Characterization of Elevated Temperature Mechanical Properties of Butt-welded Connections Made with HS Steel Grade S420M

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***Abstract*—The results of the transient and steady state tests reveal that butt welds made by joining two parts of high strength steel grade S420M together when subjected to elevated temperatures will begin to degrade in strength at a temperature above 100^{o}C. The design model for the reduction factors for mild steel described in Eurocodes 3 is therefore not appropriate for this category of high strength steel. However, the reduction factors for weld in Eurocode 3 are currently applied to model the behaviour of welds in the design of both mild and high strength steels. Connection failure, particularly during the cooling regime of a fire is considered critical and can be detrimental to the survival of a structural assembly. It is therefore fundamental to correctly assess the behaviour of welded connections in fire conditions. It is recommended in this paper that the current design model for weld at high temperatures should be reviewed to make provision for high strength steels. The indication is that the strength factors defined in Eurocode 3 are not applicable to steel grade S420M and therefore should not be used to model welded connections in this class of steel.**

***Index Terms*—butt-weld, elevated temperature, high strength steel, strain transducer**

I. Introduction

The determination of temperature dependencies of the mechanical properties of welded connections, namely yield strength and modulus of elasticity, from testing is very important because of the variation in material properties even with those of identical grades. The properties of welded joints to be utilized in modelling and design should be established by means of coupon tests. Coupon testing of the material under investigation forms part of the requirements for using the advanced method in the assessment of strength and behaviour of the material component at elevated temperatures. It should be realized that the knowledge of the effects of elevated temperature exposure on the yield strength and elastic modulus of the material being investigated is principal to the determination of the stress-strain-temperature curves. Grades of high-strength steel such as S420M, S460M, etc that are used to fabricate steel-plated deck suitable for offshore operations have been shown to have reduction factors different to those specified in Eurocode 3, Part 1-2 [1]-[4].

The extensive experimental research performed at the Laboratory of Steel Structures at Helsinki University of Technology using the transient state tensile test method [3], [4] and that reported by Fire and Blast Information Group (FABIG) [1], [5] have shown that high strength structural steel grades behave rather differently to those of mild carbon steels at elevated temperatures. On the strength of this outcome, it is imperative to conduct a uniaxial tensile test on welded connections made with high strength steels to obtain the actual mechanical properties appropriate to the material in use. However, it should be noted that the effects of elevated temperature exposures on the mechanical properties of most materials will depend on factors such as the test methods applied, heating rates and chemical composition. Test methods and heating rates are external factors whereas chemical composition is an internal factor.

Outinen and Mäkeläinen [3] affirmed that the material model of Eurocode 3, Part 1-2 [2], in which the nominal yield strength of steel is assumed to degrade only after a temperature of 400^{o}C is actually not realistic for high-strength structural steels. They found that the yield strength of the steel actually starts to degrade earlier than temperature of 400^{o}C. As part of their experimental plan, it was discovered from the high strength steels tested that the increased strengths inherent in cold-formed sections will certainly reduce to their nominal values after being subjected to elevated temperatures and then cooled down. However, they observed that the increased strength caused by cold forming begins to diminish at temperatures around 600°C-700°C. The large scale fire test programme conducted at the Health and Safety Laboratory (HSL), Buxton [6] was aimed at developing knowledge of the behaviour and spread of a pool fire as well as the response of steel deck to such fire. In the event, the steel plate unpredictably buckled under thermal loading and in the region of the connection, cracks in the weld were observed in some locations.

The traditional design of weld is such that its strength is the same or greater than that of the base metals. This concept has hitherto been adopted in design irrespective of the type and grade of steel used. Although the material behaviour of high strength steel at elevated temperatures has been shown to vary from those of mild steel, no study has been carried out for characterizing the elevated temperature material behaviour of butt-welded joints made with high strength steel. In this paper, the mechanical properties at

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elevated temperatures for this type of joint made with high strength steel are studied and the reduction factors that can be utilized in the calculation process described in the Eurocode [2] are calibrated.

