FRACTURE BEHAVIOUR, STRUCTURE AND MECHANICAL PROPERTIES OF A508 GR. 4N CLASS 3 GRADE STEEL.

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Abstract

Recent increase in output of nuclear power plant has been attained by enlargement of most major components such as pressure vessels. Such large components have almost reached a size limit from the points of manufacturing capacity. In order to solve this problem, it must be beneficial to apply by use of material of higher strength, which brings reduction of pressure vessel thickness and weight A508 Grade 4N is a high nickel pressure vessel steel with relatively high yield strength and a relatively low transition temperature. A study was undertaken to evaluate conventional as well as unconventional material properties of forging made of in our institute. This paper describes results of mechanical properties, structure and fracture behavior including nil-ductility transition temperature.

Keywords: A508 Grade 4N, Transition behavior, Mechanical Properties

1.   INTRODUCTION

A508 Grade 4N is a high nickel (3.4 %) pressure vessel steel with a relatively high yield strength and a relatively low transition temperature. Steel has an attractive combination of strength and low temperature fracture toughness. The high nickel content and refined microstructure result in a steel with excellent combination of strength, toughness and low ductile-to brittle transition temperature. A study was undertaken to evaluate conventional as well as unconventional material properties of forging made of in our institute. This paper describes results of mechanical properties, structure and fracture behaviour including nil-ductility transition temperature. Main motivation for this work was to verify of metallurgy and production technology for manufacturing of forging with sufficient metallurgical parameters as well as sufficient level of mechanical properties especially from the view of toughness.

2.   MATERIAL, TEST PROCEDURES AND RESULTS

An ingot V2A with total weight 1600 kg was produced in our institute according to ASTM A 508 [1] with VCD process. Chemical composition of ingot can be seen in **Table 1.**

