

Effect of Heat Sinks on Cooling Time to Weld Interpass Temperature

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Abstract. In high- and ultrahigh-strength steel welding, interpass cooling time is an important factor affecting productivity and welding costs. Usually, welding heat input is restricted to meet the relatively short recommended cooling times between 800 and 500 °C ($t_8/5$), which are prescribed by the need to meet weld strength and toughness properties. This, in turn, leads to the need for multipass welding with the interpass waiting times needed for the weld to cool to a sufficiently low interpass temperature. Welding productivity is affected by both the number of passes and the interpass waiting time. With a view to minimizing the total number of passes needed for a given preparation, it is beneficial for the interpass temperature to be as low as possible as this permits higher heat input for a given $t_8/5$. On the other hand, low interpass temperature requires longer interpass waiting times. Therefore, this research concerns the potential of introducing copper heat sinks adjacent to the weld to reduce the time it takes for the weld to cool down to the interpass temperature. It is demonstrated that, in the case of a butt weld in a 6 mm thick base plate MAG welded with a weld energy of 1 kJ/mm and an interpass temperature of 100 °C, copper heat sinks almost halve the interpass waiting time. This can have a marked effect on the overall productivity when welding high- and ultrahigh-strength steels and increase their attractiveness for steel construction.

1 Introduction

The current trend in the world of manufacturing and construction is to utilize materials with high strengths. As steel is popular choice of material for various machines and structures, the use of high- and ultrahigh-strength steels is becoming more popular than in the past. Steels with higher strengths than conventional structural steels such as S355, can help reduce material costs, transport costs and sometimes production costs as well. In addition to possible cost savings, using high- or ultrahigh-strength steels allow for thinner wall thickness to be used in structures which in turn allows more elegant and advanced structures to be built. However, when the structure or machine requires the use of welding, the production costs can be higher than they would be in the case of normal structural steels due to the fact that the heat input and cooling time of high- and ultrahigh-strength steels must be strictly regulated to achieve sufficient mechanical properties in the welded joint. Low heat input results in the use of multipass welding if traditional arc welding methods such as gas metal arc welding (GMAW) is used. [1]-[3]

When multipass welding is utilized in the welding process with high- or ultrahigh-strength steels, the interpass temperature used should be relatively low, because it has significant effect on the maximum allowed heat input of the next weld pass. Also, in the

case of some steels, research has shown that an interpass temperature of around 100 °C can produce superior mechanical properties compared to the use of other interpass temperatures. [4]-[6] Furthermore, in manufacturers' welding guidelines for their steels the maximum interpass temperature is usually between 100 and 300 °C depending on the strength and type of the steel; however, often the maximum interpass temperature is only 100 °C. [7], [8]

Due to the limited heat input that can be used to achieve a value of $t_8/5$ between 5 and 15 seconds, multipass welding is required if the material thickness surpasses 5 mm. Material that is between 6 and 8 mm in thickness can require up to three weld passes when a matching weld is desired in ultrahigh-strength steels. This means that the time spent waiting for the steel to cool to the interpass temperature of 100 °C can be several minutes, which is a significant amount of time in the welding process. This waiting time greatly increases production costs, especially if the welding is done manually or the structure does not allow for welding another seam while waiting for the previous weld to cool down to the interpass temperature. [8]-[11]

If the fabricators were to decide to increase the heat input and $t_8/5$ times beyond those recommended in order to increase weld deposition rates and avoid multipass welding, the heat affected zone (HAZ) would be wider and its mechanical properties of these zones would be

