Effect of forced cooling after welding on CGHAZ mechanical properties of a martensitic steel

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Abstract

The effects of forced cooling, meaning forced cooling rate and forced cooling finish temperature, on the tensile and impact toughness properties of simulated weld coarse-grained heat affected zones have been studied for a commercial grade martensitic steel with a yield strength of 960 MPa. The simulations were done by using a Gleeble 3800 to give forced cooling finish temperatures of 500, 400, 300, 200 and 100 °C and forced cooling rates of 50 and 15 °C/s. For the steel studied, strength significantly increased with no significant negative effects on impact toughness when the steel was cooled rapidly to 200 or 100 °C at 15 °C/s. The results indicate that it may be possible to improve welding productivity and mechanical properties of the steel by using forced cooling down to 100 °C to reduce waiting time between weld passes.

Keywords: coarse-grained heat affected zone; cooling rate; martensite; ultrahigh-strength steels; welding

1 Introduction

The use of ultrahigh-strength steels in welded structures is common nowadays, because of the thinner wall thicknesses and weight-saving benefits they offer compared to structures made of traditional structural steels. However, welding steels that have high- or ultrahigh-strength is often challenging in practice, because the heat input must be tightly regulated to avoid deterioration of the mechanical properties of the welded joints. This means potential cost savings in material costs. Even savings in the manufacturing process can be achieved if the wall thickness of the material being used is thin enough to allow the use of a single pass welding, which usually means materials that are thinner than 6 mm. Often however, multipass welding is required to achieve the adequately low heat input when the material thickness is equal or greater than 6 mm. When this is the case, the production times are greatly lengthened, and the time spent waiting in between of the weld passes is significant and it increases the production costs significantly. [1-3]

The requirement of having to control the heat input can be achieved by using more advanced welding technologies such as laser welding, laser-hybrid, pulsed gas metal arc welding (GMAW-P) and cold metal transfer (CMT). However, basic arc welding methods such as gas metal arc welding (GMAW) is the welding method that is usually used in the industry due the equipment being cheap to obtain and the seam tolerances being less restrictive to those of laser based welding technologies. [4] This means that achieving lower heat input in the welding process is usually done by using multiple weld passes, because lowering parameters such as current or voltage or increasing the weld speed decreases material deposition rate which in turn leads to multiple weld passes being required to fill the weld seam.

Heat input directly relates to the cooling rate of the weld, which is one of the reasons why it must be regulated, because the cooling rate has significant impact on the mechanical properties of the welded joint, in particular those of the heat affected zone (HAZ). Due to the thermal cycle caused by the heat of welding, the HAZ is a zone in which the microstructure of the base plate is changed, e.g. the size of grains or precipitates is increased. These microstructural changes lead to different mechanical properties in the HAZ from those of the base plate. Often, the changes in mechanical properties are detrimental: a loss of toughness and, in the case of ultrahigh-strength steels, a loss of strength. The heat affected zone is located in between of the fusion line and base material and can be divided into the following sub-zones: coarse-grained (CGHAZ), fine-grained (FGHAZ), intercritical (ICHAZ), subcritical (SCHAZ) and intercritically reheated CGHAZ (ICCGHAZ) which can be found only in multi-pass welds. The criteria by which the zones are divided is the thermal cycle that they have undergone and thereby, every zone has a unique microstructure and mechanical properties. Of these zones, the CGHAZ is produced by the highest peak temperatures close to the melting point of the steel while the SCHAZ is produced by peak temperatures below the temperature at which austenite forms, i.e. the A_1 temperature. Furthermore, the weakest impact toughness in the weld is usually found in the CGHAZ, or in the case of multipass welds, the ICCGHAZ, and sometimes in the ICHAZ. The low-toughness zones are known as local brittle zones (LBZ). [5-7]

Usually manufacturers provide information about the desired cooling time ranges for their steels, i.e. the time it takes for the weld to cool from 800 to 500°C (t8/5), which is typically between 4 and 20 seconds for high- and ultrahigh-strength steels. If matching welds are desired, the cooling time tends to closer to 4 seconds than 20 seconds. Furthermore, manufacturers often provide preheat and interpass temperature recommendations, which, together with the maximum allowed cooling time limits the allowed heat input. [8]

