Vol. 2, No. 1 | January - June 2019

Effect of Tempering Temperature on the Properties of Martensitic Stainless Steel AISI-420

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Abstract:

Martensitic stainless steels are commercially significant materials owing to the remarkable properties they offer because of their martensitic structure during application. The paper aimed to investigate the effects of tempering temperature on mechanical properties and microstructure. Determination of carbide morphology was also included in the study to substantiate the results. This study used AISI 420 samples of 10 mm thickness, hardened at 1050ºC and then subjected to tempering treatment at temperatures: 150ºC, 250ºC, 350ºC, 450ºC, 550ºC and 650ºC. Each sample was oil quenched after a soaking time of 25 minutes. Optical Microscopy and Scanning Electron Microscopy was conducted to examine the changes in the microstructure and the morphology of carbides. The results have shown that at various temperatures during tempering there is subsequent increase in toughness where hardness decreases and vice versa. Matrix of martensite contains some carbide precipitates. Due to Temper embrittlement occurring between 350°C-450ºC, toughness has been decreased as a result of secondary hardening between the temperatures of 450°C-550°C, hardness has been increased drastically.

Keywords: *Martensitic Stainless steel AISI 420, Tempering, microstructure, temper embrittlement, Secondary Hardening*

1. Introduction

Martensitic Stainless Steel represents a portion of the 400 series of stainless steels and are essentially Fe-Cr-C alloys containing 12-13% Cr. Martensitic grades, due to the excellent mechanical properties, high wear resistance and moderate corrosion resistance, are used in various industrial components. These wide variations of properties including strength, toughness and hardness values can be achieved through different heat treatments. [1]

Grade AISI 420 stainless steel possesses good ductility in annealed form notwithstanding the capability of being hardened up to 50 HRC. Optimum properties can be achieved with the control of the

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microstructure of these materials by means of austenitizing and tempering heat treatments [2]. An increase in austenitizing temperature results in more dissolution of carbides thus, Hardening treatment for this grade includes heating up to 1050°C, followed by quenching in oil or air which gives an optimum percentage of carbide distribution in the matrix resulting in high as-quenched hardness [3]. Tempering should be done at 150-370°C in order to get a wide variety of hardness values and mechanical properties. The tempering range of 425-550°C should be avoided [2]. The higher tempering temperatures will cause some precipitation of carbides with an alteration in mechanical properties [1]. In general, over the broad range of tempering temperatures, hardness decreases and toughness increases as the temperature is increased.

The prior heat treatment done on the steel has major influence on the final microstructure of AISI 420, which typically comprise of martensite, un-dissolved and/or re-precipitate carbides and retained austenite. The precipitation of carbides in the alloy during tempering is time dependent, which involves precipitation of M_3C followed by M_7C_3 and then $M_{23}C_6$ type alloy carbides [3][4]. The volume fraction and size of the carbide particles present in the steel and the amount of retained austenite play a major role in determining the hardness, strength and toughness of the steel [5]. The martensitic grades are generally are susceptible to surface decarburization during heat treatment, if the furnace atmosphere is not properly controlled. However, with their high chromium content, they are relatively less susceptible than many of the low alloy steels.

2. Research Objective

The present research aims to investigate the behavior of Martensitic Stainless Steel, grade AISI-420, when it is subjected to a range of tempering temperatures. Considering the superior properties of stainless steels, it becomes substantial to determine the influence of heat treatment processes on these steels. Tempering treatment can have considerable effects on the factors primarily focused in this study, namely:

1) Mechanical properties
2) Microstructure, and
3) Carbide Morphology

3. Experimental work

The chemical composition of the as-annealed sample was confirmed by R&D of Pakistan Steel mills. The composition of the sample is shown in the Table 1.

As illustrated in Figure 1, the samples were subjected to hardening at 1050°C for 25 minutes of soaking time in proportion to the dimensions of the samples (10mm x 10mm). The hardened samples were then tempered at 150, 250ºC, 350ºC, 450ºC, 550ºC and 650ºC respectively for 25 minutes. All heat treatments were performed using PROTHERM furnace, Model 140/25.

