Effect of Intercritical Annealing on Fracture Behaviour of 10GN2MFA Grade Steel

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Abstract.
The effect of intercritical annealing of 10GN2MFA grade steel on mechanical properties and fracture behaviour is studied in this paper. This type of low alloy banitic steel is usually used for production of collector bodies of steam generators for nuclear power station of VVER type. This article is focused on optimalization of fundamental utility properties and heat treatment process of the steel under investigation to increase toughness and critical temperature of brittleness. An intecritical annealing has been chosen as a useful tool for such improvement. Mechanical properties and impact notch toughness values after the intercritical annealing and conventional heat treatment regimes are compared. Effect of simulation of stress relieving including minimum and maximum allowable heating regimes on fracture properties is studied too. Intercritical annealing was added to the conventional quality heat treatment process, between quenching (normalizing) and tempering. The application of intercritical annealing improved the impact toughness significantly, an increase in the upper shelf energy and a decrease in transition temperature of steel under investigation.

Introduction

The low alloy bainitic 10GN2MFA steel is used for manufacturing of collector bodies of steam generators for nuclear power stations of type VVER 1000 in the Czech republic as well as in Russia. On the present days there are two basic procedures for manufacturing this type of steel.

Standard procedure used today in VÍTKOVICE – Heavy Machinery includes melting in electric arc furnace, ladle furnace, vacuum degassing and bottom pouring with stream protection in inert gas Ar. This procedure can guarantee phosphorus content below 0.010 % and sulphur content below 0.005 %. This type of production technology was used for all 16 pieces of steam generators collectors designed for nuclear power station Temelín.

In Russia however the process of production of this steel requires electroslag remelting to produce a more cleanness steel.

Electroslag remelting process can increase cleanness of steel significantly, this process reduces sulphur content and sulphur does not form segregations. Impurities in steel, especially high sulfur inclusions content, affect impact toughness significantly [1]. Electroslag remelting is a one of possibilities how to increase impact toughness level. On the other hand there is other possibility how to increase impact properties – to apply optimized heat treatment regime.

Because of the chemical composition of the steel under investigation an intercritical annealing (IA) has been chosen to improve impact toughness properties significantly without changes in the other mechanical properties. In the first step optimalization of intercritical annealing was develop as well as evaluation of intercritical annealing on impact toughness properties. This step is covered in this article.

The IA was originally develop for dual phase ferritic-martensite steels but very soon was applied also for the other structural steels [2-4]. In references [3,4] was very detail studied bainitic

MnNiMo steel A 508 Grade 3, which is used for production of pressure vessel heavy forgings for nuclear power station in the west. The IA was also applied and this heat treatment regime was accepted by ASME CODE.

Generally the application of IA refine the structure and improve the impact toughness significantly, an increase in the upper shelf energy and a decrease in transition temperature of steels. This type of heat treatment can be applied to many other grades of structural steels. The aim of the present contribution is to compare mechanical and impact properties after IA with standard heat treatment regime and to optimize conditions of intercritical annealing regime.

Applied heat treatment regimes:

Segment 1: Normalization 910°C/4 h/water + IA 760 °C/4 h/water + tempering 650°C/6 h/air
Segment 2: Normalization 910°C/4 h/water + IA 740 °C/4 h/water + tempering 650°C/6 h/air
Segment 3: Normalization 910°C/4 h/water + IA 720 °C/4 h/water + tempering 650°C/6 h/air

In order to get more complex information about the effect of IA on structure and mechanical properties, the effect of simulation of PWHT including minimum and maximum simulations were applied in the second step of our study. Minimum PWHT is used in the case if weld is without any defects. On the other hand maximum PWHT is applied if the welded joint permitted repairs must be used. In any case the results of mechanical properties in as received condition (before welding) shall be satisfactory and according to requirements in the Table 1. Minimum and maximum simulations were applied according to following regimes. The holding time was chosen always as large as possible to get the most conservative results.

