Effect of Tempering Temperature on Hardness and Impact Resistance of the 410-1Mo Martensitic Stainless Steels for Steam Turbine Blades

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Abstract--- **Tempering is an important process to produce the martensitic stainless steels having the desired properties. This paper reports the influence of tempering temperature on hardness and impact resistance the modified 410-1Mo steels. The steels samples were prepared by a process sequence of induction melting, hot forging, annealing, hardening and tempering. The tempered steels were subjected to hardness and impact testing. The experimental results showed that the hardness and the impact resistance of the steels depended strongly on tempering temperature and they changed considerably at temperature 600°C. The secondary hardening appeared at tempering temperature around 400-550°C. The correlation of impact energy with hardness was found to fit the linear line with negative gradient with increasing of hardness value. The fractured surfaces of the impact test specimens were analyzed using SEM images.**

Keywords: martensitic stainless steels, steam turbine blades, tempering temperature, hardness, impact resistance

I. INTRODUCTION

During services the steam turbine blades operate within condition of high stress and high temperature erosive-corrosive environment of steams. The blades are usually made from martensitic stainless steels of 13Cr type (403/410) due to its high strength, high toughness and corrosion resistance [1,2]. However, failures of the blades made from this type of steels were frequently found in the last stage of low pressure blades, particularly due to environmentally assisted craking [3,4,5,6]. Improving mechanical properties and corrosion resistance of the 13Cr type martensitic stainless steels can be accomplished by chemical composition modification and heat treatment.This type of steels should be experienced by proper heat treatment process to achieve the desired mechanical and corrosion properties. A standard heat treatment process subjected to the martensitic stainless steels consists of quenching and tempering which respectively contributes to the final properties of the steels. Quenching this type of steels from high temperature where austenite phase formed and carbide dissolution occured results in microstructure consists of mainly hard and brittle martensite, small amount of retained austenite, and may some carbides exist [7,8]. Tempering process should be accomplished following quenching for reducing hardness to increase ductility and toughness.

The 410-1Mo martensitic stainless steels is a modification of 410 type steels recently developed by incorportion about 1%Mo which exhibit higher tensile strength and higher elongation at breaks compared to the standard 410 type steels [9]. The heat treatment response on the properties of this steels are being investigated and a part of the results has been published elsewhere [10]. This work reports the influence of tempering temperature on hardness and charpy impact resistance of the 410-1Mo martensitic stainless steels. Fractographic analysis of impact samples and correlation between hardness and impact resistance are also presented.

II. EXPERIMENTAL PROCEDURE

The steel ingots of 5x5x10 cm in size were prepared by using an electric induction melting furnace. The ingots were then hot forged at around 900-1125°C until the cross section dimension of the ingots decreased to about 3x3 cm. The square specimens of 1 cm in thickness were cut from forged steels for chemical composition testing using Optical Emission Spectrometer (OES). The chemical composition of the steels is presented in Table 1. The other parts of the forged steels were annealed at temperature 800°C for 20 h for softening to facilitate machining the samples of charpy impact test and of hardness test. The machined samples were subjected to austenizing at 1050°C for 1 h followed by quenching in oil. The austenized samples were then tempered at various temperature of 300, 400, 500, 550, 600, 650 and 700^{o}C for 1 h followed by air cooling. The heat treated samples were surface ground to remove scales and machined to prepare samples for impact and hardness tests.The hardness of the steel samples was measured by Rockwell C diamond indentor of 120^o with indentation load and time of 15 Kgf and 3s, respectively. The impact test was conducted at room temperature by charpy impact tester using V- notch samples with dimension of 10x10x55 mm according to ASTM E 23.The fracture surfaces images of the broken impact samples were taken by using Scanning Electron Microscope (SEM).

Table I. Chemical composition (wt. %) of the 410-1Mo martensitic stainless steels prepared in this work.

Steel	C	S	P	Mn	Si	Cr	Mo	Ni	Fe
13Cr-1Mo	0.13	0.003	0.02	0.94	0.31	13.13	0.80	0.29	Bal.

III. RESULTS AND DISCUSSION

The hardness of 13Cr-1Mo martensitic stainless steel after quenching at 1050^{o}C and tempering at various temperature is presented in Figure 1. At low tempering temperature 300^{o}C the steel still exhibits high hardness of about 47.6 HRC. The hardness of the steel decreases to about 45.8 HRC at tempering temperature 400^{o}C and only slightly changes untill tempering at 550^{o}C. At tempering temperature 600^{o}C the hardness of the steel significantly decrease to about 36.6 HRC and continue to decrease at higher temperature. Finally, at the upper tempering temperature in this study of 700^{o}C the steel has low hardness of about 28.8 HRC.