The ideal interpass temperature often is around 100°C for high- and ultrahigh-strength steels. However, the time it takes for the steel to cool down to 100°C can be several minutes. This means that when welding steels thicker than 6 mm the time wasted waiting for the weld to cool down accumulates unwanted costs to the manufacturer. For example, some ultrahigh-strength steels require the use of three weld passes or more when the material thickness is equal to or exceeds 6 mm. [8-12] Therefore, in the production of structures from high- and ultrahigh-strength steels, it would be beneficial to use external forced cooling to minimize the waiting time between weld passes. Forced cooling is particularly beneficial in shortening the cooling time from 500 °C to 100°C since lower the temperature of the steel is, slower the cooling rate becomes.

However, besides its effect on productivity, the application of forced cooling will also affect the mechanical properties of the weld. In particular, the cooling rate below 500°C can have an appreciable effect on mechanical properties. HAZs tend to comprise mixtures of martensite and bainite, which generally form at temperatures below 500°C. The toughness of the most brittle sub-zone, i.e. the CGHAZ, will depend on the details of its microstructure, which, in turn, depend on the details of the steel chemistry and the exact cooling path. The CGHAZ toughness of some steel chemistries might suffer from forced cooling down to temperatures below 500°C while others might benefit. For example, in a study conducted by Hoy et al. [13] it was shown that six different low carbon steels became brittle as they were cooled down rapidly to below 300°C. In another study conducted by the authors, a commercial grade high-strength steel became tougher when rapidly cooling down to 100°C [14].

The rapid cooling to the interpass temperature can lead to the formation of lower bainite, which can be highly beneficial to the mechanical properties of the HAZ as mixtures of martensite and lower bainite can have strengths and toughnesses that are superior to martensite of or bainite alone. [15,16]

This research paper focuses on the effect of the forced cooling finish temperature (FCFT) and forced cooling rate on the tensile and impact properties of the CGHAZ, because it is usually an area with low toughness in welded joints. If the steel can be externally cooled at accelerated rates directly to the interpass temperature without negative impact on the of mechanical properties, significant amounts of time can be saved in the process of ultrahigh- and high-strength steel welding. By eliminating wasted time, the attractiveness of ultrahigh- and high-strength structural steels to designers and fabricators can be increased leading to their wider application.

2 Experimental procedures

The experimental part of this study has been carried out following the steps set out in a previous article published by the authors [14], but with a different material. Simulated CGHAZs were produced using a Gleeble 3800 thermomechanical simulator and tested for Charpy V impact toughness and tensile properties.

The material used in the tests was a 10 mm thick commercial grade ultrahigh-strength steel. The material was chosen due to its suitability for the construction industry in ultrahigh-strength applications and the fact that it has a mainly martensitic microstructure. The steel being studied had a minimum specified yield strength ($R_{p0.2}$) of 960 MPa, a tensile strength (R_m) in the range 980 - 1150 MPa, an elongation to fracture (A) of at least 12% and a specified minimum impact strength of 40 Joules at -40°C, when the thickness of the material is equal or less than 53.00 mm. The chemical composition of the steel as given by the manufacturer is shown in Table 1.

The recommended cooling time t8/5 for the steel is from 5 to 15 seconds according to the manufacturer [4]. The steel has a typical carbon equivalent (CEV) of 0.58 which is associated with challenging weldability. CEV = C + Mn/6 + (Cu + Ni)/15 + (Cr + Mo + V)/5, where the symbols represent the steel alloy content in wt.%. [17]

Table 1: Chemical composition of the steel (wt.% max) [17]

C	Si	Mn	P	S	Cr	Cu	Ni	Mo	B
0.20	0.50	1.60	0.020	0.010	0.80	0.30	2.00	0.70	0.005

The test specimens used in the Gleeble tests were cut transverse to the rolling direction of the rolled plates and had the dimension of 10x5x55 mm and 160xØ10 mm. The specimens were cut from plates by using water jet cutting to avoid changes in the temperature of the steel. After the cutting, the 10x5x55 mm samples were machined to fulfil the required tolerance of the standard ISO 148-1 for the Charpy V-notch specimens. The notches for the Charpy V-notch tests were only machined after the Gleeble simulations. Charpy V testing was made according to ISO 148-1 at -40°C using three specimens per simulated case. After testing, ductile fracture percentages were evaluated in according to the same standard.