Buckling of a plate under thermal loading is expected because of the restrained thermal expansion at the boundaries caused by the cooler surrounding regions. The crack along the weld line as observed in the HSL trial, however, may be attributed to improper welding procedure such as poor joint preparation, poor cleaning, incorrect welding parameters, form of connection between stiffeners and plate and also whether full penetration weld was achieved. It should be noted that the behaviour of weld in fire condition has not well been fully documented. However, Eurocode 3 [2] recommends that the design strength of a full penetration butt weld, for temperatures up to 700^{o}C, should be taken as equal to the strength of the weaker part connected. It is most likely that the weld will fail in fire earlier than the base metal. Therefore, an understanding of the mechanical properties of welds at elevated temperatures is required to effectively model their performance in fire conditions in order to assess their strength and integrity. Most offshore structures are fabricated with plate elements, which are joined together by different types of weld. Hence, the behaviour of welded connections is crucial to the assessment of offshore stiffened steel-plated deck.

II. EXPERIMENTAL PROGRAMME

The experimental programme was designed in accordance with the requirements of BS EN ISO 15614-1:2004+A1:2008 [7] and BS EN ISO 6892, Part 1 [8] to quantify the effect of elevated temperature on the mechanical properties of a butt-welded connection made with high strength steel. It comprises the test set up and the coupon test specimens that were prepared from butt-welded joint test pieces. Two test methods are possible in the implementation of this test programme, namely the steady-state test method and the transient test method. Steady-state test method is relatively easy to conduct because at a predetermined temperature level, stress and strain can be readily measured as the specimen is mechanically loaded to failure. However, in the case where load and deflection are the measured parameters, stress and strain can be carefully worked out by initially applying a compliance curve to specimen deflection within the gauge length due to the general movement of the testing machine.

In effect, there are two options available to measure strain on a specimen, namely the measurement obtained using the frame's extension readout and also by placing an extensometer (strain transducer) directly onto the specimen [9].

Conversely, in transient test method a predetermined load level is imposed on the test specimen such that temperature and strain can then be measured as the specimen is thermally loaded to failure. The resulting temperature-strain curves for the various stress levels can then be converted to stress-strain curves at elevated temperatures. However, it is well known that the mechanical strain produces the required stress. As a result, the thermal elongation is deducted from the total strain to obtain the mechanical strain. In order to accomplish this, the test was repeated without the application of mechanical loads and the thermal strains were measured. The initial grip on the specimen induced an infinitesimal load that prevented the specimen from undergoing compression during heating. In the design programme, the following parameters were considered.

- Heating rate: A heating rate of 20^{o}C/min and 30^{o}C/min were used initially to heat up the test specimens to the target temperatures. Thereafter, the 20^{o}C/min heating rate was finally adopted in the experimental programme as discussed in the following paragraph.
- Temperature range: Temperature range from ambient up to 600^{o}C was covered. This comprises the following: 20, 100, 200, 300, 400, 500 and 600^{0}C for the steady-state test method.
- Test method: Transient and steady-state test methods were employed.
- Welding consumable: The parent metal was grade S420M steel. The welding consumable was selected based on the requirement of BS EN ISO 15614-1:2004+A1:2008 [7] and Eurocode 3, Part 1-8 [10].

Heating rates of 20^{o}C/min and 30^{o}C/min were initially utilized to investigate their effect on the mechanical properties of the material under investigation. Two specimens were tested each at 400^{o}C and 500^{o}C using heating rates of 20^{o}C/min and 30^{o}C/min. There were no significant differences between the results based on the two heating rates. Hence, the lower heating rate was adopted.