Table I: Chemical composition of 420 Martensitic stainless steel

Element	Wt.%
C	0.34%
Si	0.40%
Mn	0.38%
P	0.03%
S	0.02%
Cr	12.67%
Ni	0.29%
Mo	0.08%

After tempering treatment, all the samples were investigated for their hardness with Rockwell hardness tester (Wolpert Tester Model N23AB) for all corresponding heat treatments as well as toughness was measured through charpy impact test according to ASTM standard E-23. The steel samples were then grounded, polished and etched using Vilella's reagent (90ml ethanol, 10ml HCl and 2gm picric acid). Microstructure of these samples were studied at optical microscope as well as scanning electron microscope over and above, energy dispersive x-ray (EDX) to verify the precipitated types of carbide in the microstructure.

4. Results and Discussion

The hardness value of 92 HRB is measured from as-received sample which is in annealed condition and contains the carbides precipitates in fully ferritic matrix. After quenching from austenitizing temperature of 1050°C in oil medium, this hardness value is measured to be 58.5 HRC and the toughness as 7 J as shown in figure 1. This high hardness is attributed to the formation of lath martensitic structure, shown in figure 2. This as-quenched structure of fresh lath martensite is quite brittle and should be stress-relieved or tempered to restore some ductility. The little amount of carbides which was not dissolved at austenitizing temperature is also present in lath martensite matrix. The Ms Temperature of AISI 420 is found to be 380°C with carbon content of 0.34%.

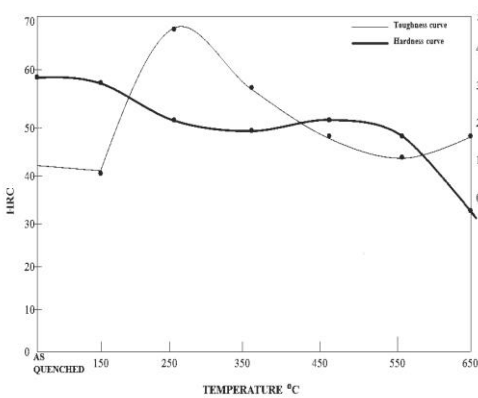

Fig 1:Hardness and toughness versus tempering temperature

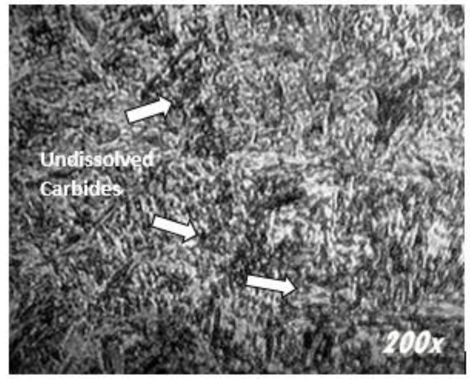

Fig 2:Optical micrograph of as quenched microstructure containing carbides in lath martensitic matrix.

4.1. Tempering at 150°C

By tempering up to 150°C, slight change in hardness and toughness with 58 HRC and 7J respectively as shown in figure 1, was observed because of the softening effect due to the depletion of carbon from martensite matrix is compensated by the precipitation of well-dispersed carbides but no increase in carbide precipitation occurs. According to Porter and Easterling [6], the carbide identified at this tempering temperature, as shown in figure 3, is the transition-carbide $Fe_{2.4}C$ of diameter 2nm due to some partial diffusion of carbon from supersaturated martensite.

4.2. Tempering at 250°C

At tempering temperature of 250°C, hardness of the steel drops to 52 HRC with significant increase in toughness of 42.5 J. During tempering between approximately 149°C and 316°C, a relaxation of the martensite structure occurs whereby the volumetric stresses associated with the formation of martensite upon quenching are relieved [7]. Volumetric stresses result in martensite structure decreasing in hardness while according to figure 1, at the same temperature the high impact energy is due to the presence of retained austenite within the lath martensite, which is very soft as related to martensite, absorbing fracture energy. According to [8], tempering the hardened steel at 250°C facilitate precipitation of epsilon-carbides with restoration of distorted BCT structure by diffusing some trapped carbon into matrix. At this temperature some epsilon-carbides start transforming to Fe_3C [6].