The 160xØ10 mm Gleeble specimens were also machined to their final dimensions for tensile testing following the Gleeble simulations. Final dimensions gave a gauge length of 10 mm and a nominal diameter of 6 mm. Elongation, yield and tensile strength testing were carried out with a Zwick 100kN testing machine using three specimens per simulated case.

A Gleeble 3800 was used to impose thermal cycles on the steel to simulate the CGHAZs that might be produced by enhancing the cooling rate of welds down to different temperatures followed by cooling in still air. A peak temperature of 1350 °C was chosen to promote rapid austenite grain growth resulting in a CGHAZ with a low impact and fracture toughness. [18,19] The specimens were heated to 1350°C at 400°C/s where they were held for one second before rapid cooling at 50 or 15°C/s. These cooling rates correspond to t8/5 times of 6 and 20s. The rapid cooling stage was terminated at different temperatures, i.e. 500, 400, 300, 200 and 100°C, after which cooling was continued following the rates given in Table 2, which are representative of the free cooling of a weld in air. Fig. 1 shows examples of two thermal cycles, i.e. where rapid cooling was terminated at 500 or 100 °C. It should be noted that due to the manner in which cooling is achieved in the Gleeble simulator and the latent heat evolved during the decomposition of austenite, it was not always possible to maintain linear cooling at a constant rate below about 500 °C. This was particularly true for the high cooling rate of 50 °C/s as can be seen in Fig. 1.

The low-temperature cooling rates shown in Table 2 were derived from measurements on a T-joint welded between square structural hollow sections with the dimensions 150x150x8 mm and 100x100x8 mm with a 5 mm fillet weld using a heat input of 1.5 kJ/mm. The temperature of the weld was measured down to 100°C and formed the basis for the cooling data shown in Table 2. It is worth noting that the measured cooling times in some of the temperature ranges were significantly different to times calculated following the Rosenthal theory.

Table 2: Simulated air cooling rates [14]

Temperature range °C	Cooling rate °C/s
500-450	7.10
450-400	5.00
400-350	3.85
350-300	2.77
300-250	2.00
250-200	1.28
200-150	0.69
150-100	0.29

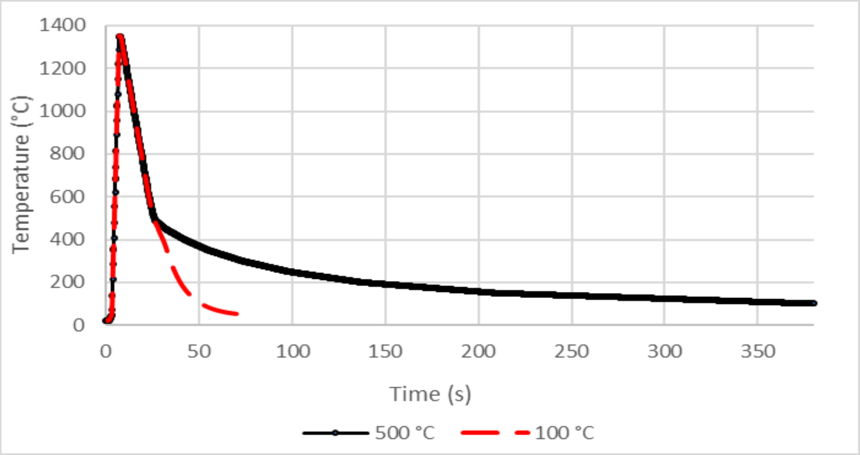

Fig. 1: Thermal cycles for forced cooling limits of 500 and 100 °C with cooling speed of 50 °C/s [14]