III. TEST SETUP, TEST SPECIMEN AND INSTRUMENTATION

An elevated temperature tensile testing device was used to study and measure the load-deflection and stress-strain data from the test coupons. The test setup is an Instron electromechanical testing system with a load capacity of up to 250 kN as shown in Fig. 1. The device comprises a load cell, tension bars, a high temperature extensometer, an environmental chamber, heating elements, thermocouples and the test piece. The load cell is mounted on the crosshead and is attached to the upper tensioning bar. It is insulated completely from the excess temperature radiation that emanates from the chamber load train port. The high-temperature extensometer is fitted internally to the specimen and supported by a string as shown in Fig. 2. The chamber has three horizontal openings, two at the top and one at the bottom to allow high-temperature loading rams to transmit the tensile load from the test machine to the test specimens. The second opening at the top of the chamber is to make provision for the strain transducer cable. However, radiation losses from these openings are considerably limited.

The studied material is a joint made with thermo-mechanically rolled weldable fine grain structural steel supplied by Metal Suppliers Ltd. The base material is low alloy steel with a nominal thickness of 10mm. The welding consumable used was a Fortrex E 7018 which is a basic-

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coated, hydrogen controlled electrode designed for all positional welding of various types of steel including the medium tensile steel being studied.

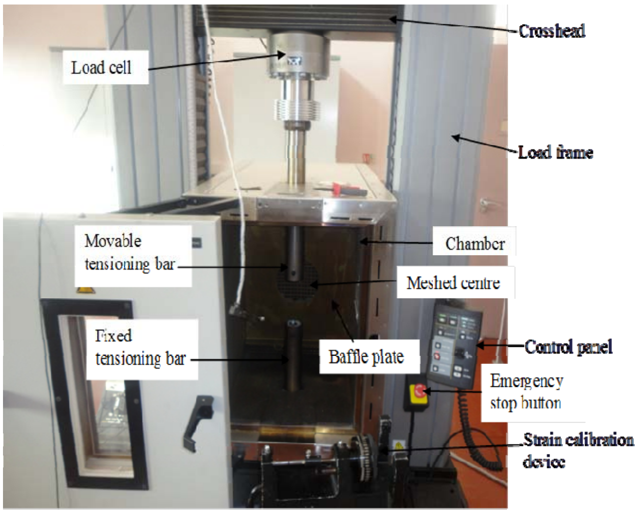

Fig. 1. Elevated temperature tensile testing device

Two types of test specimens for the butt-welded joint were prepared. The first consisted of weld-parent metal specimens while the other comprised all-weld specimens. The test pieces were prepared in accordance with weld qualification of BS EN ISO 15614-1:2004+A1:2008 [7] by welding together two plates each measuring 350 mm long, 150 mm wide and 10 mm thick, the width of the weld being 6 mm. A special jig shown in Fig. 3 was designed for this purpose in order to eliminate the possibility of any welding distortions which are likely after a welding operation. The jig comprises four holding-down bolts with adaptable cantilever supports and a base which provides an allowance for a backing plate.

The welding process parameters were chosen in accordance with weld qualification procedure of arc welding [7], [11]. The backing plates were taken from the same set of plates being joined together. With this type of design, it was not necessary to preheat the plate components before welding as the expected curvature was avoided by proper confinement provided by the open frame metal formwork. After the welding of the test pieces and having cooled down, the test specimens were then chipped off and machined into cylindrical shapes to obtain the required form for the tensile testing operation.

Finally, using the recommended coefficient of proportionality the ends of the original gauge length were marked by scribed lines on the test specimens about 30 mm apart; the parallel length being approximately 42 mm. The transition radius between the parallel length and each of the threaded grips was 6 mm in accordance with the recommended practice [8]. The overall length of the specimen was 100 mm as shown in Fig. 4. However, it may not be necessary to situate those marks to specify the gauge length in the case when the extension at fracture is to be measured using an extensometer because the strains are calculated directly. The design of the test specimens was carried out in accordance with BS EN ISO 6892, Part 1 [8].

Adequate care and precaution were ensured during welding to eliminate the possibility of fluxes remaining following each welding run. After each pass, the resulting slag was chipped off completely before the next welding run was made.

