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Effects of Deep Cryogenic Treatment on the Mechanical Properties of Medium Carbon Spring Steels

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Abstract: The cryogenic treatment is a method frequently used in the development of the wear resistance of alloy steels due to the increase in their hardness driven by the mechanisms such as the conversion of retained austenite to martensite and the formation of secondary carbides. In recent studies, it has been reported that besides the hardening mechanisms, the cryogenic treatment can also improve the mechanical properties of the alloys by reducing the residual stresses and modifying the microstructure. This research aims to investigate the impact of deep cryogenic process (-196°C) on the microstructures of medium carbon spring steels contain various alloying elements. The conventional heat treatment (CHT) and the deep cryogenic treatment (DCT) procedures were applied to the spring steels which have various alloying elements. Hardness, tensile and notch toughness tests were performed to determine the mechanical properties. Consequently, the aim is to determine the applicability of the cryogenic treatment in the improvement of the mechanical properties of medium carbon spring steels.

Keywords: Steels, Cryogenic Treatment, Mechanical Properties, Alloying

Introduction

Medium carbon steels contain between 0.25% and 0.60% carbon by weight. This steel group is generally used in tempered martensite structure due to high strength requirements. Conventionally the steel is tempered right after the quenching process, thus achieving optimum values in hardness and toughness. Improving the mechanical properties of the spring steel produced by the conventional forming and heat treatment process can only be achieved by modification of the material microstructure. The cryogenic process, which triggers mechanisms such as the reduction of residual stress and retained austenite structure, homogenization of the grain structure, and finally the formation of secondary carbide structures, is a heat treatment process that has been successfully applied for many product groups for years (Baldissera & Delprete, 2008).

In the conventional heat treatment process (CHT), a significant amount of compressive stress occurs in the material as a result of the quenching process. After the tempering process, it is seen that the samples lose these compressive stresses to a great extent (Bensely et al., 2008). This reduction can be attributed to the precipitation of nano-fine carbides in the structure and the removal of tetragonal supersaturated martensite (Preciado & Pellizzari, 2014). The transformation of austenite to martensite at cryogenic temperatures creates internal stresses and causes crystalline defects such as dislocation and twinnings. Cryogenic process restricts the movement of dislocations by the increase in the density of crystal defects and nano-cluster carbides. Thanks to this mechanism, the compression stress in the samples is relatively preserved (Villa et al., 2014). Carbide forming elements, such as molybdenum, play an important role in preventing grain growth in the primary carbide structure. In addition, they contribute to the protection of compressive stresses in the structure by triggering the precipitation of secondary carbide structures (Michaud et al., 2007). Since spring steels work

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under varying loads, it is highly desirable to maintain these compression stresses in the structure. (Myeong & Yamabayashi, 1997). Besides, the mechanisms of performance increase caused by the cryogenic process, especially for medium carbon steels, have not been fully revealed. Scientific explanations regarding the microstructural changes, process conditions and the structure-property relationship observed as a result of the process are still under development.

In this study, deep cryogenic process (DCT) was applied to medium carbon spring steels such as 55Cr3, 51CrV4, 52CrMoV4. As a result of the application of the cryogenic process to these steels containing different alloying elements, it was aimed to improve the mechanical properties of steels. The change in the efficiency of the cryogenic process with the effect of alloying elements such as Cr, Mo, V was also investigated.

Method

Three spring steels with different alloys were selected in the study. The average chemical compositions of spring steels are given in Table 1. Conventional heat treatment (CHT) and deep cryogenic process (DCT) at -196 ° C were applied to steels and the effect of the cryogenic process on mechanical properties was investigated. Details on experimental variables are given in Table 2.

Table 1. Average chemical compositions of spring steels

Material	%C	%Si	%Mn	%Cr	%V	%Mo
55Cr3	0,57	0,30	0,85	0,80	-	-
51CrV4	0,50	0,25	0,90	1,10	0,12	-
52CrMoV4	0,50	0,25	0,90	1,10	0,10	0,25

The tensile strengths of the steel samples were measured with a 250kN capacity Shimadzu tensile device using ASTM E8 / E8M-13 standard to determine the mechanical properties that change due to cryogenic processing. Notch toughnesses were measured using the ASTM A370 standard based on the Charpy method. MFL Systeme device was used in the measurements. Hardness measurements were carried out by Shimadzu HMV-2000 microhardness tester. The measurements were obtained by applying a 300 grf load for 10 seconds.

Table 2. Experimental variables and coding

Procedure	Code
Quenching (850°C (Oil)) Tempering (500°C;1 Hour)	CHT
Quenching (850°C (Oil)) Cryogenic Process (-196°C; 24 Hours) Tempering (500°C;1 Hour)	DCT

Results and Discussion

First, the microhardness of samples was measured on the Vickers hardness scale. The average hardness of the steel groups for the base and heat-treated samples are presented in Table 3.

Table 3. Average hardness values of the samples (HVickers, 300 grf – 10 seconds)

Sample	52CrMoV4	51CrV4	55Cr3
Base	351,6	328,3	332,2
CHT	401,7	393,0	390,8
DCT	432,4	410,3	406,3

As expected, a result has emerged that varies proportionally to the alloy quantity of steels. The relatively high alloyed steel group has recorded a more significant hardness increase compared to the other two steel groups with its higher carbide-forming ingenuity and increased hardenability. The mechanical strength of the samples was also measured by tensile and notch impact tests. Accordingly, the notch impact toughness of steels was measured using the ASTM A370 standard based on the Charpy method. The results are listed in Table 4.