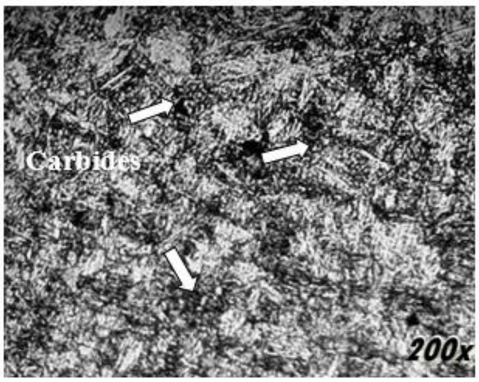

Fig 3:Optical micrograph hardened and tempered at 150°C. Microstructure contains carbides in lath martensitic matrix.

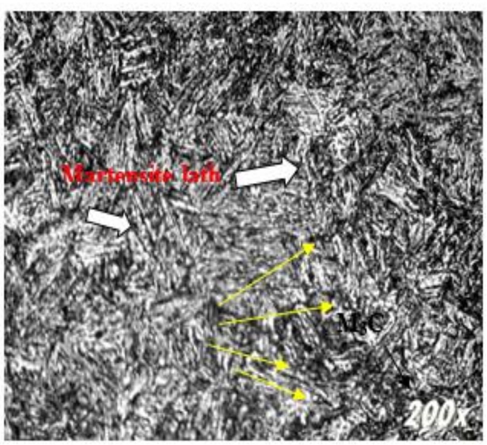

Fig 4:Optical micrograph hardened and tempered at 250°C. Microstructure containing carbides in lath martensitic matrix

4.3. Tempering at 350°C

Tempering at 350°C, the hardness then reached to 50 HRC and with decreases in toughness up to the value of 27.5 J as shown in figure 1. Decreases in hardness show that the relaxation of martensite persisted above 250°C while decrease in toughness is the result of tempered martensite embrittlement (TME) caused by the precipitation of carbides (Fe_3C) occurring at the expense of epsilon-carbide. Tempered martensite embrittlement is thought to be resulted from the combined effects of cementite precipitation on prior-austenite grain boundaries or inter lath boundaries and the segregation of impurities at prior-austenite grain boundaries. Besides if at grain boundary, the morphology of M_3C is predominantly more sheet-like and this would be the prime cause of low ductility in this temperature range. The transformation of retained austenite into ferrite and cementite also causes temper embrittlement [6].

4.4. Tempering at 450°C

The hardness as calculated at 450°C is 52.5 HRC with toughness 15 J as shown in fig.1. The increase in hardness in this range is attributed to secondary hardening phenomenon, which is due to the complex-forming carbides having noticeable effect on the retardation of softening and increase in hardness. It has been illustrated that the M_3C carbides are first detected after 200°C and these carbides remain until 450°C [9] but it was stated by Isfahany [4] that in the temperature range of 400-500°C, M_7C_3 starts to form within the martensitic laths. Above 350°C, the M_3C carbides progressively dissolve and M_7C_3 carbides start precipitating. A small amount of retained austenite is also remained as shown in figure 6.

4.5. Tempering at 550°C

With further increase in temperature at 550°C, the hardness drops to 51 HRC. This is due to softening phenomenon taking place when the M_7C_3 carbides start to coarsen which also caused drop off toughness to 12.5 J. Due to coarsening, M_7C_3 partially transform to $M_{23}C_6$ carbides [4] which is more stable form of carbides and remained at all temperature.

4.6. Tempering at 650°C

Here the hardness value is rapidly decreased to 36HRC and an increase in toughness occurs with 17 J. The softening occurs due to start of recrystallization above 600°C, as near to the sub-critical annealing range for AISI 420 that is to be 675-705°C [7]. After this temperature $M_{23}C_6$ carbide, occurring at the expense of M_7C_3, start to coarsen causing measurable decrement in hardness. The increase in toughness and decrease in hardness is due to recovery of meta stable martensitic phase but the lath structure remains [6] as shown in fig.8. Toughness should be considerably enhanced around 650-700°C temperature range but the ductility was restricted by the presence of coarse carbides, even however tempered martensite was present.

