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EFFECT OF AGING TIME AND BORON ADDITION ON THE PROPERTIES OF 9-12% CR POWER PLANT STEELS – OUTCOMES FROM DIFFERENT EXPERIMENTAL INVESTIGATIONS

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Abstract

The relation between the aging time and the mechanical properties of the investigated steels was demonstrated graphically as a result of an experimental work in this paper. The effect of trace boron in steels, especially the influence of boron on microstructure and properties of 9–12% Cr steels were also summarized. Three alloys with and without boron of 9% Cr steels were prepared. The specimens prepared for testing were aged at 20 ^{o}C and 650 ^{o}C for time range of 3000 to 10000 hrs. Concerning the effect of boron addition to the 9–12% Cr steels, some results of recent investigation studies by other researchers were also mentioned in this paper for more information about the role of this alloying element in improving of high alloyed chromium steels.

Keywords: boron addition, aging time, creep strength, embrittlement.

Introduction

In recent years, the construction of ultra super critical (USC) power generation plants with higher efficiency has been accelerated by the demand of reducing $C0_2$ emission for the protection of global environment. The USC power plants require new heat-resistant steels with improved creep rupture strength and steam-oxidation resistance at elevated temperature around 650 ^{o}C. Over the last few years, extensive studies have been made on 9–12% Cr ferritic heat-resistant steels containing W, which are expected to have improved creep rupture strength. There are also many investigations of the addition of B into ferritic heat-resistant steels to improve creep lives [1].

These investigations have proved that new ferritic steels with a controlled addition of boron possess excellent creep resistance compared to conventional steels like P91, P92, P122, etc., and this has been attributed to the delay in coarsening of the carbides during creep owing to partial replacement of carbon by boron in these compounds [2]. These steels are not modifications of any others; though their structures were designed by using basic metallurgical fundamentals in an attempt to create steels which combine good corrosion/oxidation resistance with excellent high temperature creep strength. Their excellent high temperature strength is thought to be primarily due to a uniform dispersion of very fine particles, which are resistant to coarsening at elevated service temperatures [3].

1. Experimental Procedures

The experimental work of this paper covered the investigation of three types of 9% Cr steels that are being used for HP/IP components in power generation plants. Two of these steels were cast types, and the third one was forged type. Every type of these steels was divided into other subtypes (subcodes) according to the state of the steel during testing. Some tests were carried out for basic conditions of steel, and others were performed for aged conditions at different temperatures and different aging times. *Table 1* shows these types of steels, some of their alloying elements, and their conditions at the tests.

Three types of mechanical tests were carried out to determine the properties of these steels, Charpy impact tests at different temperatures, tensile tests at different temperatures, and metallographic tests.

Table 1. Types of the investigated steels and the content of the main alloying elements

Steel type	Content of alloying elements (wt %)					Steel subcode	Aging temp (^{o}C)	Aging time (hrs)
	Cr	Mo	W	Co	B			
						5.0 (base)	20	0
Cast Steel	9.7	1.4	–	0.9	–	5.1 (aged)	650	3000
						5.2 (aged)	650	6000
(code 5)						5.3 (aged)	650	10000
						7.0 (base)	20	0
Cast Steel	8.9	0.46	1.7	-	0.003	7.1 (aged)	650	2000
						7.2 (aged)	650	2000
(code 7)						7.3 (aged)	650	6000
						10.0 (base)	20	0
Forged Steel	9.5	0.45	1.8	1.0	0.0035	10.1 (aged)	650	3000
						10.2 (aged)	650	6000
(code10)						10.3 (aged)	650	10000

2. Results and Discussion

2.1. Impact Tests

The impact energy KV of steel # 5 increased by increasing aging time at 650 ^{o}C up to 6000 hours (*Fig. 1*), and decreased when the steel was aged for 10000 hours.

In case of steel # 7, KV decreased by increasing aging time at the same aging temperature.

As a consequence of the increase of the KV-values of the steel code 10, the ductility is the lowest among the three investigated steels (*Fig. 2*), this may be attributed to the higher content of boron in this steel.

The difference of KV-values between the base and aged materials up to 6000 hours is greater in case of steel code 10 than those of the other steels code 5 & 7.

2.2. Tensile Tests

An electro-mechanical machine with a maximum force of 100 KN was used to perform these tests. The specimens were prepared according to the A_5-round type.

Both the yield and tensile strength of the steels code 5 & 10 gradually decreased with increasing aging time as shown in *Fig. 3*, except the sharp drop of the yield strength of the free-boron steel code 5 after aging of 3000 h to 6000 h.

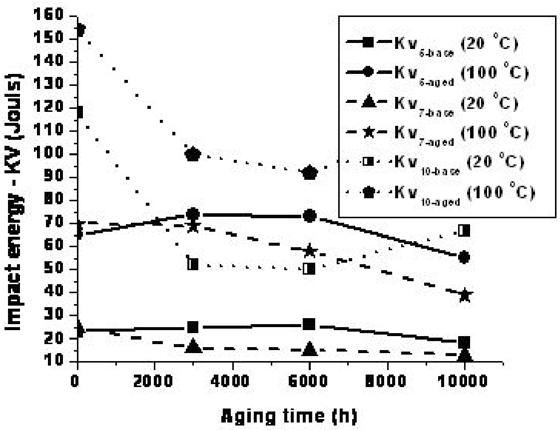

Fig. 1. KV of the investigated steels at 20 ^{o}C & 100 ^{o}C.