3 Results & Discussion

3.1 Impact Toughness

Mean absorbed energy values are shown in Fig. 2 and mean ductile fracture surface percentages in Fig. 3. It can be seen that when the cooling rate was 50 °C/s, compared to FCFT of 500 °C, the toughness of CGHAZ suffered when FCFT was 100 °C, which would be the ideal FCFT from a productivity point of view. However, as Fig. 3 demonstrates the percentage of ductile fracture of the specimens increased when the FCFT was 100 instead of 500 °C, regardless of cooling rate. Meaning that with increased number of specimens it might be that the toughness of the CGGAZ does not decrease by lowering he FCFT to 100 °C regardless of cooling rate. when the cooling rate was reduced to 15 °C/s, the variation in toughness mean values was not significant as with the faster cooling rate of 50 °C/s. Furthermore, in this experiment the toughness value achieved with FCFT of 100 °C was greater than the value achieved with the traditional FCFT of 500 °C when the cooling rate was 15 °C/s.

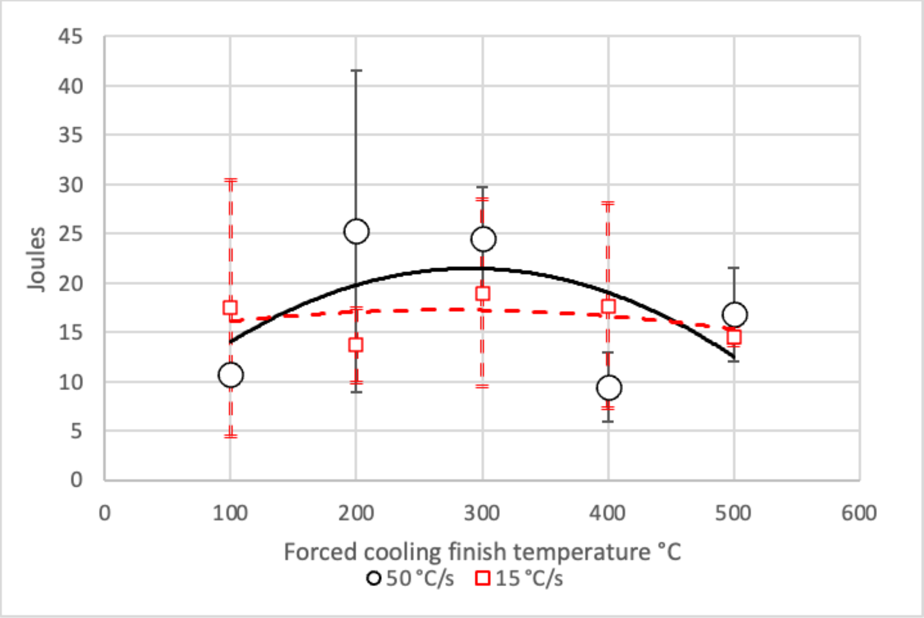

Fig. 2: Charpy V impact toughness at -40°C

Regardless of cooling rate or FCFT all fracture surface mean values had ductile fracture percentage of less than 50%, but cooling rate of 50°C/s had few individual specimens with ductile fracture percentage of 50%. No specimen in this study exceeded 50% ductile fracture value.