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significantly worse than the mechanical properties of the base steel. This in turn would diminish the benefits of using high- or ultrahigh-strength steels. The HAZ is an area in the weld that has undergone microstructural changes that are generally detrimental to the joint. The HAZ can be divided into different sub-zones such as the coarse-grained HAZ (CGHAZ), the fine-grained HAZ (FGHAZ), the intercritical HAZ (ICHAZ), the subcritical HAZ (SCHAZ) and the intercritically reheated CGHAZ (ICCGHAZ). Often the weakest tensile strength of the joint is found in the SCHAZ or ICHAZ and the lowest impact toughness is usually found in the CGHAZ, ICHAZ or ICCGHAZ. The differentiating factor between these zones is the thermal cycles that they have undergone. For example, the CGHAZ is the zone that is closest to the fusion line and is caused by peak temperatures in the region of 1350 °C or more. On the opposite side of the peak temperature spectrum is the SCHAZ that is produced by peak temperatures in the vicinity of 600 °C, i.e. below the temperature at which austenite starts to form during heating – the A_{c3} temperature. Furthermore, the ICCGHAZ is produced by reheating the CGHAZ of a previous weld pass to an intercritical temperature between A_{c3} and A_{c1} (the temperature at which the microstructure is fully austenitic on heating). Intercritical peak temperatures are often around 750 – 850 °C. Since the ICCGHAZ has lower impact toughness than the base metal, the number of weld passes required in the weld should be minimized to reduce the incidence of such sub-zones. [12]-[14]

The time the weld takes to naturally cool down to the interpass temperature of 100 °C is in most cases several minutes, which makes the welding process highly inefficient. It would seem logical, therefore, to explore ways in which the weld can be cooled down to the interpass temperature as fast as possible.

The methods available for cooling the weld are limited, because the weld must be protected from hydrogen and other impurities. This means that the weld cannot be in direct contact with water that would otherwise be a good coolant. This research paper focuses on the cooling potential of water cooled copper heat sinks in the cooling the weld rapidly to the interpass temperature of 100 °C. Other potential options for cooling the weld are compressed air, liquid argon, liquid nitrogen or solid carbon dioxide (CO₂). However, compressed air has poor cooling potential unlike solid CO₂ that has 100 times greater cooling potential than compressed air. [15] The problem with solid CO₂ is the delivery system and the mass of the cooling medium. Usually the CO₂ is delivered as snow, which means that it has a very small mass which translates to poor cooling potential for extended cooling. Furthermore, coolants like liquid argon, liquid nitrogen and solid CO₂ are consumables, which makes them costly to use compared to water cooled copper heat sinks for example. At the temperature involved, conduction is the most effective way to transfer heat and copper is a good thermal

conductor which is the reason why copper was chosen as the thermal conductor in this work. Furthermore, unlike CO₂ in cryogenic cooling, the water used to cool the heat sinks need not be consumed which makes the process inexpensive to use and environmentally friendly.

2 Experimental procedures

The welding was carried out with a Kemppi Pro MIG 500 and a Motoman-yasnac RX robot on a basic S355 structural steel. The welding parameters can be seen in Table 1 and the welding jig in Fig. 1.

The welded specimens had dimensions of 120x145x6 mm, 145 mm being the length of the weld and the welding geometry used was a V preparation with an angle of 50 degrees, an air gap of 1 mm and a root height of 1 mm. The temperature of the weld was measured at two separate locations: the middle of the weld length-wise and 20 mm from the end point of the weld. The thermocouple wires can be seen in Fig. 1. As the measured temperatures were between 800 and 100 °C, the thermocouple type used in the experiments was K20-2-350, which has maximum temperature limit of 1200 °C. The thermocouple measures the temperature from the closest short-circuit point, which in this experiment was the bottom of the weld. The frequency used in the temperature measurement was 30 Hz. The process parameters are listed in Table 1 and 2. Furthermore, technical drawings of the cooling blocks and weld seam geometry can be seen in Figs. 2 and 3. The cooling blocks were used on half of the experiments out of 6 weld runs, meaning three parallel runs were used in this experiment.

Table 1. Welding parameters used

Parameter	Value
Current (I)	167 A
Voltage (U)	22.7 V
Travel speed (v)	220 mm/min
Angle of the weld torch	15°
Wire feed (f)	9.8 m/min (Autorod 12.51, Ø0.8 mm)
Welding energy (E)	1.03 kJ/mm
Heat input (Q)	0.83 kJ/mm
Gas flow rate	16 l/min (Mison 25)
Working temperature (T)	21°C
Weld passes	1

Table 2. Copper (C110) cooling block parameters

Parameter	Value
Copper block length (l)	150 mm
Copper block width (w)	60 mm
Copper block height (h)	40 mm
Coolant passage diameter (d)	12 mm
Water flow rate (v)	6 l/min
Incoming water temperature (T)	4 °C
Distance from weld	12 mm

The water used in the heat sinks had a constant inflow temperature, since the cooling system was an open type.