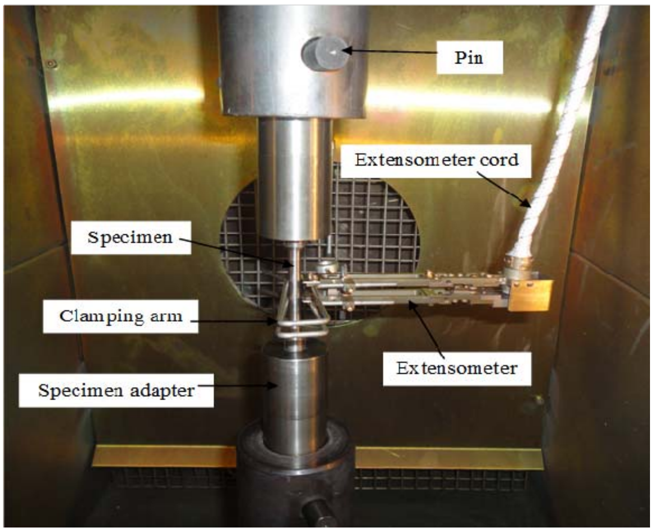

Fig. 2. Test specimen arrangement when using high-temperature extensometer

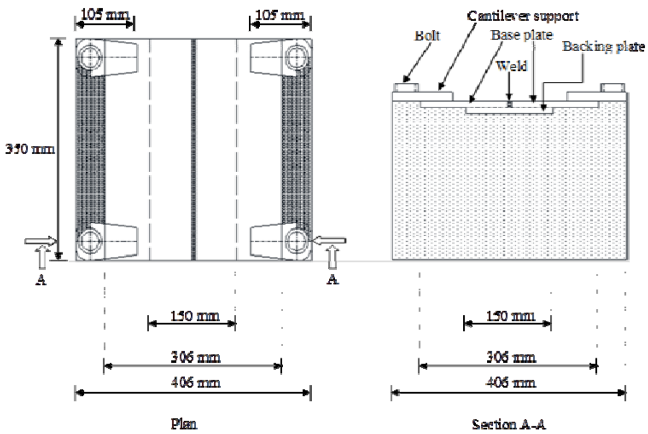

Fig. 3. Jig for the butt welding of flat plates

There were built-in thermocouples which recorded the temperature of the gas inside the chamber. Fig. 5 represents a typical test piece that was utilised to determine the mechanical properties of butt-welded joints at elevated temperatures. The test specimens were taken from both ends of the test piece as shown by the dotted rectangles. Two type K control thermocouples were attached to the surface of the test specimen to record the temperature sequence during heating as shown in Fig. 4. A heating rate of 20^{o}C/min was defined to raise the temperature inside the environmental chamber up to 600^{o}C using the programme parameters available. A centrifugal fan motor is mounted behind the chamber with a shaft extending through insulation to the impeller fans. The function of the impeller is to pull air through the meshed centre of the baffle plate and drive it over the Inconel sheathed heating elements into the chamber for an even distribution. This process helps to circulate the temperature within the chamber and the

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insulation in the chamber keeps the outer skin of the chamber very close to the room temperature condition. The baffle is usually painted matt black to provide a contrasting background within the chamber to enhance video recording and optical measurement.