Table 4. Average notch toughness values of the samples (Charpy, J(Joule))

Sample	52CrMoV4	51CrV4	55Cr3
Base	10	11	13
CHT	32	24	26
DCT	46	37	34

In the literature, hardness values and notch toughness values show linearity and are generally interpreted together. The main influence for notch toughness is alterations of microstructure. Changes in notch toughness after cryogenic processing are associated with carbide precipitation. Primary carbides deposited in inter-dendritic regions are particularly important for notch toughness values in steel materials. The interface interactions of these carbide structures with the matrix are determinant in notch toughness mechanism (Das et al., 2010). As a result of the notch impact tests, the relatively high alloyed steel group was distinguished from the other steel groups, just like the hardness values. The increase in this steel group was much more noticeable (44%).

As the final mechanical test, the effects of cryogenic processes on the tensile strength and elongation of steels were examined. There is an intense discussion in the literature in interpreting the results of tensile strength. In addition to the existence of scientists who reported an increase in toughness as well as gain in mechanical values with cryogenic process (Ghasemi-Nanesa & Jahazi, 2014; Vahdat et al., 2013); some scientists report a decrease in toughness as a result of the increase in mechanical strength with cryogenic treatment (Senthilkumar et al., 2011; Zhirafar et al., 2007).

Graphs of maximum tensile strength and elongation at break for all steel groups are given in Figure 1a-b. The stress/strain graph of the relatively alloyed 52CrMoV4 sample is shown in Figure 2.

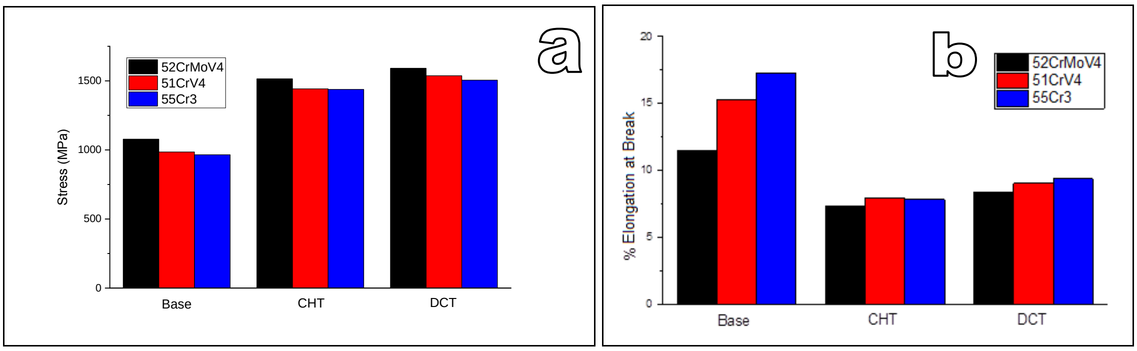

Figure 1. Graph of (a) maximum tensile strength (b) elongation at break for steels

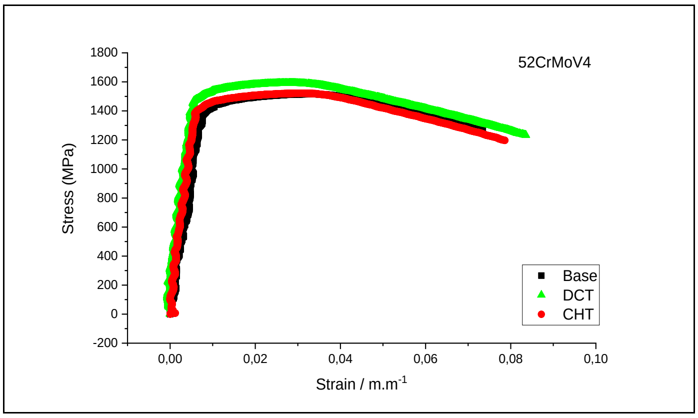

Figure 2. Stress-strain plot of 52CrMoV4 sample

As can be seen in Figure 1, an increase in static toughness values was observed in all steel groups as a result of the cryogenic process. This increase can be seen much more comfortably when the 52CrMoV4 data, which is the relatively most alloyed steel group, is traditionally plotted. As seen in Figure 2, there has been a significant increase in the static toughness of the material as a result of the significant increase in the elongation at break despite the minimal increase in tensile strength. This increase was calculated as 19.43% by calculating the area below the chart line. As seen in Table 4, this increase has also found its correspondence in notch toughness values. The main reason for this increase is reported as high-density second carbide precipitates. Although the cryogenic process triggered carbide formation, it was possible to gain toughness without losing tensile strength by delaying the coarse kinetics of carbides (Özden & Anik, 2020; Vahdat et al., 2013).

Conclusion

- As a result, an increase was observed in the microhardness, notch impact toughness and tensile strength of the samples treated with the cryogenic process compared to the samples treated with conventional heat treatment.
- The amount of increase increased with the alloying level of steel.
- Accordingly, cryogenic treatment can be presented as an effective method for improving the mechanical properties of medium carbon spring steels.

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