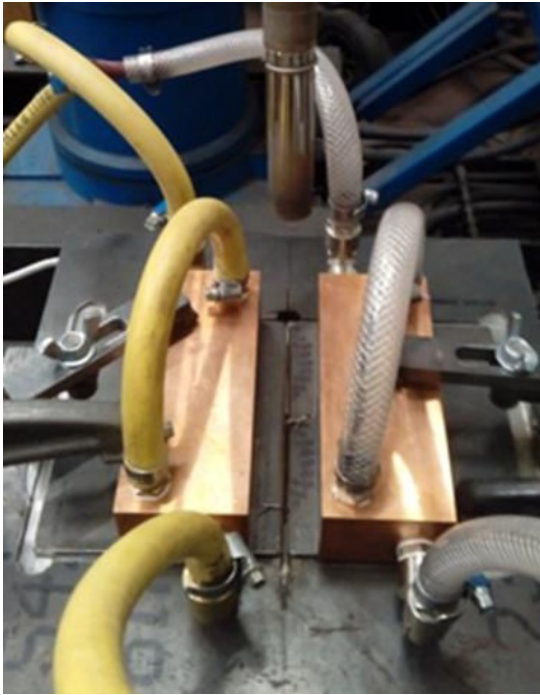


Fig. 1. Weld set-up with two thermoelements and cooling blocks

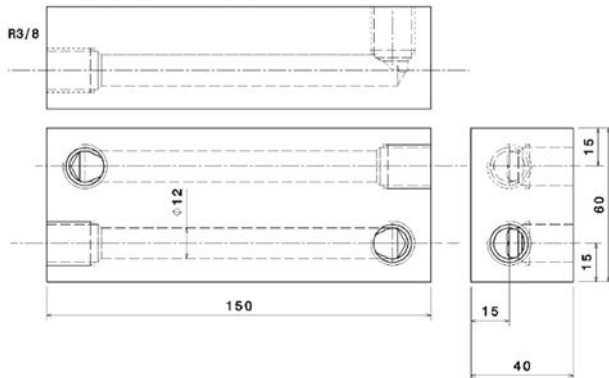


Fig. 2. Cooling block technical drawing (mm)

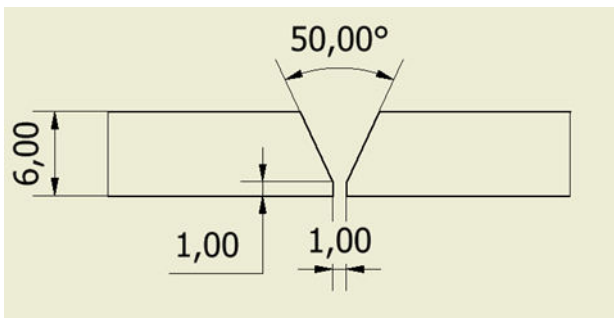


Fig. 3. Weld seam dimensions (mm)

3 Results & Discussion

Fig. 4 shows cooling curves for welds with and without the cooling blocks. As can be seen, the effect of the cooling blocks is only seen below 500 °C. At temperatures above 300 °C the difference in cooling times is not significant enough to justify the implementation of the copper heat sinks, in most situations. Furthermore, the difference between $t_{8/5}$ times is not significant being only 2.2 seconds at most in the middle of the weld and 2.9 seconds at most at the end of the weld. The individual $t_{8/5}$ and $t_{8/1}$ times for every experiment can be seen in figures 5 and 6.