Table 1 Basic chemical composition of the steel, wt%

C	Mn	Si	P	S	Cu	Ni	Cr	Mo
0.09	0.27	0.08	0.011	0.008	0.09	3.75	1.68	0.48

V	Ti	As	Sn	Sb	Al	Nb	N	O
0.008	0.006	0.005	0.004	0.003	<0.010	0.003	0.0029	0.0052

After forging in VITKOVICE HEAVY MACHINERY on final dimensions (150 x 250 x 1800 mm) and before final heat treatment specimens were cut to construct continuous cooling transformation diagram (CCT). The basis of a parameter selection many heat treatment operations is knowledge of the supercooled austenite transformation kinetic during the cosines cooling from the austeninitizing temperature. The obtaining of the optimum properties of the steel is possible only after the application of suitable heat treatment operations. Sample is austenitized and then cooled at a predetermined rate and the degree of transformation in measured using special equipment – dilatometer. Obviously, a large number of experiments are required to build up a complete CCT diagram. CCT diagram for steel under investigation is given in the **Figure 1**.
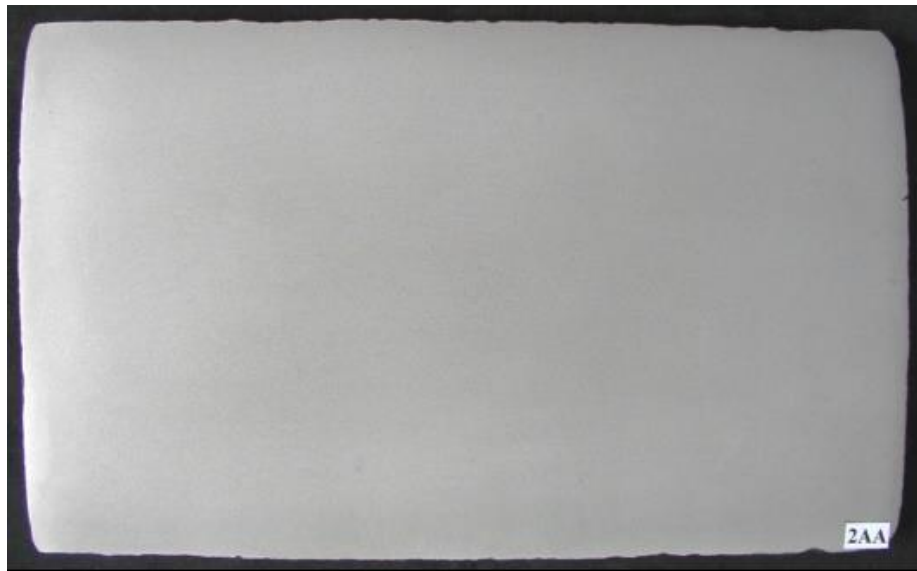
After final heat treatment containing austenitization at 890 °C following water quenching and tempering at 650 °C with cooling on air both tensile tests and impact tests have been carried out. Results of basic mechanical properties (tensile test at room temperature and impact tests at -29 °C, which is ASME specified temperature) are summarized on **Table 2**. Based on successful test results macro and microstructure analysis, inclusion content, following by testing of unconventional properties (FATT, T_{NDT}, RT_{NDT} transition temperatures as well as evaluation of fracture behaviour with fracture mechanics tests could be started. Results of macrostructure investigation are presented in **Figure 2**.
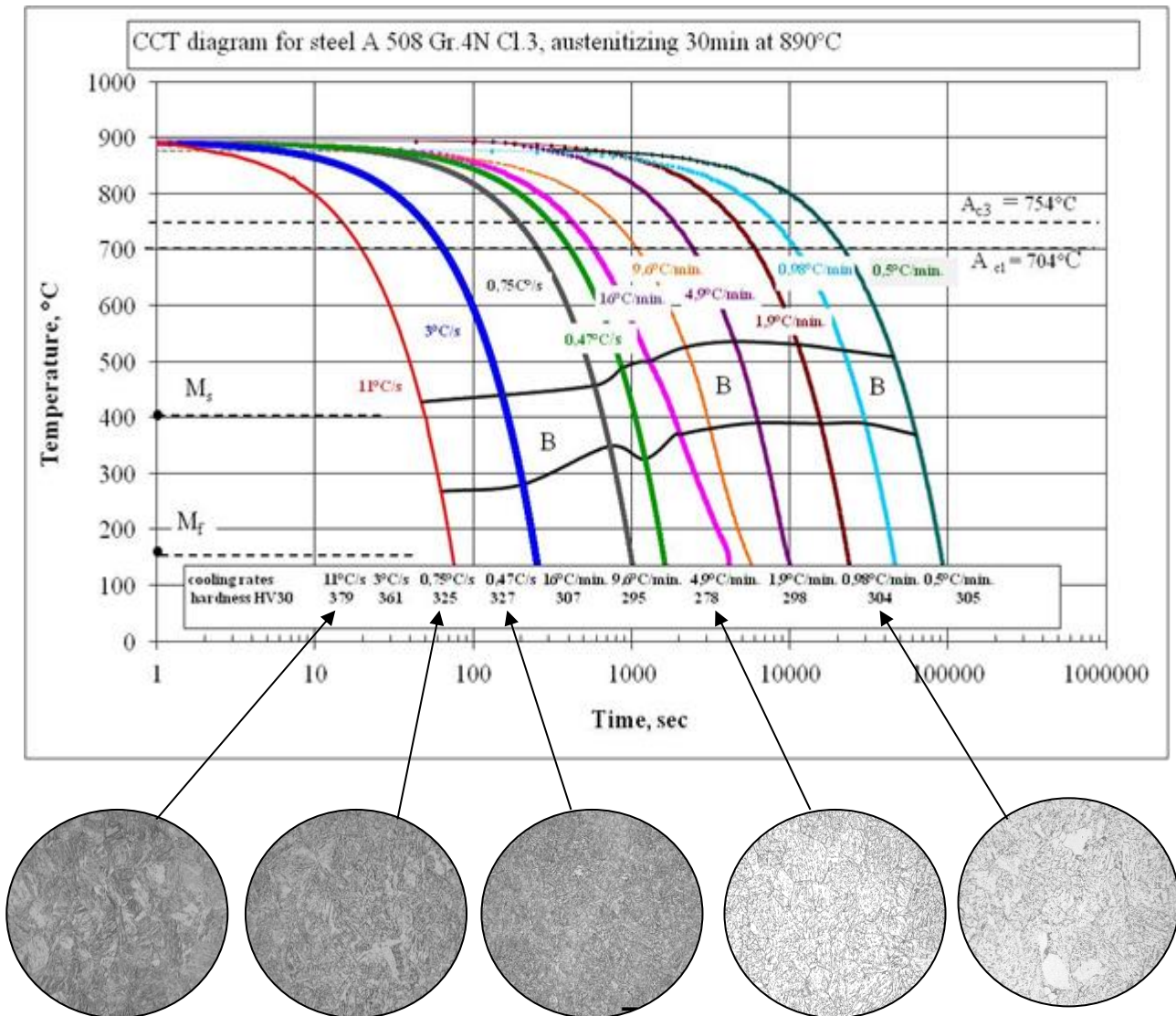
Figure 1 CCT diagram of A 508 Gr.4N Cl.3 steel with examples of microstructure

