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Original Research Article

Comparative evaluation of various experimental and numerical simulation methods for determination of $t_{8/5}$ cooling times in HPAW process weldments

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ABSTRACT

The aim of this article is to provide a quantitative comparison and efficiency verification of the methods of estimating $t_{8/5}$ cooling time in the process of HPAW of S960QL steel.

The measurements of $t_{8/5}$ welding time were conducted at the face of weld with the use of thermoelectric, pyrometric and thermovision methods. A FEM model of the joint was made, and welding simulation was done. The results of the calculations were then confronted with experimental data, and measuring methods were evaluated.

Differences in the results of $t_{8/5}$ time measurements were determined for the analysed methods and arranged according to the precision of results presented; the applicability of FEM for predicting the value of $t_{8/5}$ time was investigated.

The usability of temperature measuring methods for determining cooling time was determined, the weaknesses of non-contact measurement in terms of diversification of cooling time in a section of a welded joint were shown, and the advantages of numerical method were demonstrated.

It was established that joining experimental methods for measuring cooling time of a joint with FEM analysis allows to obtain a desired resolution of prediction. In this way, the technology for hybrid welding of advanced high-strength steels can be designed more efficiently.

1. Introduction

One of the main parameters of the analysis of both the characteristics of phase transitions of steel in the welding process and joint properties is cooling time in the temperature range of 800–500 °C – $t_{8/5}$. For an engineer, it is an elementary piece of information describing resultant mechanical properties of a welded joint, apart from the amount of supplied heat. The speed of cooling in the temperature range of 800–500 °C determines the characteristics of transitions in steel (Fig. 1)

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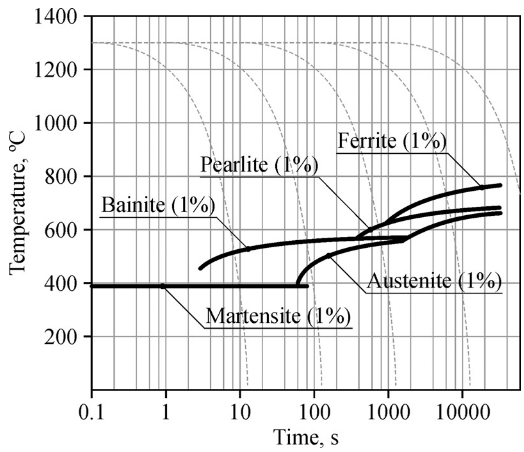

Fig. 1 – Time–temperature-transformation diagram (TTT) for S960QL steel.

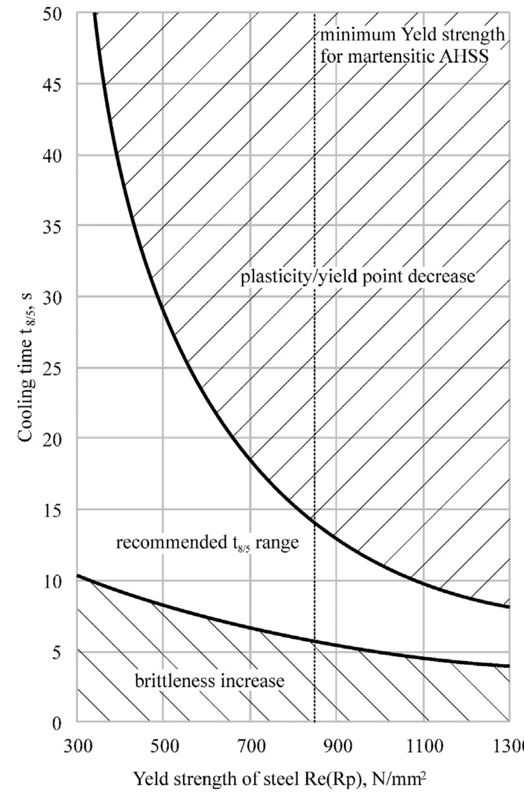

Fig. 2 – Recommended range of $t_{8/5}$ time values in the function of yield point for constructional steels.

2. Literature survey

In case of typical constructional steels whose yield point is up to 355 MPa, the span of cooling time values in the temperature range of 800–500 °C is very wide and can amount to tens of seconds [1,2]. In case of Advanced High Strength Steels, the span of optimum $t_{8/5}$ times decreases to a few seconds due to high susceptibility of these materials to lowering strength of HAZ as a result of tempering. The use of appropriate measuring method or prior prediction of cooling dynamics by means of computer simulation is crucial in order to obtain a welded joint in AHSS that would display required mechanical properties. The use of hybrid welding methods, for example, Hybrid Plasma Arc Welding, makes measuring the temperature of the joint more complicated due to complex geometry of the weld pool and considerable size of a welding head. In addition, AHSS are characterised by narrow recommended $t_{8/5}$ range (Fig. 2).

Advanced welding processes, which modulate and control welding current in order to optimise fusion speed and penetration depth, and minimise material spattering in the arc, create difficulties in determining the amount of supplied heat. The accuracy of the amount of heat in welding determined on the basis of voltage and current parameters is limited due to averaged data obtained from devices that measure welding power sources.

Determining the amount of heat on the basis of the heat input formula, which includes the relation between arc energy and welding speed, also gives a result that is far from being actual in the majority of cases.

The analysis of the amount of heat on the basis of the area of fusion zone, in turn, is difficult, especially in industrial environment, due to low repeatability of results [3–5].

In such a case, registering joint temperature as a function of time gives a chance for a reliable determination of the amount of heat supplied into the joint on the basis of measurements of cooling dynamics with the conditions that the measurement is repeatable and independent from external conditions.

From a high number of methods for measuring temperature, two are most commonly used in welding:

- contact method – with the use of a thermocouple, possibly a coefficient thermistor;
- non-contact method – with the use of a pyrometer or a thermovision camera.

2.1. *Contact temperature measurement of the weld area with the use of a thermocouple*

Contact measurement with a thermocouple involves registering the changes in the voltage between a set of two different thermoelements and a frame of reference located in a known temperature placed in the weld pool or at a certain distance from the weld axis on the surface of the welded element in openings corresponding to the spots in the points of reference (Fig. 3). It is also possible to pressure weld the thermoelements with the examined construction [2,6–12].

2.2. *Non-contact temperature measurement of the weld area*

Non-contact temperature measurement comprising pyrometry and thermography is based on registering bodies' radiation in the range of electromagnetic wave length from a few to several micrometres. Measuring equipment used in welding is dominated by pyrometers and thermovision cameras [13,14].

Pyrometers are devices registering the temperature from a designated area with the use of photoelectric sensor. The measuring spot depends on the optical system and distance