Minimum simulation of PWHT: heating on 350°C, heating rate max. 50°C/h on temperature 620 °C/holding time 2.5-3 h, heating max. 50°C/h on temperature 650°C, holding time 15-16 h, cooling rate max. 25°C/h on temperature 300 °C, air

Maximum simulation of PWHT: heating on 350°C, heating rate max. 50°C/h on temperature 620 °C/holding time 2.5-3 h, heating max. 50°C/h on temperature 650°C, holding time 24-30 h, cooling rate max. 25°C/h on temperature 300 °C, air

The results obtained from tensile tests and Charpy impact tests including impact energy at –10 °C as well as calculation of critical temperatures of brittleness are presented in the Table 2.

Tensile tests and Charpy impact tests were carried out according to latest EU standards.

Microstructure after IA and tempering was found very fine grain, formed by ferrite and little islands with ferrite-carbides mixture (see Fig. 1 and Fig. 2).

Table 1: 10GN2MFA mechanical properties requirements

Mechanical properties at										Critical temperature of brittleness T_{K0}
+20℃					+350℃				-10℃	
$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]	Z [%]	KCV [J.cm^2]	$R_{p0,2}$ [MPa]	R_M [MPa]	A_5 [%]	Z [%]	KCV [J.cm^2]	
345-590	540-700	18	60	59	min.295	min.490	15	55	39	max. –10℃

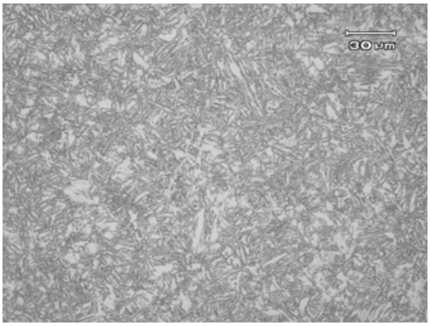

Fig.1 Microstructure after IA 760°C

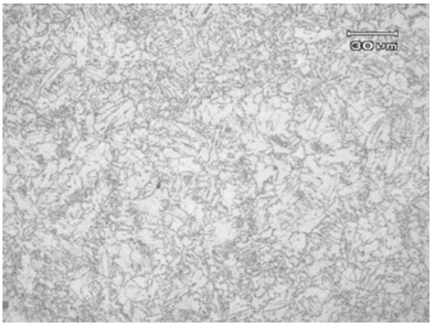

Fig.2 Microstructure after IA 760°C+ tempering

Discussion

The results presented in Table 2 clearly show, that after IA between temperatures 720 °C and 760 °C with following tempering at 650 °C mechanical properties from tensile test meet all requirements given in the Table 1. Impact properties are characterized both very high impact toughness level at –10 °C and very low value of critical temperature of brittleness T_{K0}.

A very moderate drop in tensile properties was identified in all cases after application of simulation PWHT (minimum as well as maximum regimes) both at room and at elevated temperatures. This decreasing of yield stress at room temperature was found to be between 2 and 13 % and for tensile strength between 2 and 7 %.