During tempering, the mainly microstructural evolution is the relaxation of martensite to ferrite which contributes to decreasing of hardness as tempering temperature increases. The microstructure of the tempered 410-1Mo has been reported in Ref.[10], consisted of tempered martensite, delta ferrite and carbides.The stability of hardness at temperature around 400-550^{o}C as shown in Figure 1 may be attributed to secondary hardening where carbide precipitation of M_7C or $M_{23}C_6$ occurs [11]. Coarsening of these stable carbides at temperature higher than 550^{o}C may contribute to decreasing of the hardness [12]. Although it is not so evident, addition of about 1% Mo and slightly higher Cr content of this steel compared to standard 410 steels may contribute to secondary hardening. The standard 410 steels (12Cr) usually shows little or no secondary hardening and softening occurs at tempering temperature over 500^{o}C [11].

Figure 2 shows the variation of room temperature impact resistance of the 13Cr-1Mo martensitic stainless steel with tempering temperature. It is observed that the values of impact energy as a function of tempering temperature exhibit opposite trend to the one showing by hardness values. The impact energy of the steels remain at low values until tempering temperature 550^{o}C and sharply increases to about 74 J at temparature 600^{o}C. The impact energy continues to increase to 85 J at temperature 650^{o}C and shows sharply increases again to about 127 J at temperture 700^{o}C. This high impact energy of the steel tempered at such a high temperature are strongly related to the relaxation of the martensite to the softer phase of ferrite, coarsening of the carbides and may be the formation of reversed austenite [13].

X. LIU et al [14] reported the steels with almost similar composition to the standard 410 steels tempered at 650^{o}C exhibited impact energy of 100 J which is higher than that resulted in this work for 410-1Mo steel tempered at the same temperature. Meanwhile, other researcher [11] reported the martensitic stainless steel having higher content of Mo and Ni compared to the 410-1Mo steels of this work showed impact energy lower than 75 J at tempering temperature 650^{o}C, which is lower than that obtained in this work of 85 J for 410-1Mo steel. These results show that the increasing of Ni and Mo content in the 410 steels decreases the impact energy of the steels. However, the 410-1Mo steel quenched and tempered at 625^{o}C directly after forging without annealing has been reported having higher tensile strength and elongation than the 410 steel [9]. Therefore, the process sequence should be optimized to achieve better properties of the 410-1Mo martensitic stainless steel.

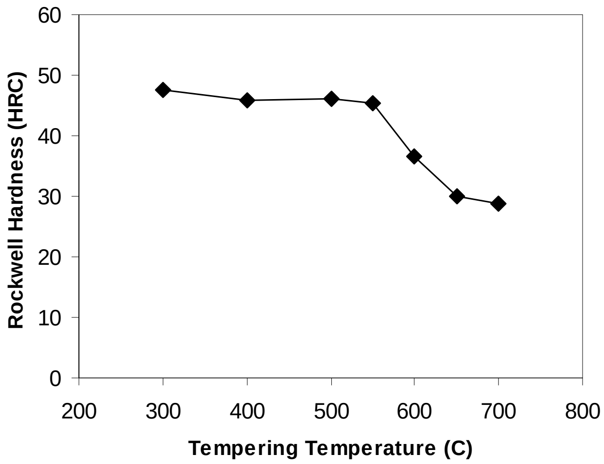

Figure 1. Hardness of 13Cr-1Mo martensitic stainless steel after tempering at various temperature.

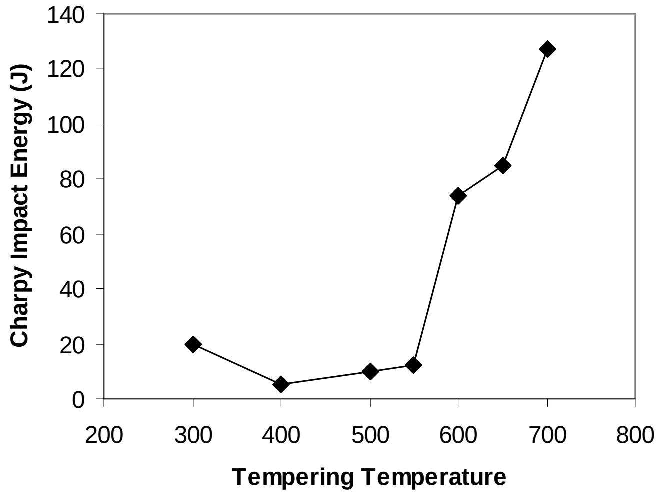

Figure 2. Impact energy of 13Cr-1Mo martensitic stainless steel after tempering at various temperature.

The correlation of impact energy with hardness of the 13Cr-1Mo steel after quenching and tempering is presented in Figure 3. It is clearly observed from Figure 3 that the correlation of impact energy with hardness is found to fit the linear line with negative gradient with increasing of hardness value. It follows the usual role that steels with higher hardness exhibits lower impact resistance. Furthermore, with large negative gradient of -5.64, it is worth noting that the impact resistance of the 410-1Mo steels strongly depends on the hardness value.

