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Cryogenic Process Optimization for Medium Carbon Spring Steels

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Abstract: Spring steels are extensively used in load bearing elements of road and railway vehicles. The basic microstructure of these parts, which are subjected to high cycle fatigue, is tempered martensite. The improvement of the mechanical properties of these steels can only be achieved by modifying the material microstructure. In the microstructure of steel parts produced in different diameters, the formation of retained austenite and residual stresses is inevitable. For spring steels operating under heavy load, it is very important to remove the residual austenite form. Although the cryogenic treatment process is applied as a standard process for high alloyed and high carbon steels, it is not optimized for low alloy and medium carbon steels. In this study, different types of cryogenic treatment (Deep Cryogenic Treatment (DCT) / Shallow Cryogenic Treatment (SCT)) and tempering applications were carried out on spring steels with different alloying levels. With the outputs obtained from these experiments, optimization of cryogenic process parameters for medium carbon spring steels is aimed.

Keywords: Steels, Cryogenic treatment, Alloying

Introduction

Spring steels classified as medium carbon steels, with carbon contents ranging from 0.25 percent to 0.60 percent. Conventional heat treatment (CHT) can improve the mechanical properties of certain alloyed steels (austenitizing, quenching and tempering). However, using CHT, converting the full austenite structure to martensite may not always be achieved, and remaining austenite can reduce the steel's mechanical properties (Özden et al., 2020a). The austenite structure is entirely or partially transformed into martensite, cousing hardness and strength improvement throughout the cryogenic procedure (D. Das et al., 2009; Özbek et al., 2014). The cryogenic technique has been claimed to boost wear resistance by up to 270 percent (Senthilkumar et. al., 2012).

The idea of subzero cooling, which was introduced in the mid-1920s, was extensively studied in the 1940s, and thanks to these studies, the foundation for the complementary process known as the cryogenic process was laid (Villa et al., 2017). Cryogenic treatment is an effective method used to increase hardness, toughness, wear and fatigue resistance similar to CHT and has been used commercially for years to increase the service life of many metal materials.

The application of the method is usually in two temperature zones. These temperatures are -145°C for shallow cryogenic treatment (SCT); for deep cryogenic treatment (DCT) it is -190°C. In commercial applications, there

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are cold working (CW) applications around -80°C. The material is subjected to cryogenic treatment at the temperature and time determined according to the process, and then it is brought to room temperature at a certain rate. This is usually followed by a tempering process with a temperature of 150 – 500 °C (Das, 2011).

Cryogenic treatment is used as a very common method for high-carbon and high-alloy steels that contain a heavy retained austenite structure. However, studies are ongoing to clearly demonstrate the relationship of cryogenic treatment in the strengthening of lower alloy steels (Özden et al., 2020b). Although the structure-property relationship of the cryogenic treatment process applied in medium carbon steels has not been clearly revealed but it has been reported that the cryogenic process, which triggers mechanisms such as residual stress relief and grain homogenization, provides an increase in toughness properties without compromising strength values (Özden et. al., 2020). In this study, different cryogenic conditions were applied to three different spring steels and the cryogenic process was tried to be optimized by considering the tensile strength and toughness values.

Method

In the study, medium carbon spring steels 55Cr3, 51CrV4, 52CrMoV4 alloyed with different alloying elements were used. The steels were produced by ÇEMTAŞ (Bursa) in 55 mm diameter by continuous casting method. After obtaining the casting products, they were reduced to 19 mm in diameter by hot rolling and cut into 20 cm in length. Optical emission spectrometry analysis results of steels are presented in Table 1.

Table 1. Optical emission spectrometry analysis results of steels

Weight %	C	Si	Mn	Cr	Mo	V	P	S
55Cr3	0,57	0,30	0,85	0,91	-	-	0,010	0,005
51CrV4	0,52	0,28	0,84	0,93	-	0,13	0,008	0,004
52CrMoV4	0,54	0,26	0,87	1,12	0,19	0,11	0,009	0,003

Tensile tests were used to examine the effect of cryogenic treatment on strength and toughness. For this purpose, cryogenic treatment was applied to the samples at different temperatures (-196 °C, -145 °C) and times (12 – 24 - 36 hours). Following this process, the several samples were tempered at two different tempering conditions. Variables of applied heat treatments are presented in Table 2. Tensile tests were carried out in accordance with ASTM E8 / E8M-13 standard with a 250kN capacity Shimadzu tensile device.