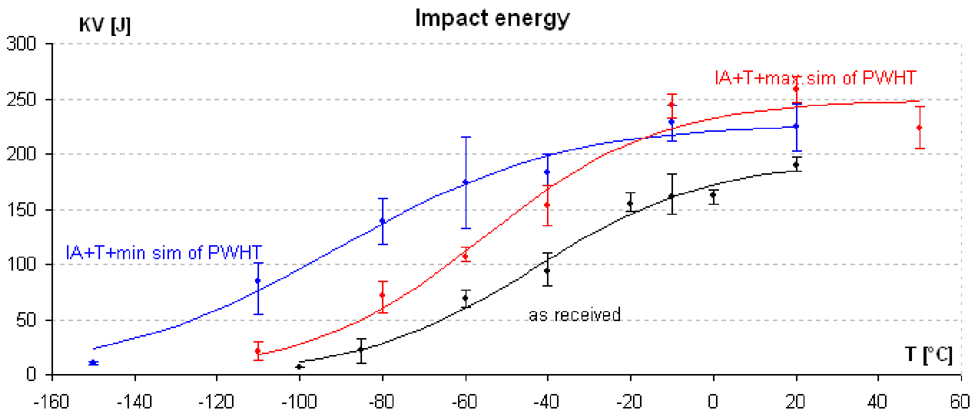

Fig.3: Effect of IA and simulation of PWHT on temperature dependence of impact energy for segment 1

Table 2: Effect of heat treatment on mechanical properties of 10GN2MFA grade steel

State	Temperature [°C]	$R_{p0,2}$ [MPa]	R_m [MPa]	A_5 [%]	Z [%]	$KCV_{-10°C}$ [Jcm^{-2}]	T_{K0} [°C]
Required properties	+20	345	540	18	60	39	-10
	+350	295	490	15	55		
Segment 1	+20	489	593	28	77	270	-59
	+350	402	576	26	73		
Segment 2	+20	473	583	30	75	300	-60
	+350	394	575	23	73		
Segment 3	+20	464	576	28	74	330	-75
	+350	379	567	25	74		
Segment 1 + min. sim.	+20	478	560	31	76	246	-55
	+350	352	525	26	73		
Segment 2 + min. sim.	+20	438	561	30	74	188	-39
	+350	332	531	30	73		
Segment 3 + min. sim.	+20	417	566	28	74	223	-40
	+350	343	532	27	73		
Segment 1 + max. sim.	+20	454	551	29	76	225	-50
	+350	344	520	25	68		
Segment 2 + max. sim.	+20	413	558	29	72	199	-37
	+350	335	537	27	72		
Segment 3 + max. sim.	+20	432	554	35	75	218	-35
	+350	340	521	27	71		

At elevated temperature (+350°C) the lowering of yield stress was found to be between 9 and 16 % and for tensile strength between 6 and 10 %. Generally upper limit of differences is valid for maximum simulation of PWHT and the lower limits come from segment 1 (IA at +760 °C).

Very similar effect was noted in the case of results of Charpy impact tests after both simulations. Effect of simulations on the impact toughness was interpreted in the form of critical temperature of brittleness shift, as shown in the Table 3. The shift in the temperature dependence of impact energy for segment 1 can be very good seen also in the Fig.3.

However all three variants of IA give fully satisfactory results according to the technical requirements. Even in the worst case (segment 3 – IA 720 °C) the average value of impact toughness at –10 °C was found to be 188 Jcm^{-2}. This value is five times greater then required and nearly twice greater than value after conventional heat treatment regime (101 Jcm^{-2}).

Based on the experimental results presented in the Table 2 and Table 3 and also based on the fracture mechanics test results presented in the Fig.4 [5] we can conclude that optimum temperature for IA of 10GN2MFA steel is 760 °C with following tempering at 650 °C. In this case impact toughness at –10 °C even after application of simulation heat treatment does not drop below 225 Jcm^{-2} as well as the temperature shifts due simulation of PWHT are minimum.

Table 3: Effect of simulations on critical temperature of brittleness

Identification	Min. simulation of PWHT	Max. simulation of PWHT
	ΔT_{K0} [°C]	
Segment 1	4	9
Segment 2	21	33
Segment 3	35	40