Fig. 4 shows a different effect of the aging time on the elongation % of the two steels, (code 5 & 10) which increased with increasing aging time up to 6000 hours, after that it decreased.

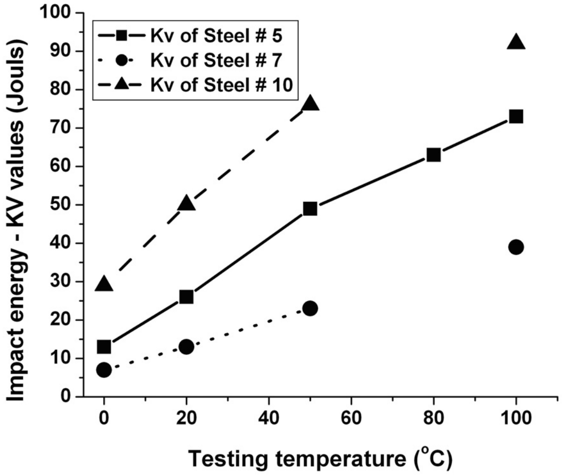

Fig. 2. KV of the three steels (code 5, 7, and 10) aged for 6000 h, at 650 ^{o}C.

2.3. *Metallographic Tests*

This test was applied to the three investigated steels and their subcodes. The results of this test were as follows; (1) the micrographs of the steel code 5 showed fine grains of tempered martensite with carbide precipitations and some δ-ferrite grains as it is shown in *Fig. 5a*, (2) In case of steel code 7 the micrographs (*Fig. 5b*) showed coarse grains of tempered martensite with carbide precipitations and also some δ-ferrite grains, (3) fine grains were also observed for steel code 10 in the micrograph shown in *Fig. 5c*.

Generally when hardenable steel is quenched lath martensite grains are produced, and after tempering of these grains precipitation process of metallic carbides takes place. These carbides are MC-carbides such as VC & NbC, and $M_{23}C_6$-carbides such as $(Fe, Cr, Mo)_{23}C_6$, $M_{26}C_6$-carbides such as $(Fe, Cr, Co, V, Nb)_{26}C_6$.

3. Recent Studies of the Boron Effects on 9–12% Cr Steels

New ferritic steels that can be used in ultra supercritical fossil power plants operating at temperatures above 650 ^{o}C are developed worldwide. One of the techniques employed for the development of the new steels is the controlled addition of boron, and new steels containing boron are being tested in different countries. Results from these studies have shown that the creep properties of the newly developed boron-containing ferritic steels are significantly superior to those of the more conventional steels like the P91, P92, and P122 steels [2].

TOSHIAKI and his co-authors [1] have investigated the effect of B on creep strength in a 9Cr-3W base ferritic heat-resistant steel by analysing creep rate curves

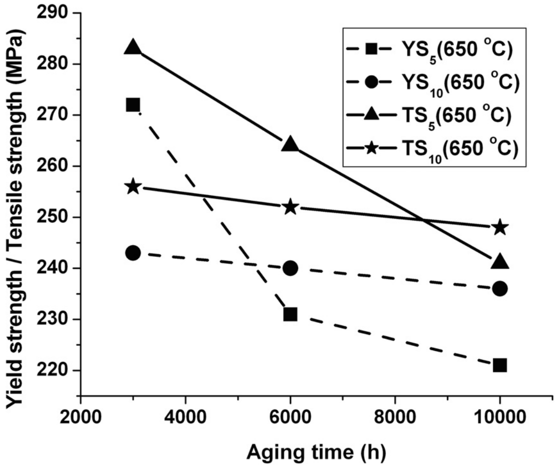

Fig. 3. Effect of aging time on the yield & tensile strength of the steels code 5 and 10.

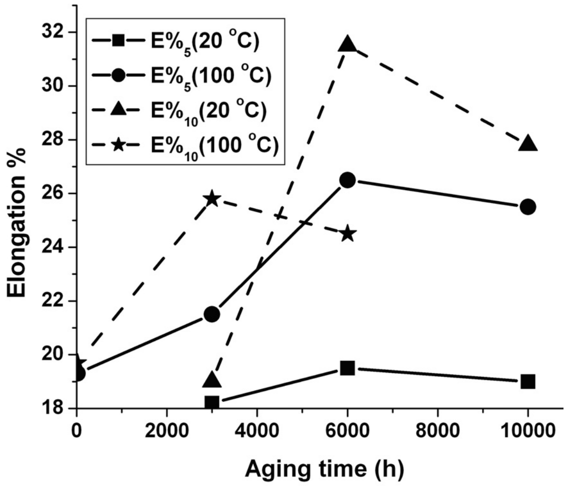

Fig. 4. Effect of aging time on the elongation % of the steels code 5 and 10.

and by characterization of B in precipitates, and they found that the boron content in $M_{23}C_6$ carbides in the vicinity of prior-austenite grain boundaries is relatively higher than that inside the grains. This suggests that B improves microstructural stability in the vicinity of grain boundaries through the stabilization of $M_{23}C_6$ carbides and suppresses the coarsening by enriching B into them. They have also mentioned that the amount of effectively utilized B is important to improve creep strength and high-temperature normalizing can increase this property.