Figure 4 presents SEM images of the fracture surface morphology of the 410-1Mo steel after impact testing. The impact fracture surfaces of the steel tempered at 400^{o}C exhibit cleavage morphology over the entire surfaces as displayed in Figure4.a indicating brittle fracture operated in the steel. The similar fracture morphology is clearly demonstrated by the steel tempered at 500^{o}C (Figure 4(b)) which has relatively similar low impact resistance with the steel tempered at 400^{o}C (Figure 2). As the tempering temperature increases to 600^{o}C, the dimple morphology exists in some small area in the fracture surface (Figure 4(c)), consistent with increasing of impact energy of the steel. The dimples become dominant with increasing tempering temperature to 700^{o}C as shown in Figure 4(d) supporting respective largest impact resistance among the investigated steels.

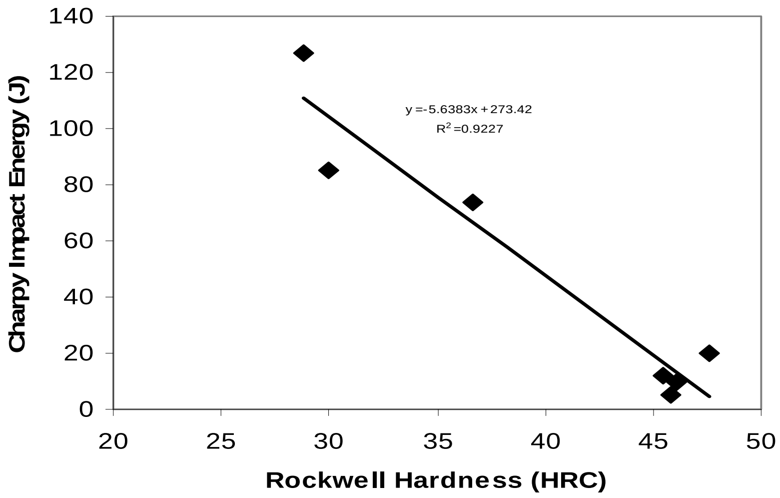

Figure 3. Correlation of impact energy with hardness of 13Cr-1Mo martensitic stinless steel after tempering.

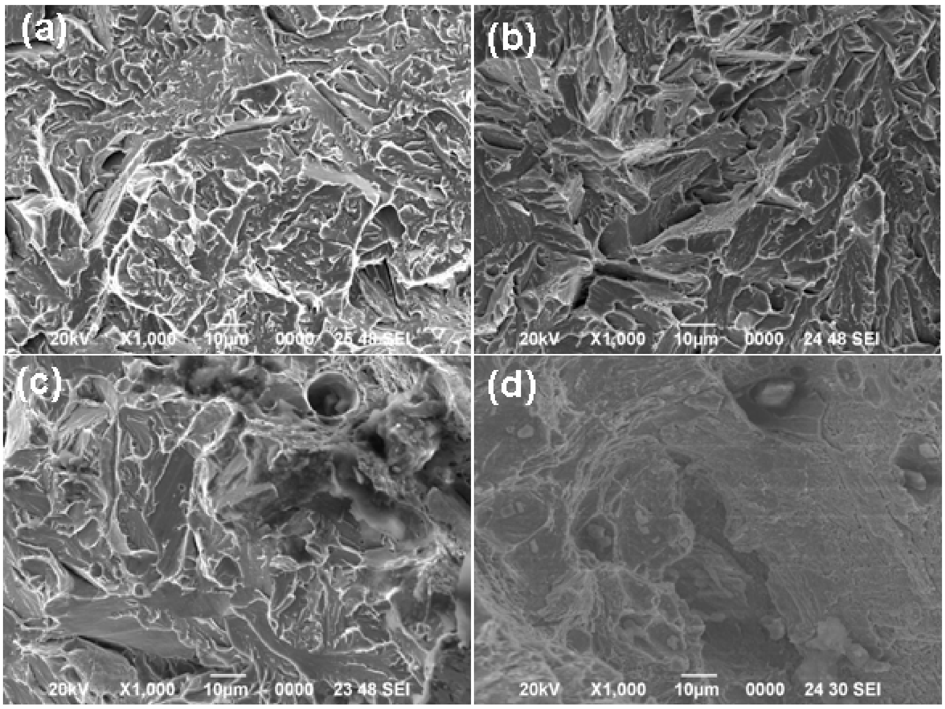

Figure 4. Impact fractured surface of the 13Cr-1Mo martensitic stainless steel after tempering at (a) 400 ^oC (b) 500 ^oC (c) 600 ^oC (d) 700^oC

IV. CONCLUSION

The hardness and impact energy of 410-1Mo martensitic stainless steels have been investigated with respect to tempering temperatures. The hardness and the impact resistance of the steels depended strongly on tempering temperature and they changed considerably at temperature 600^{o}C. The are a stability of hardness at temperature around 400-550^{o}C attributed to secondary hardening due to addition of about 1% Mo and slightly higher Cr content of this steel compared to standard 410 steels. The impact energy continues reached a largest value about 127 J at tempering temperture 700^{o}C. The correlation of impact energy with hardness is found to fit the linear line with large negative gradient of -5.64 indicating the impact resistance of the 410-1Mo steels strongly depends on the hardness value. The steels tempered 500^{o}C still exhibited cleavage morphology over the entire fractured surface, whereas the dimples morphology existed dominantly on the fractured surface of the steel tempered at 700^{o}C.

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