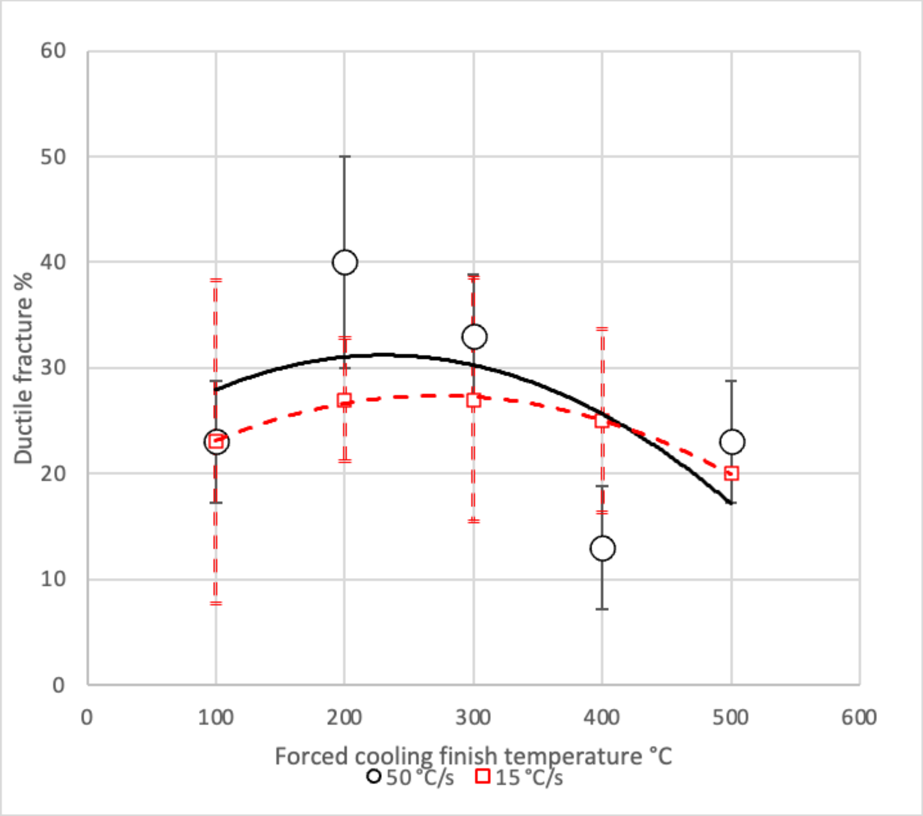

Fig. 3: Percentage of mean ductile fracture at -40 °C

It is worth noting that, when one-way ANOVA test is used to analyze the results, at the 95% confidence level, the P-value with both of the cooling rates exceeds 0.05. This means that it cannot be said based on these results that the FCFT has an effect on impact toughness of the HAZ. However, it does not seem likely that the impact toughness of CGHAZ would suffer when the FCFT is lowered from 500 to 100 °C with the 15 °C/s, which is more practical realistic cooling rate of the two rates used, considering real welding situations and current technology.

3.2 Strength

The strength of the CGHAZ was tested with two different cooling rates of 50 °C/s, and 15 °C/s. The values shown in Fig. 4 and 5 are the average values of three specimens. Figs. 4 and 5 show that for both of the forced cooling rates tensile and yield strengths at room temperature increased with decreasing FCFT.

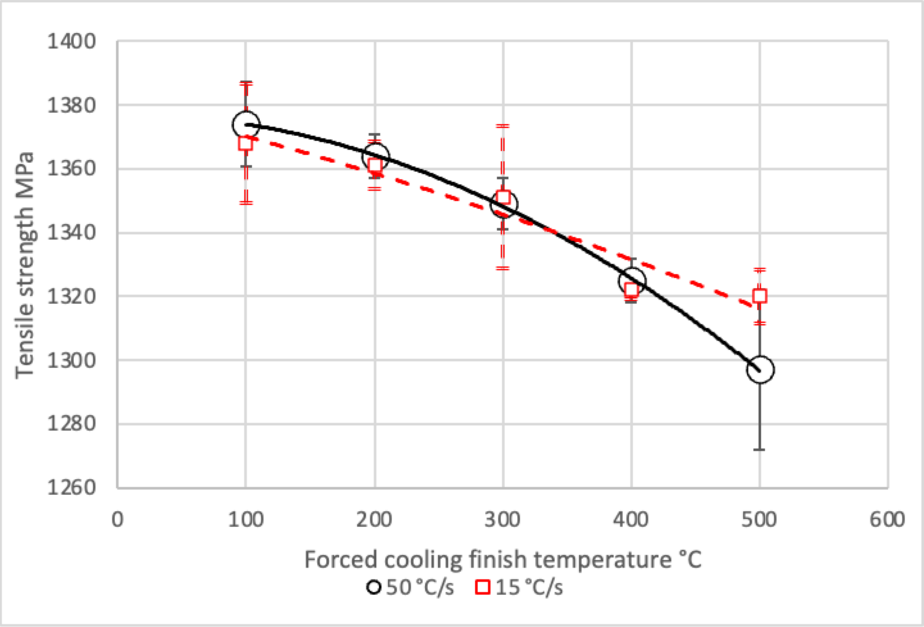

Fig. 4: Tensile strength of the CGHAZ

The increase in tensile strength was 5.4 % between 500°C and 100°C with the faster cooling speed of 50°C/s and 3.6 % with the slowest cooling rate of 15°C/s. In this study, the greatest increase in tensile strength was observed between 500°C and 100°C, with cooling speed of 50°C/s.