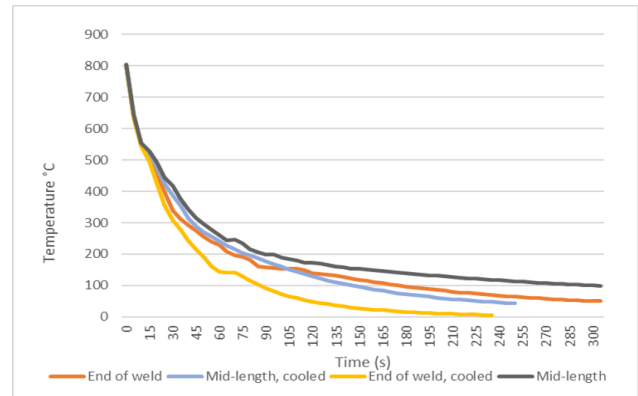


Fig. 4. Cooling curves of one experiment

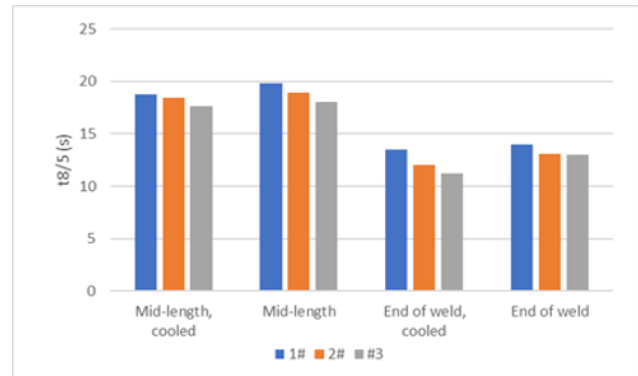


Fig. 5. Individual $t_{8/5}$ times for all of the experiments

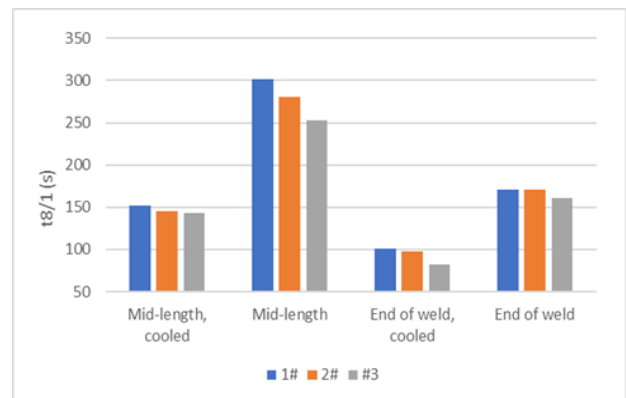


Fig. 6. Individual $t_{8/1}$ times for all of the experiments

However, differences in the cooling times from 800 to the required interpass temperature of 100°C, t_{8/1} were substantial. On average, t_{8/1} was 132 seconds shorter when cooling was applied compared to non-cooled weld at the middle of the weld. The time difference was 74 seconds at the end of the weld. Without cooling, t_{8/1} was 279 seconds, which means that the heat sinks reduced the cooling time by 47%. At the end of the weld without the heat sinks, t_{8/1} was 168 seconds. With the heat sinks this time was reduced to 94 seconds, which means that the cooling time was reduced by 74 seconds, i.e. 44 %. These results show that from a productivity point of view it would certainly be beneficial to employ heat sinks by reducing the waiting time between weld passes.

4 Conclusion

Implementing external cooling based on water cooled copper heat sinks in multipass welding can be highly beneficial in the welding of high-strength steels that require strict heat input control. In this research, it was shown that the cooling time from 800 °C to the interpass temperature of 100 °C can be accelerated by up to 159 seconds. In situations where multiple welding passes are required this technology has the potential of accelerating the welding process significantly. This can offer the possibility of reducing the cost of welding high and ultra-high strength steels, which can help make the use of these steels in structural applications more attractive from an overall profitability point of view.

The efficiency of the cooling blocks might also be increased, and the cooling rate accelerated further by moving the cooling blocks closer to the weld seam after the weld torch has passed by and is out of the way. Further research is needed to explore the magnitude of such a strategy along with the cooling potential of cooling blocks with high and ultra-high strength steels thicker than 6 mm.

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