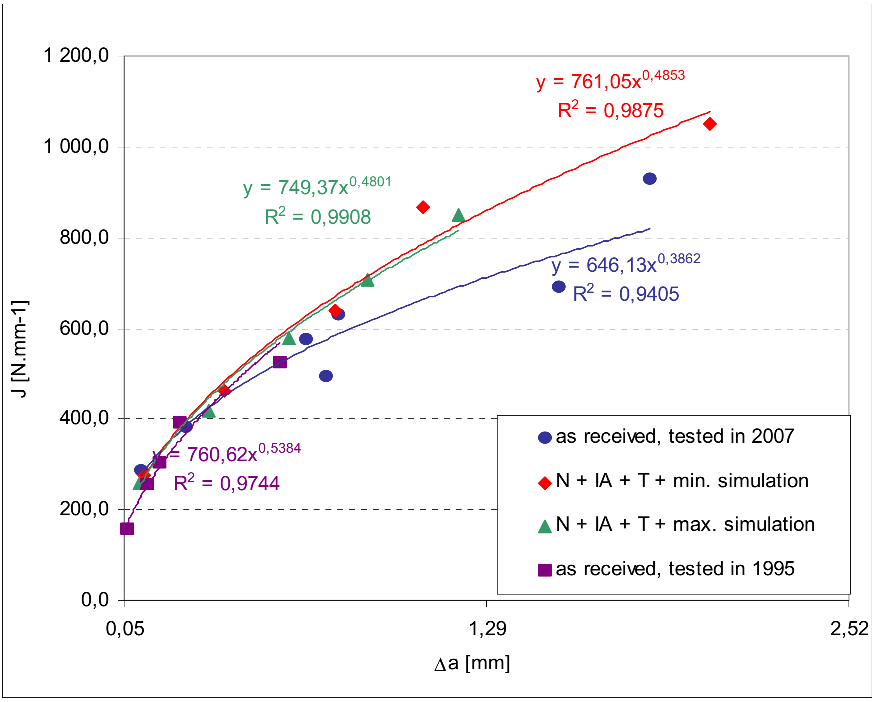

Fig.4: Effect of IA and simulation of PWHT on temperature dependence of impact energy for segment 1

Summary

The results of the work can be concluded as follows

- Intercritical annealing increases impact properties significantly without affecting other mechanical properties. High impact toughness level was not decreased even after simulations.
- The critical temperature of brittleness was found after intercritical annealing to be between –75 and –60 °C
- Intercritical annealing from temperature 760 °C appears to be an optimum heat treatment regime
- Initial value of stress intensity factor is both for as received state and states after PWHT simulations same and reach the value $K_{J0,2}$ = 270 $MPam^{0,5}$. Presented R curves given in the Fig. show very high material resistance to stable crack growth.
- Further work is necessary to get an idea about structure stability during exposition on working temperature, we prepare to evaluate the effect of intercritical annealing on unconventional properties (stress corrosion cracking, etc.)

Acknowledgements

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References

[1] Korcak,A., Matocha,K.,Kander,L.: Kollektory teplonositela PG – izgotovlenie i poverka na stoikost protiv korozionnogo raztreskivania, Vitkovice – Heavy Machinery a.s., (internal)

[2] A.Schwedler: Einfluβ der Wärmebehandlung im Bereich der A_{c1}/A_{c3}-Temperatur auf das Gefüge und Eigenschaften niedriglegierter Baustähle, Stahl und Eisen, 99,V 10, 1979, 22-34

[3] B.-J.Lee, H.-D.Kim, J.-H.Hong: Calculation of α/γ equilibria in SA 508 Grade 3 Steels for intercritical heat Treatment, Metall. And Mater. Trans. A, 29A, May 1998, 1441-1447.

[4] H.-D.Kim, Y.-S.Ahn, Y.-J.Oh, G.-M.Kim, J.-H.Hong: Effect of intercritical annealing on toughness and strength of SA 508 Gr. 3 heavy section forging steel, 13th Int. Forgemaster Meeting, Advances in Heavy Forgings, October 12-16, 1997, Pusan, Korea, Vol. II, Sesion 5, 197-208.

[5] Kander,L. a kol.: Effect of intercritical annealing on properties of 10GN2MFA grade steel used for nuclear power station. In Proc. 21. dny tepelneho zpracovani, Jihlava 2006, p.193