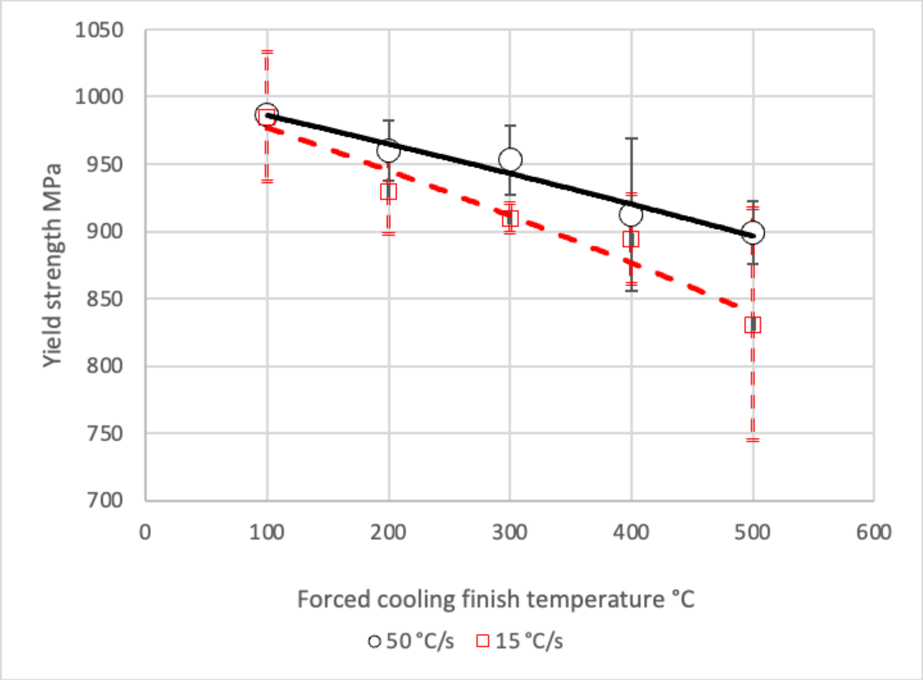

Fig. 5: Yield strength (0.2% proof stress) of the CGHAZ

The highest yield strength values were obtained with the cooling speed of 50°C/s combined with a FCFT of 100°C. The highest yield strength achieved with the slowest cooling speed of 15°C/s was obtained with FCFT of 100°C as well.

According to one-way ANOVA test however, it cannot be said with 95% confidence that FCFT has effect on the yield strength when the cooling rate is 50°C/s. However, with the cooling rate of 15°C/s the P-value is 0.036, meaning that FCFT very likely has a effect on yield strength. With the same confidence level of 95%, the FCFT has a effect on tensile strength of the CGHAZ. Considering tensile strength, the cooling rate of 50°C/s had P-value of 0.0003 and 15°C/s had P-value of 0.0045.

Overall, decreasing the FCFT to 100°C had no detrimental effect on the tensile or yield strength regardless of cooling rate in this study. However, the Y/T-ratio suffered if the FCFT was lowered to 100°C as can be seen in Fig. 6. The Y/T-ratios are still fully acceptable to most structural applications regardless of this negative effect of lowering the FCFT. For most structural applications Y/T-ratio of 0.85 or below is acceptable. On the basis of these results, as the FCFT is decreased to 100°C the CGHAZ becomes less able to deform before fracture, but the difference between FCFT of 500 and 100°C is only 0.03 with cooling rate of 50°C/s. The change is more significant with a cooling speed of 15°C/s as the Y/T-ratio suffers by 0.09.