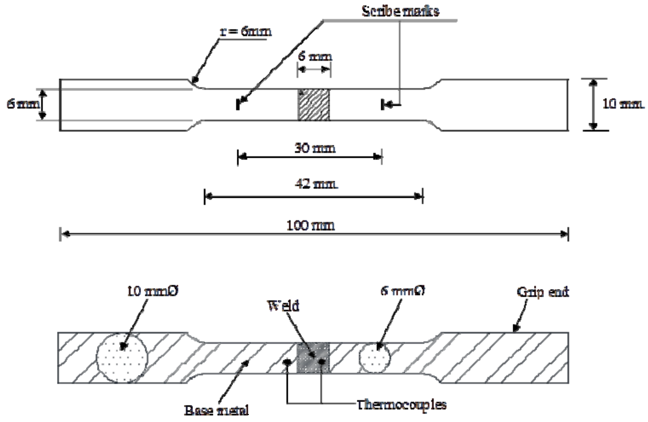


Fig. 4. Typical test specimens

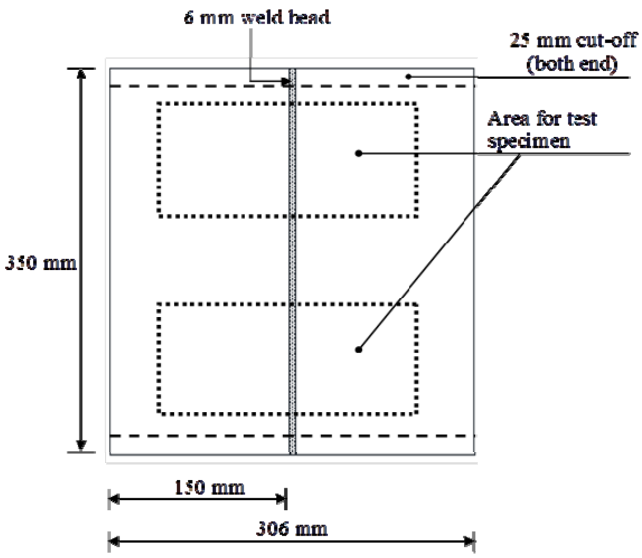


Fig. 5. Test piece showing locations of test specimens for the butt joint in plate

IV. TEST CONDITION AND TEST MEASUREMENT

The test pieces were gripped by suitable means of threaded adapters made of high strength stainless steel 304H. These adapters were in turn placed in the hollow parts of the tensioning bars with provision for slotting in two restraining pins. In order to minimize possible flexural effects, the test specimens were held in such a way that the force was applied as concentrically as possible. The force-measuring system was in each case set to zero by balancing the load and crosshead displacement after the test loading train has been assembled, but before the test piece was actually gripped at both ends [8]. Moreover, at the start of the test the ambient temperature inside the furnace was recorded using type K thermocouples attached to the test piece. With the device configured as described in section III, the temperature in the environmental chamber was programmed to follow a heating rate of 20^{o}C/min.

Using the steady state method, a deformation rate of 1mm/min was used for all tests conducted both at ambient and at elevated temperatures. In the transient state method, a predetermined stress was applied to each of the test specimens, and with the load sustained the specimen was heated to failure. The two parameters recorded in this test are temperature and strain. The type K thermocouples fitted to the specimen were used to take the incremental readings of the steel temperature while the strain measurement was recorded through a controller using the data logger

V. TEST CONTROL, TEST METHOD AND GEOMETRIC VERIFICATION OF TEST SPECIMEN

Different weld beads were first run on grooves prepared on surfaces of two metal plates with a thickness of 10 mm. The welded joint test pieces were thereafter detached from the welded plates by cutting off the unwanted regions about 25 mm span from both ends transverse to the direction of the weld. All the test specimens were then carefully machined into circular cross section. A micrometer screw gauge was be used to verify the diameter of each specimen at a number of locations along the parallel length after machining into the required form. The loading rate, both thermal and mechanical, was controlled. It should be noted that thermal loading only started after the required mechanical loading was attained and sustained at that value under transient state condition.

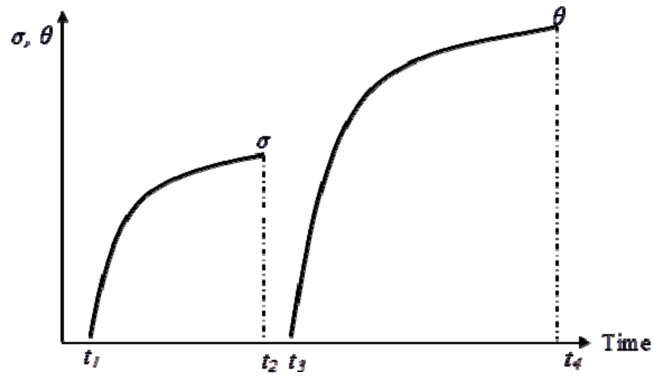


Fig. 6. Variation of thermo-structural loading with time under transient condition