Table 2. Heat treatment variables

Procedure	Code
Quenching *(850°C (Oil))* Tempering *(500°C;1 Hour)*	Conventional Heat Treatment (CHT)
Quenching *(850°C (Oil))* Cryogenic Process *(-145°C; 24 Hours)* Tempering *(500°C;1 Hour)*	Shallow Cryogenic Treatment (SCT)
Quenching *(850°C (Oil))* Cryogenic Process *(-196°C;12-24-36 Hours)* Tempering *(500°C;1 Hour)*	Deep Cryogenic Treatment (DCT)

Results and Discussion

In order to monitor the effect of cryogenic treatment temperature on these steel groups, firstly, shallow (-145°C) and deep (-196°C) cryogenic treatment was applied to 51CrV4 steel for 24 hours and the tensile test results were compared. No significant change was observed in the shallow cryogenic treated sample compared to conventional heat treatment. On the other hand, an increase in tensile and strain values were observed after deep cryogenic treatment, and an increase in static toughness of approximately 18% was observed. According to the results, it was concluded that the shallow cryogenic process could not produce a significant level of carbide in this steel group. The strain-strain diagrams of the tensile tests are presented in Figure 1 and the numerical data of the tests are presented in Table 3.

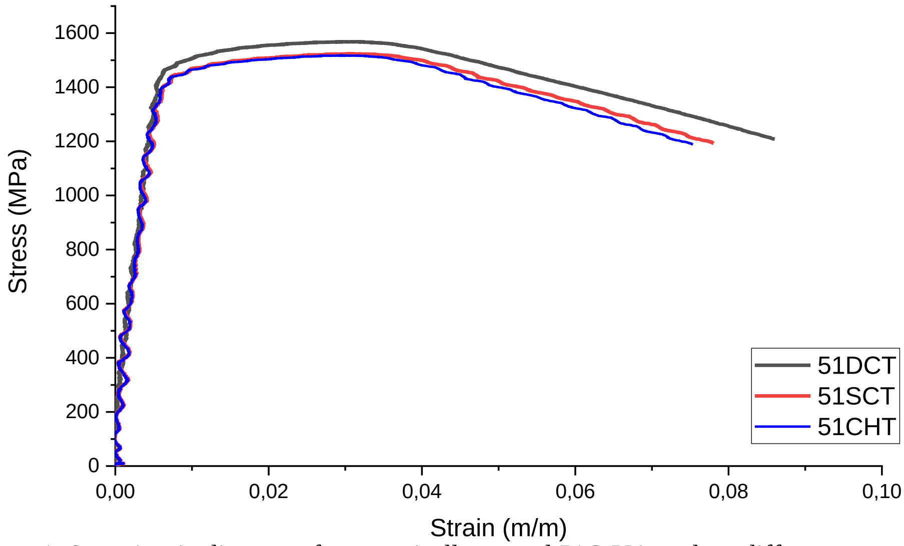

Figure 1. Stress/strain diagram of cryogenically treated 51CrV4 steels at different temperatures

Table 3. Tensile strength and strain comparison of cryogenic treated 51CrV4 steel at different temperatures

Sample	Tensile Strength (MPa)	Strain (m/m) (%)
51CHT	1517	7,53366
51SCT (-145°C, 24h)	1523	7,80379
51DCT (-196°C, 24h)	1568	8,60249

Afterwards, the effect of cryogenic treatment time was investigated by applying cryogenic treatment to 55Cr3 samples in three different time periods (12 – 24 – 36 hours). The tensile strengths of the samples after cryogenic treatment are given in Figure 2.

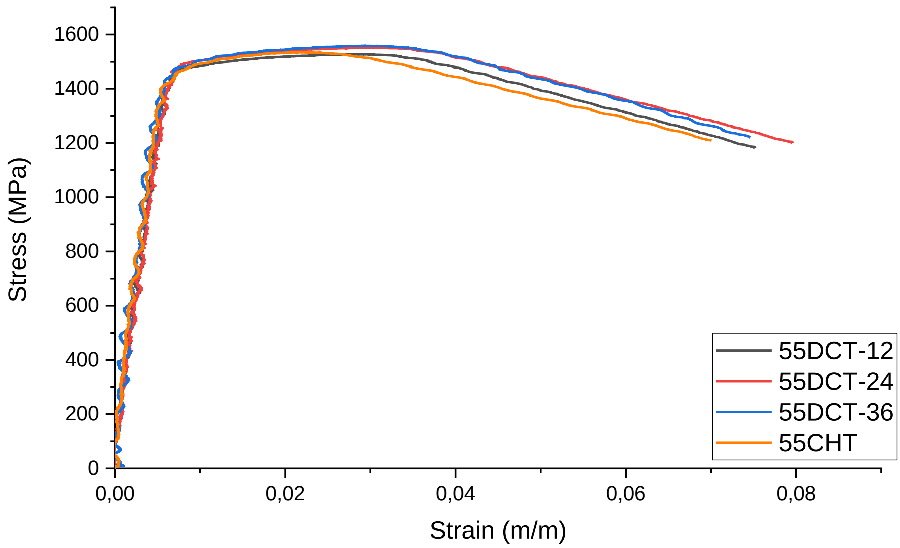

Figure 2. Stress/strain diagram of cryogenically treated 55Cr3 steels at different time periods