Furthermore, stronger HAZ can better resist local necking by helping to cause overmatching and by doing so moving part of the deformation during cross-weld overloading in to the base steel. This can be very important to structures if they are in danger of overloading or located in earthquake prone areas. Lower the Y/T-ratio is the more the material can tolerate plastic deformation before breaking. [20,21]

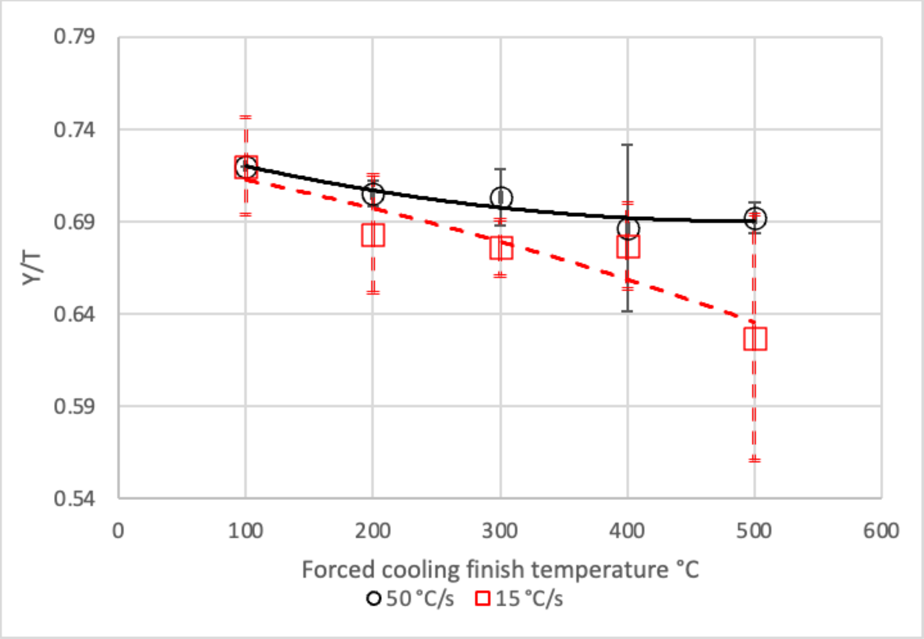

Fig. 6: Y/T ratios of the CGHAZ

3.3 Uniform Elongation

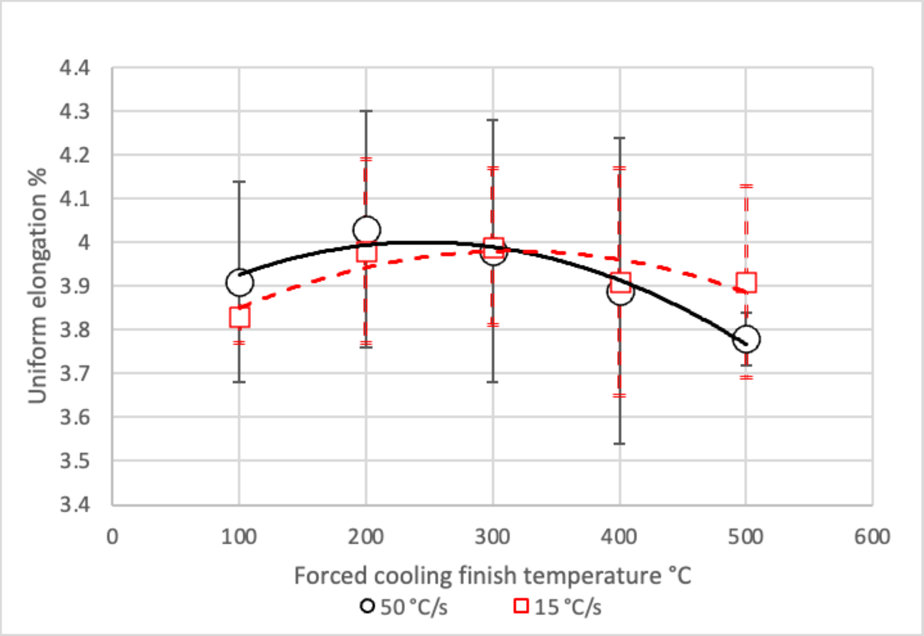

Fig. 7: Uniform elongation of CGHAZ

As shown in Fig. 7 the uniform elongation of the CGHAZ is similar between FCFT of 500 and 100°C. However, according to one-way ANOVA tests it cannot be said that FCFT affects the elongation at all regardless of cooling speed as the P-value exceeds 0.8. Based on the results in this study and one-way ANOVA tests it can be said however, that it is unlikely that the elongation to fracture would suffer as the FCFT is lowered.