A schematic of temperature and load-time relations under transient test condition is illustrated in Fig. 6. To describe the calculation procedure that is required to establish the stress strain relationship in the transient state test method, Figs. 7 and 8 are used here to represent the computation method for converting the transient state test data to stress strain curves. As the load level approaches that of the material yield strength, the maximum temperature reached prior to rupture of the test piece decreases. It should be noted that the material did not fail when the maximum temperature of 600^{o}C was attained for load levels less than 0,4 (LL < 0,4). However, the excess strains for load levels less than 0,4 (LL < 0,4) were not included in the computation of stress strain curves at elevated temperatures because such strains are usually due to creep, which was not intended in the present investigation. The parameters of interest in the stress strain curve include proportional limit, yield strength and elastic modulus. The measured stress strain data was consequently used to calibrate the reduction factors for the butt weld at elevated temperatures. These reduction factors were then used to propose a modified stress strain curve using the calculation procedure described in Eurocode 3 [2].

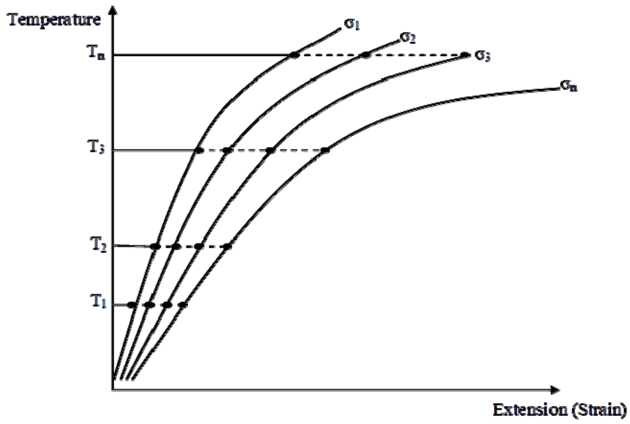


Fig. 7. Temperature-strain curves to be measured

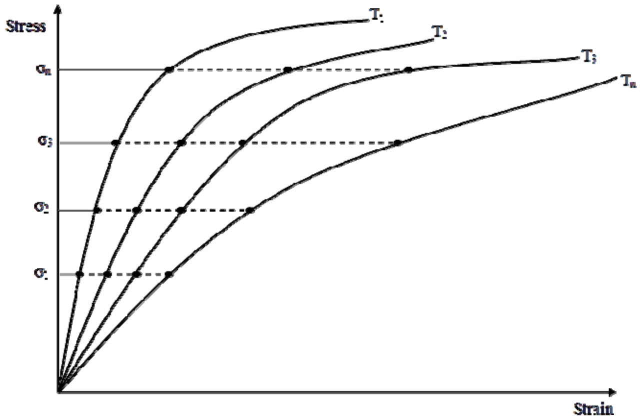


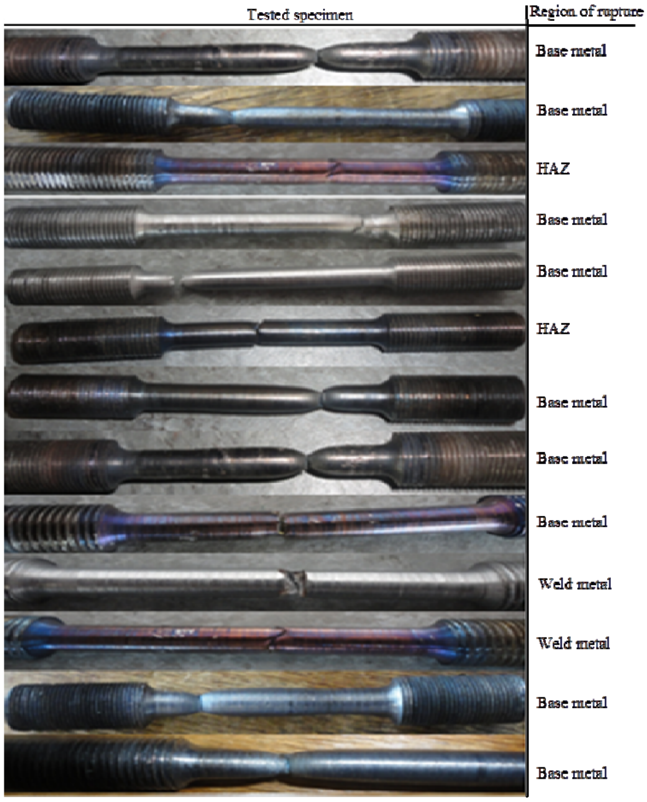
Fig. 8. Stress-strain curves to be computed