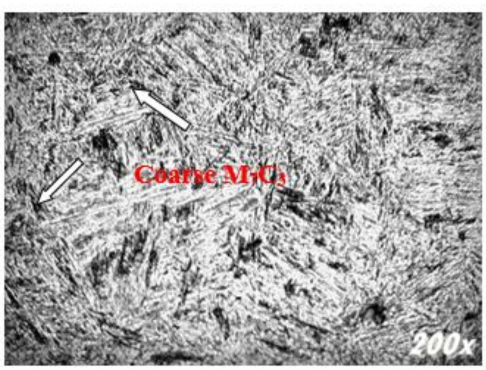

Fig 5:Optical micrograph hardened and tempered at 350°C. Microstructure contains M3C carbides in lath martensitic matrix

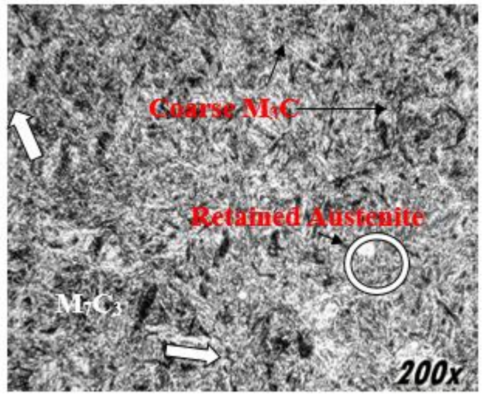

Fig 6:Optical micrograph hardened and tempered at 450°C. Microstructure contains carbides with retained austenite in lath martensitic matrix

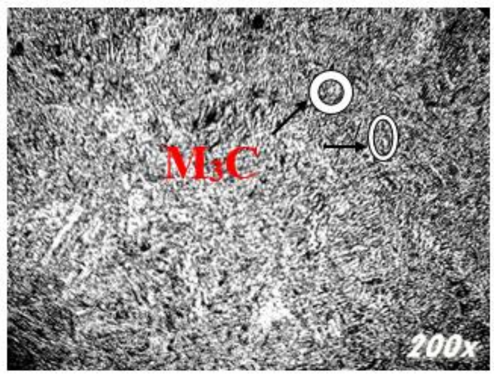

Fig 7: Optical micrograph hardened and tempered at 550°C. Microstructure containing carbides in lath martensitic matrix

5. Conclusion

An investigation of the effect of tempering temperature on AISI 420 Martensitic Stainless steel was conducted. After interpreting the results of this study on the basis of mechanical testing such as hardness and toughness and optical microscopy, the chief findings in this work are summarized as follows:

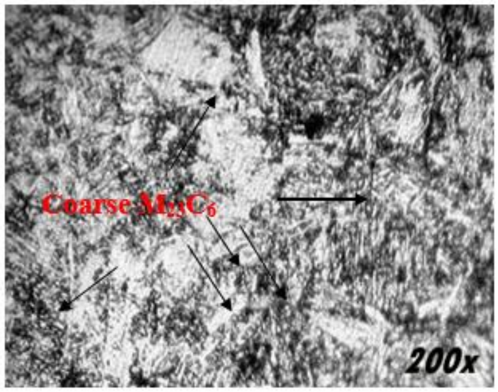

Fig 8: Optical micrograph hardened and tempered at 650°C. Microstructure containing carbides in lath martensitic matrix

1. Nice combination of mechanical properties of AISI 420 Martensitic stainless steel can be obtained by tempering near the range of 250ºC with soaking time of 25 minutes as per dimension of 10x10mm sample.
2. Secondary hardening was obtained between the tempering temperatures of 400-500°C because of formation of secondary carbides M_7C_3. Hence this temperature range should be avoided if good toughness is required.
3. Decrease in toughness was observed between the tempering temperatures of 350-550^{0}C.
4. The toughness again improved with rapid decreased in hardness of 36 HRC at 650^{0}C due to start of recrystallization above 600°C, as the sub-critical annealing range for AISI 420 was found to be 675-705°C. At this temperature $M_{23}C_6$ carbides coarsened and this resulted in measurable decline in hardness.

ACKNOWLEDGEMENT

We would like to acknowledge Department of Metallurgical Engineering of NED University of Engineering and Technology, Karachi for provision of facilities regarding this work and all the support and cooperation.

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