SHAJU K. ALBERT and his colleagues [2], concluded that the boron-containing

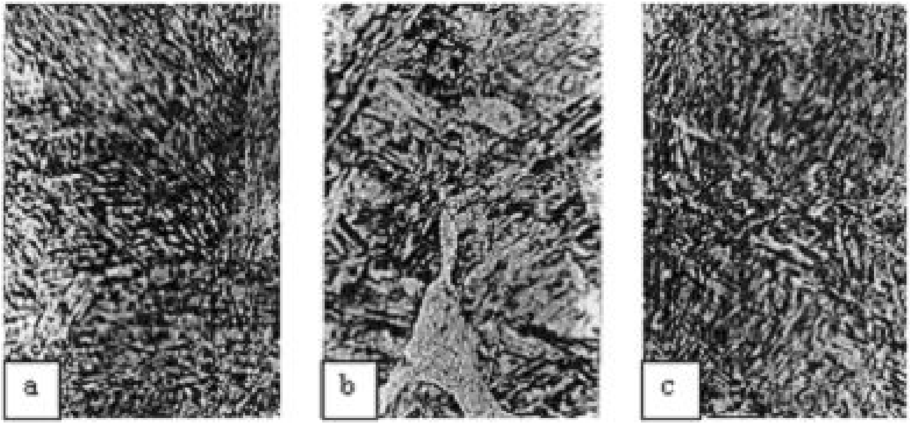

Fig. 5. Micrographs for; (a) steel code 5, (b) steel code 7, (c) steel code 100

steel they investigated have shown that the presence of boron in the carbides retards coarsening of these carbides and the recovery of the dislocation substructure. Thus, based on all of these results, it is concluded that boron is effective in delaying the coarsening of the particles, which, in turn, delays the dislocation substructure coarsening. It turned out also from their results that the type IV-cracking is suppressed in the weld joints of this steel.

WARREN M. GARRISON [3] pointed out in his report that boron segregates to grain boundaries under both equilibrium and non-equilibrium conditions and reduces, or eliminates the detrimental embrittling effects of such segregating impurities as P, S and others. Thus, boron protects the austenite grain boundaries from phosphorus segregation during heat treatment and service.

G. HAYWOOD and D. NAYLOR [4], pointed out that boron has a dramatic effect on the transformation characteristics and hardenability and it retards the formation of ferrite and pearlite, thus enabling martensite to be formed during fast cooling.

P.HOFER and his co-workers [5] investigated the boron distribution in various phases such as $M_{23}C_6$, M_6C, MX, and Laves phases in the as-received condition of the steel grade X18CrMoVNbB 9-1 (B2). They found that the distributions of these carbides are finer in boron containing steels compared to that of other steels, and these steels show a pronounced difference in the microstructure evolution that is different from conventional 9-12 % Cr steel, which is reflected by a low minimum creep rate.

4. Conclusion

4.1. Effect of Aging Time on the Impact Energy of Cr Steels

In general the impact energy of steels decreases by increasing aging time due to precipitation processes and increasing hardness. The toughness of steel code 5 decreased and the reason could be the absence of (B & W) additions and the cast condition of this steel. The toughness of steel code 7 improved because of the presence of B & W additions, while the toughness of steel code 10 highly improved due to homogenous microstructure of the forged steel, and the presence of B with W & Co additions all together in this steel.

4.2. Effect of Aging Time on the Yield Strength and Tensile Strength of Cr Steels

Generally both the yield strength & tensile strength of the steels decrease by increasing aging time as in the case of steels code 7 & 10. Because of the precipitation processes the situation changed for the steel code 5 where both increased up to aging time of 3000 hours and then decreased again by increasing aging time.

4.3. Effect of Boron Addition to Cr Steels

Controlled addition of boron improves the toughness property due to the homogenous recrystalized microstructure of steel especially in the forged condition. Boron improves microstructural stability in the vicinity of grain boundaries through the stabilization of $M_{23}C_6$ carbides and suppresses their coarsening by its enrichment into them. It was also observed that the distributions of these carbides are finer in boron containing steels, which is reflected by a low minimum creep rate.

Boron addition suppresses the occurrence of type IV-cracking in the weld joints of boron-containing-steels. Another advantage of boron addition to steel is the reduction or elimination of embrittling effects by protecting of austenite grain boundaries from phosphorus segregation during heat treatment and service. Retarding the formation of ferrite and pearlite is another effect of boron, thus it enables martensite to be formed during fast cooling.

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