VI. ANALYSIS OF RESULTS

A total of 54 samples were tested in the laboratory for the grade S420M steel. The maximum temperature reached using both test methods was 600°C, which is the limit for the environmental chamber that was used for the test programme. As demonstrated in Table 1, failure of the specimens at regions other than the weld implies that full penetration weld was achieved and most of the specimens were ruptured by necking while a few of them did not show such failure pattern. Sha and Chan [12] have demonstrated that steady state test method often gives conservative results while transient state test method is identified to provide more accurate results.

First the results from the two test methods are compared and then the calculation parameters derived from the transient state test were used to develop the reduction factors for the design variables of interest. The effect of high temperatures on the mechanical properties of a butt welded joint made with high strength steel is therefore evaluated. The comparison of result with the Eurocode design model demonstrates that the strength of weld prepared by joining the parts of EN 10113-3 S420M steel will begin to degrade much earlier than those of low carbon mild steel. The welded specimen is observed to lose more than half of its room temperature strength at 2% strain once it has reached a temperature of 600°C.

Table 1 Random selection of tested parent-weld metal specimens based on uniaxial tensile testing



The test results are shown in Figs. 9 to 11. The experimentally determined data for proportional limit, yield strength and linear elastic range for the welded joint made with S420M steel appear to follow the results of Mäkeläinen et al. [4] very well. However, at a temperature of 400°C the weld appears to be stiffer than the parent metal and this phenomenon thus enhances the yield strength of the weld at 400°C as shown in Figs. 12 and 13.

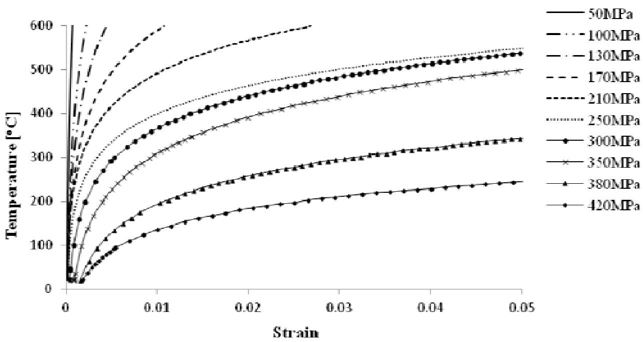


Fig. 9. Temperature-strain curves at various load levels in the transient state test for the base-weld metal specimen

An interesting result here is that within the temperature range of 20 - 600°C at which the study was conducted, the yield strength was lower than the EC 3 design strength values.

I observed that though the weld appears to have higher stiffness than that of mild steel in this range of temperature, the material started to degrade in strength much earlier as it

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softens. At a temperature of 100^{o}C the butt weld made by joining mild steel plates together seems to be more elastic than those made with S420M steel. However, the trend reverses as the material reaches a temperature of 300^{o}C as shown in Fig. 14.

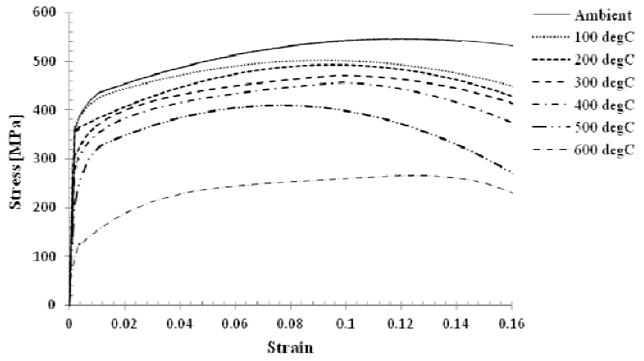

Fig. 10. Stress strain curves for butt weld made with S420M steel based on steady state test

