strength MPa | impact transition temperature 50J | impact transition temperature 100J |
|---|---|---|---|---|---|---|
| 750 | 1 | 166 | 427 | 534 | - 88 | - 75 |
| 750 | 3 | 163 | 393 | 533 | - 92 | - 75 |
| 850 | 1 | 161 | 397 | 550 | -105 | -100 |
| 850 | 3 | 163 | 377 | 548 | - 82 | - 76 |
| 950 | 1 | 169 | 432 | 533 | - 76 | - 72 |
| 950 | 3 | 167 | 401 | 523 | - 85 | - 80 |
| base material | 165 | 416 | 537 | -117 | -108 | |

## Discussion of test results

Depending on plate thickness and operational conditions different thermal fields, maximum temperatures and cooling speeds are obtained in flame straightening. Very local high energy input as it is typical for line heating will create a thermal field with steep temperature gradients. Under these conditions the HAZ is limited to the subsurface area and the backside is still cold. When the flame proceeds or the torch is taken away the heat dissipates quickly into adjacent cold material. This leads to rapid cooling as it is known in welding.

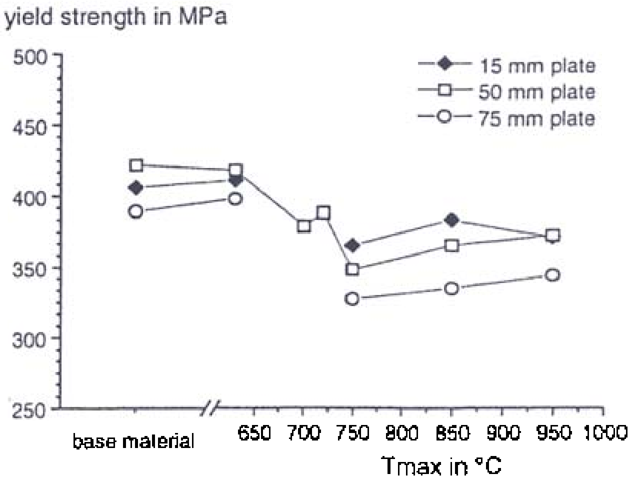

Figure 7. Yield strength after furnace heat treatment followed by air cooling, simulating the conditions of wedge heating

Due to the high cooling rates a direct control of actual maximum temperature at the surface is impossible. The procedure therefore requires experienced operators, who are able to control temperature by distinguishing the colour of the heated spot.

Thanks to the lean chemical composition hardenability of the TM steels is low. A quickly cooled HAZ consisted of fine grained mainly ferritic microstructure. The tensile properties were not significantly changed despite of a wide range of applied maximum temperatures. No softening occurred under any of the test conditions. For some test conditions a local increase in yield and tensile strength was obtained but the effect was limited to the very surface and only reached some 10 %.

As long as no temperature was reached, that caused excessive austenite grain growth no local embrittlement was observed. It is known from welding that large austenite grains are generally limited to areas, which have been heated to more than 1000 °C. Consequently, 950 °C should be acceptable still providing a certain safety margin.

When softer flames are used or larger areas heated, e.g. by waving the torch, it takes longer to reach the required surface temperature. Whilst heating the heat already has time to spread deeper into the surrounding material and the thermal gradient becomes less pronounced. This leads to retarded cooling when the flame is taken away. At the same time a more important part of the cross-section may be affected so that more caution is needed to guarantee full load bearing capacity of the construction. High speed pyrometers or appropriate contact thermocouples can be used to control the temperatures during the operation. The operator should calibrate the procedure on test plates in order to be able to avoid excessive temperatures. Hardness tests on the treated surface could be used for quality control in the final condition.

Slowest and longest heating cycles are obtained when the full plate or flange thickness is homogeneously heated to temperature. This situation which is typical for wedge heating, was simulated by furnace heat treatment.

The lowest tensile properties were obtained after a selective austenizing at 750 °C followed by air cooling. The yield strength was lowered by some 50 MPa. It is worth notying that the tensile strength was hardly altered. The yield strength suffered from single large ferrite grains caused by the slow selective transformation. Compared to the applied furnace heat treatment wedge heating in practice generally will have faster heating, due to the direct impingement of the plate surface by the flame. Furthermore, the time of exposure at high temperatures will normally be much shorter. Both differences should give critical material properties less compared to the tests. In considering these critical conditions of the test conditions the softening of 50 MPa is relatively small. The parent plate requirements could still be met for the tested plates. Consequently even after these critical conditions it can be expected that after a certain work hardening the TM steels would stand full design stress.

To avoid any risk the temperature for wedge heating should be restricted to temperatures clearly below the transformation temperature. Higher temperatures would at the same time reduce the straightening effect.

## Conclusion

The tests carried out on steel grade S355ML have shown that thermomechanically rolled heavy plates can be flame straightened without particular difficulties.

In line heating surface temperature of at least 900 °C can be tolerated without detrimental influence to mechanical properties. An experienced operator can follow this limit by controlling the colour of the hot spot directly after removing the flame.

In case of flame straightening procedure where the full thickness of the plate is heated and hence slower cooling is obtained, temperatures should be restricted to 700 °C to avoid any risk of local softening. If longer holding times apply the temperature limit should be reduced to 600–650 °C. Since heating and cooling happen much slower for this technique the temperature can be reliably controlled by contact thermocouples, pyrometers or temperature indicating crayons.

The results of the investigation presented in this paper allow to assume that within above process limits the materials properties are not affected.

TM steels of very high yield strength e.g. S690M may be more prone to softening [8] or embrittlement by flame straightening, they may therefore require closer temperature ranges.

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## References

[1] *Weirich, G.:* Der Praktiker (1980) No. 2, p. 61/63.

[2] *Beyer, M.; et al.:* Beitrag des Flammrichtens zur Genaufertigung im Schiffbau, Proc. DVS Schweißen und Schneiden '98, DVS Verlag, Düsseldorf, 1998.

[3] *Pfeiffer, R.:* Handbuch der Flammrichttechnik, DVS-Verlag, Düsseldorf, 1996.

[4] *Hubo, R.; Hanus, F.:* Hansa (1992) No. 8, p. 776/78.

[5] *Streißelberger, A.; Oswald, W.; Bauer, J.; Hanus, F.:* Stahl u. Eisen 111 (1991) No. 5, p. 65/73.

[6] SEW 083: Schweißgeeignete Feinkornbaustähle, thermomechanisch umgeformt, Verlag Stahleisen GmbH, Düsseldorf, 1991.

[7] *Hanus, F.:* Flammrichten thermomechanisch gewalzter Baustähle, Proc. DVS Sondertagung Schweißen im Anlagen und Behälterbau 1994, DVS-Verlag, Düsseldorf, 1994.

[8] *Ornig, H.; et al.:* Berg- u. Hüttenm. Monatsh. 138 (1993), p. 248/57.