Consistent with the existing literature, it has been experimentally verified that the effect of cryogenic treatment on the tensile strength of the medium carbon low alloy steel group increases with the holding time, but the extension of the time does not provide a visible gain (Vahdat et al., 2013). Although the specimens had the highest tensile strength after 36 hours, no significant improvement in strain values was observed. The 12-hour cryogenic treatment increased the strain of the material but did not lead to an improvement in strength. A 24-hour immersion time seems ideal for this steel group. Numerical data on tensile tests are given in Table 4.

Table 4. Tensile strength and strain comparison of cryogenic treated 55Cr3 steel at different time periods

Sample	Tensile Strength (MPa)	Strain(m/m) (%)
55CHT	1534	7,00546
55DCT-12 (-196°C, 12h)	1527	7,52053
55DCT-24 (-196°C, 24h)	1551	7,96199
55DCT-36 (-196°C, 36h)	1558	7,46351

Spring steels are a steel group that is used extensively in the automotive industry. Line designs are available depending on intense automation in the production of these steels. Performing the cryogenic treatment as a complementary process, typically post-hardening, prior to tempering, requires a restructuring of the manufacturing process. In order to evaluate the possibility of ease of application, the applicability of cryogenic treatment to structures already hardened for these steel groups was also investigated. For this reason, 52CrMoV4 steels were subjected to conventional heat treatment followed by cryogenic treatment and then tempering heat treatment. The stress-strain graphs of the samples are presented in Figure 3.

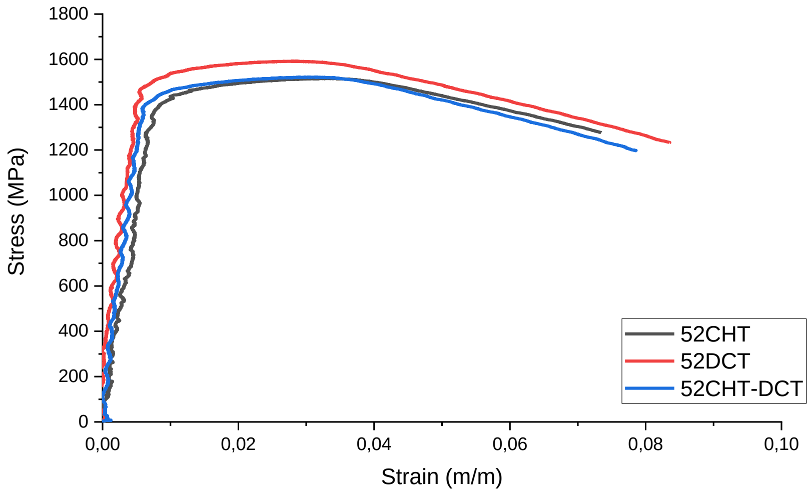

Figure 3. Stress/strain diagram of cryogenically treated 52CrMoV4 steels in different tempering conditions

52CHT-DCT samples have the lowest strength value with the effect of increasing tempering number. After the second tempering, the tetragonality and dislocation density of martensite decreased relatively, resulting in an increase in the strain value. In contrast, the typical cryogenic process continued to have the highest stress-strain value. The numerical data of the experiment are presented in Table 5.

Table 5. Tensile strength and strain comparison of cryogenic treated 52CrMoV4 steel at different tempering conditions

Sample	Tensile Strength (MPa)	Strain(m/m) (%)
52CHT	1515	7,34687
52DCT	1591	8,35312
52CHT-DCT	1521	7,86562

Conclusion

In our research, cryogenic process optimization was performed for low alloy medium carbon spring steels using three steels with different alloy levels. Accordingly, it was observed that SCT treatment had a strengthening effect compared to CHT, but this effect was significantly lower than the effect created by DCT treatment. In addition, it has been observed that the increased time of DCT process performed over 24 hours has limited strength-increasing properties for this steel group. In this context, it was found significant that the cryogenic process time was limited to 24 hours, due to the importance of the toughness value.

Finally, the applicability of the cryogenic process to the already produced parts was investigated, but the desired values were not observed in the toughness and tensile strength values. As a result of these studies, it was concluded that the optimized cryogenic treatment process for medium carbon spring steels is a typical 24-hour deep (-196°C) cryogenic treatment.

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Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors

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