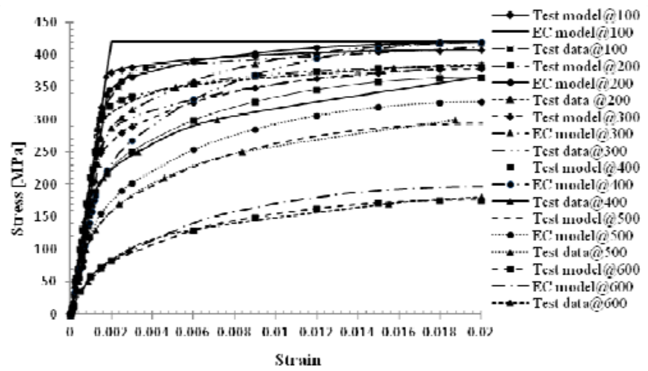

Fig. 11. Comparison of stress strain curves from test data, test model and EC 3 design model

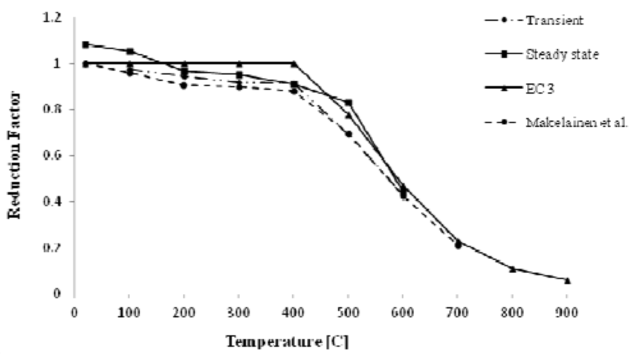

Fig. 12. Yield strength reduction factor for weld and base metal

The proportional limit of the weld based on the steady state test at temperatures below 150^{o}C was lower than the corresponding transient state test. The weld made with S420M steel showed more elastic behaviour above this temperature up to about 480^{o}C with the steady state test method.

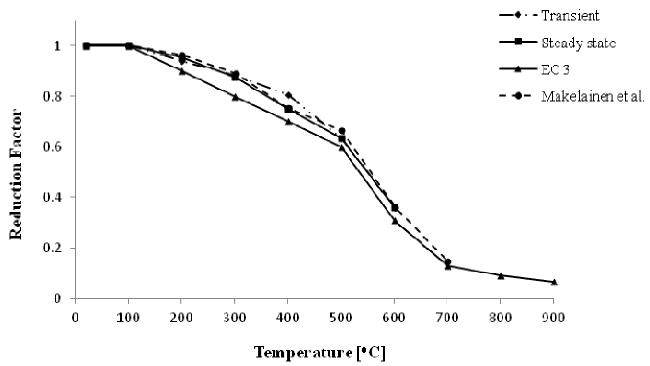

Fig. 13. Reduction factor for the linear elastic range for weld and base metal

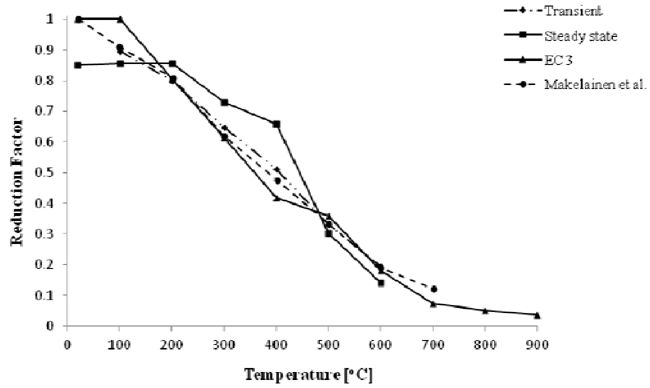

Fig. 14. Proportional limit reduction factor for weld and base metal

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