Table 2 Mechanical properties of the steel A508 Gr.4N Cl.3

Steel grade	Rp0.2 [MPa]	Rm [MPa]	A [%]	Z [%]	KV -29°C [J]
A508 Gr.4N Class3	536	638	23	74	230
ASME requirements	min. 485	620-795	min. 20	min. 48	48

**Figure 2** Macrostructure of steel A508 Gr.4N Cl.3 after final heat treatment

Inclusion content has been determined according to ASTM E 45 [2], which is well known test method covers procedure for determining the non-metallic inclusion content of wrought steel. For evaluation was used method A (worst fields). Each field was compared to the square fields depicted in Plate I-r a search for the worst field, that is, the highest severity rating, of each inclusion type A, B, C, and D for both the Thin and Heavy series. The severity level of these worst fields was reported for every specimen examined, here however due to space reason only average results are reported in **Table 3**.

Table 3 Inclusion content of the A508 Gr.4N Cl.3 grade steel

Worst field (method A)							
Type A		Type B		Type C		Type D	
Thin	Heavy	Thin	Heavy	Thin	Heavy	Thin	Heavy
1.2	0.6	1.1	0.8	0	0	1.25	0.3

To obtain more information about transition range of steel under investigation series of Charpy impact tests have been carried out to evaluate position of transition range on temperature axis and quantify all most widely used transition temperature. Results of Charpy impact tests are plotted in the form of temperature dependence of impact energy in the **Figure 3**.

Similar dependencies were obtained both for percent of shear fracture and lateral expansion. From these dependencies transition temperatures were calculated – see **Table 4**. Two last columns in **Table 4** represent nil ductility temperature evaluated according to ASTM E 208 [3] and reference nil ductility temperature RT_{NDT} that make connection between results of drop weight tests and Charpy impact test. For details of RT_{NDT} evaluation see ASME Code [4].
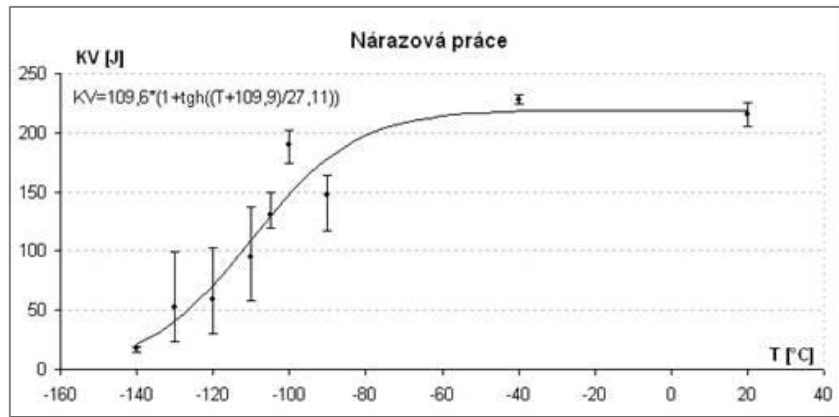
Figure 3 Temperature dependence of impact energy

Table 4 Transition temperatures of steel under investigation

$T_{27 J}$	$T_{41 J}$	$T_{68 J}$	FATT	$T_{0.9 mm}$	RT_{NDT}	T_{NDT}
-138 °C	-130 °C	-121 °C	-114 °C	-120 °C	-115 °C	-120 °C