3.4 Microstructure

Extensive microstructural investigations were not undertaken in this study. In general, mechanical properties are, of course, the result of the microstructure that results from the applied processing parameters. The changes that can be produced by the application of forced cooling after the welding of the steel used in this study is shown in Fig. 8, which shows the microstructures of simulated CGHAZs obtained with FCFTs of 500, 300, 200 and 100°C. The differences are striking, for example lower FCFT of 100°C is showing a much larger quantity laths that are most likely martensite than the higher FCFT of 500°C. Furthermore, lower FCFTs resulted in finer grain size. Martensite and bainite are the microstructures that can be behind the increase in tensile and yield strength. However, if the microstructure in lower FCFTs was bainite, it would be lower bainite which tends to have good impact toughness properties. Martensite in other hand can be brittle, meaning larger quantities of martensite could potentially have negative effect on impact toughness. In this study, the FCFT of 100°C produced finer grain size which is beneficial to the impact toughness. Combination of the positive effect finer grain size with the larger quantity of martensite would explain the increase in tensile and yield strength while impact toughness remains relatively untouched.

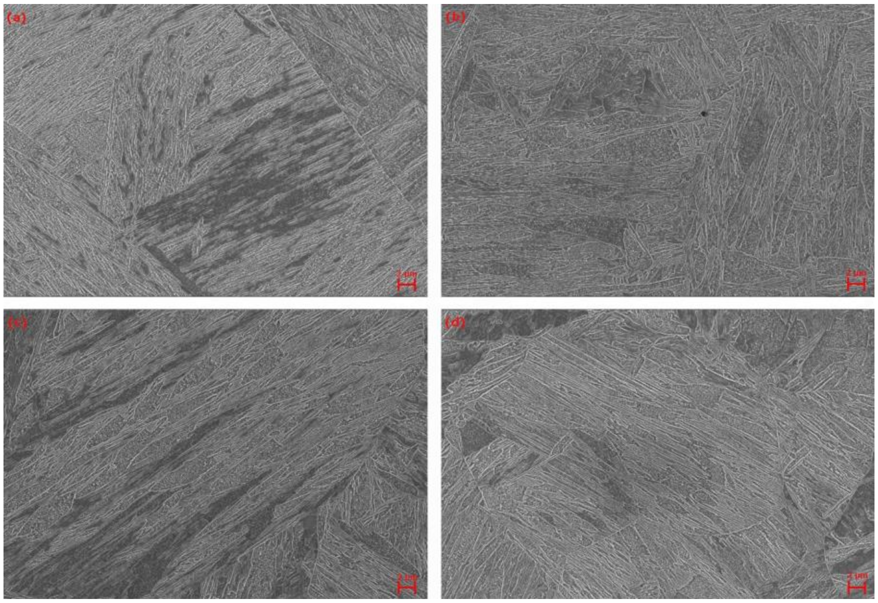

Fig. 8: Microstructure of the simulated CGHAZ with a cooling rate of 50°C/s; (a) FCFT 500°C, (b) FCFT 300°C, (c) FCFT 200°C, (d) FCFT 100°C

4 Conclusion

Based on the preliminary investigation carried out in this study, the mechanical properties of the welded joint can benefit from introducing forced cooling to the welding process to cool the joint rapidly to the interpass temperature when multipass welding is used. The yield and tensile strengths increased as the steel was cooled down rapidly to 100°C while the cooling did not have a detrimental effect on the impact strength or elongation to fracture. This means that external cooling could be introduced to the multipass welding process to shorten the production times without having a negative impact on the mechanical properties of the CGHAZ.

However, as the study focused solely on the effect of the cooling on the CGHAZ, further studies that consider the properties of other subzones in the HAZ should be carried out in the future.

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