Recently developed so called Master curve concept based on evaluation of reference temperature T_0 was used for evaluation of fracture behaviour [5,6]. In this concept modern statistical methods, and an improved understanding of elastic-plastic test methods, have been coupled to define a transition curve of static fracture toughness versus temperature that is derived using only fracture mechanics-based test data. Main advantage is that uncertainty associated with the empirical postulates involving non-fracture mechanics data that had to be employed in the past for ASME Code has been eliminated. ASTM E 1921 [6] presents now the experimental and computational procedures that are to be used to arrive at a reference temperature, T_0. Temperature T_0 is defined as the temperature at which a set of data having six or more valid K_{JC} values converted to 25.4 mm size equivalence will have a median 100 MPa$\cdot$m$^{0.5}$. Master curve is an empirically derived universal transition range curve of fixed shape for static fracture toughness versus temperature. It is known to characterize the transition range of commercially made ferritic steels and weld metals. The Master curve essentially verifies the ASME postulate, differing principally in the reference temperature indexing method, using T_0 instead of RT_{NDT} and a median transition curve shape instead of K_{IC} lower bound. Fracture toughness tests were carried out at test temperature -140 °C to obtain median of fracture toughness about 100 MPa m$^{0.5}$. Based on experimental data Master curve with tolerance bounds for fracture probability correspond to 5 and 95 % have been plotted in the **Figure 4**.
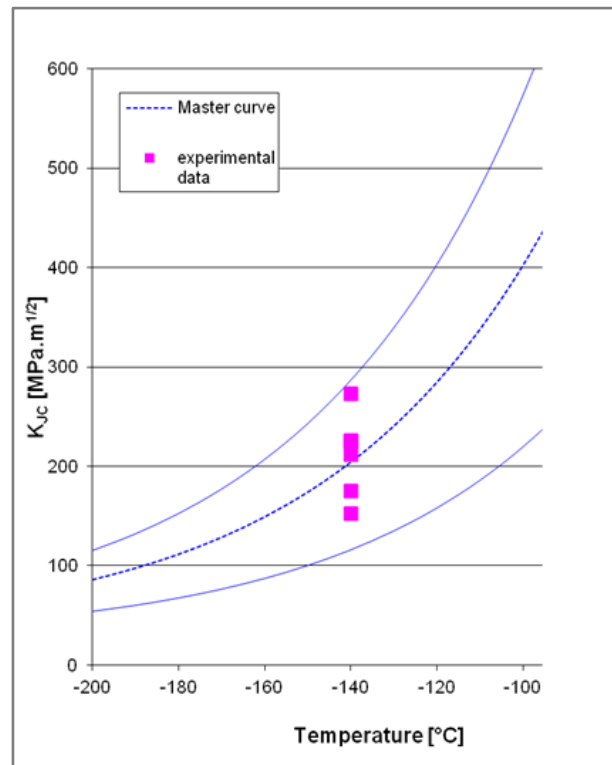
Figure 4 Master curve of steel A508 Gr.4N Cl.3 (including tolerance bounds for 5 and 95 % fracture probability

3.   RESULTS AND DISCUSSION

3.1.   Structure and mechanical properties

Microstructure of the steel under investigation was found to be fully bainitic in whole range of cooling rates – see CCT diagram – **Figure 1**. Only two cooling rates with – v = 4.43 and 4.73 respectively (correspond 0.98 and 0.5 °C/min) showed a very small amount of ferrite localized mostly in small isles. Total amount of ferrite has been found to be below 2 %. Macrostructure analysis shows, that structure is clear without any segregation. From the **Table 3** can be clearly seen that non-metallic inclusion content characterized by worst field method is good and indicates sufficient level of metallurgy during production. These results are in very good accordance with reference [7].

Mechanical properties summarized in **Table 2** meet all requirements with sufficient level. During this work several tempering temperatures have been chosen to get information about structure and properties including toughness in wide interval. Tempering temperature 650 °C was chosen from the point of view maximum toughness level.

3.2.   Impact properties and fracture toughness

Excellent toughness was confirmed by Charpy impact tests, temperature dependencies of all characteristics earned from Charpy impact tests declared very low transition temperatures (see **Table 4**) usually used for toughness characterization of pressure vessel steels used in nuclear power engineering. Additionally, nil ductility temperature as well as its normalized value RT_{NDT} also confirmed perfect toughness properties. Our results are on the same level or better compared with [8].

Temperature dependence of fracture toughness has been presented in the form of Master curve – see **Figure 4**. Value of evaluated reference temperature agree very well with results presented in [9] where large comparison of available fracture toughness data was carried out from the point of view variability of fracture toughness in the transition range. Based on experimental data from more than 800 fracture toughness test results a new model describing behavior of A508 Gr.4N has been introduced in [9]. Our experimental results completely agree with the findings presented in [9].

4.   CONCLUSION

Paper summarized results of structure analysis and mechanical properties including fracture toughness data for A508 Grade 4N Class 3 pressure vessel steel. Obtained results show on good metallurgical level during manufacturing process. Heat treatment was primarily focused on optimizing toughness properties characterized by low transition temperatures based on Charpy as well as on DWT tests. Transition temperatures have been found to be between -138 and -114 °C. Fracture toughness was characterized using recent concept called Master curve approach based on evaluation of reference temperature T_0. Value of reference temperature T_0 was found to be – 188 °C and also confirmed excellent toughness properties of the steel under study. Our results are in a very good agreement with results presented in references [7-9].

ACKNOWLEDGEMENTS

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