Süleyman Demirel Üniversitesi
Fen Bilimleri Enstitüsü Dergisi
Cilt 27, Sayı 1, 103-106, 2023

Süleyman Demirel University
Journal of Natural and Applied Sciences
Volume 27, Issue 1, 103-106, 2023

DOI: 10.19113/sdufenbed.1154957

Effect of Intercritical Annealing on the Properties of Dual Phase Steel via Finite Element Method

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(Alınış / Received: 04.08.2022, Kabul / Accepted: 29.01.2023, Online Yayınlanma / Published Online: 25.04.2023)

Keywords
Automotive,
DP Steel,
Simheat NxT,
Thermo-Calc,
Finite Element Method

Abstract: Dual-phase (DP) steels are becoming more and more popular for automotive applications. They offer a weight reduction with a combination of energy absorption for crash zones. Rails, reinforcements, back panels, cross members, and pillars can be given as application examples. DP steels microstructure consists of a soft ferrite with hard martensite. The martensite provides strength while the ferrite provides ductility. The strength level of DP steel is correlated with the martensite fraction in the microstructure, and the fraction of martensite can be controlled via intercritical annealing. In this work, thermodynamic analysis of St52 steel was carried out with Thermo-Calc software. A_1 and A_3 temperatures were determined by calculating the temperature-dependent phase fractions. Intercritical annealing temperatures were determined according to the calculated critical temperatures (A_1 and A_3). The intercritical annealing process was modelled by using Simheat NxT software. In this modelling and simulation study, the intercritical annealing temperature impact on the final microstructure and hardness of DP steel was investigated.

Sonlu Elemanlar Metodu ile Kritikler Arası Tavlamanın Çift Fazlı Çeliğin Özelliklerine Etkisi

Anahtar Kelimeler
Otomotiv,
DP Çeliği,
Simheat NxT,
Thermo-Calc,
Sonlu Elemanlar Metodu

Öz: Çift fazlı (DP) çelikler, AHSS kaliteleri arasında otomotiv endüstrisinde yaygın olarak kullanılan bir çelik grubudur. Çarpışma bölgeleri için enerji emilimi ve ağırlık azaltma sunarlar. Günümüzde jantlarda, ön ve arka panellerde kullanılır. DP çeliklerinin mikroyapısı, ferrit ve martenzit fazlarının kombinasyonundan oluşur. Sert martenzit adaları mukavemet sağlarken, sünek ferrit fazı şekillendirilebilirliği sağlar. DP çeliğinin mukavemet seviyesi, mikroyapıdaki martenzit miktarı ile ilgilidir. Martenzit miktarı, kritikler arası tavlama işlemiyle düzenlenebilir. Bu çalışmada Thermo-Calc yazılımı ile St52 çeliğinin termodinamik analizi yapılmıştır. A_1 ve A_3 sıcaklıkları, sıcaklığa bağlı faz fraksiyonları hesaplanarak belirlenmiştir. Hesaplanan kritik sıcaklıklara (A_1 ve A_3) göre kritikler arası tavlama işlemi Simheat NxT yazılımı kullanılarak modellenmiştir. Bu modelleme ve simülasyon çalışmasında, kritikler arası tavlama sıcaklığının DP çeliğinin nihai mikroyapısı ve sertliği üzerindeki etkisi araştırılmıştır.

1. Introduction

Recently, various needs have emerged with novel developments in the automotive industry. Lighter and safer materials are at the forefront of these needs, while at the same time, it is essential to reduce fuel consumption [1]. In response to these requirements, new alloy and process design optimization studies continue with the improvement of new steel grades [2-3]. Due to the continuous demand for steel with superior properties, new steel grades appeared and found application in industrial applications. Modern designs, innovative forming methods, and novel heat treatment techniques have recently become the major research topic in the automotive industry to make cars lighter and safer [4]. Dual-phase (DP) steel microstructure contains ferrite with martensite and the phase fraction of martensite in DP steels ranges anywhere from 10 to 50% [5-6]. The hard martensite provides strength, while the soft ferrite provides ductility [7-8]. The strength level of DP steel is

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correlated with the martensite fraction. In terms of mechanical properties, DP steels exhibit continuous yielding behavior with a high level of elongation [9-11]. In addition, the high work hardening rate of DP steels gives them an excellent capacity for energy absorption. The high mechanical properties make DP steel indispensable materials for the automotive industry [7-12]. DP steel production includes the determination of the ferrite-austenite area temperature values (A_1 and A_3), heating to the appropriate process temperature at the determined critical temperature ranges, and obtaining the two-phase region (ferrite & austenite) by holding it for a certain time and quenching until it reaches room temperature to obtain desired microstructural features [13-14].

The temperature for intercritical annealing treatment is controlled in the two-phase region of the Fe-Fe_3C phase diagram. An increase in the annealing temperature leads to a higher fraction of martensite. The annealing process is followed by a subsequent quenching step, to form a ferrite-martensite microstructure with desired volume fractions. In addition, alloy chemistry is important during the processing of DP steels [13-15]. In DP steels carbon plays a critical role, it enables the formation of martensite. In addition to carbon, manganese, chromium, molybdenum, boron, and nickel were added to DP steels to increase the hardenability. Briefly, DP steels with desired properties can be achieved by controlling the alloy chemistry and processing parameters [12-15]. The effect of the annealing and tempering conditions, phase distribution and different alloy chemistries on the properties of DP steels have been studied extensively [12-21].

However, the microstructural development and mechanical properties of DP steels have not been investigated in depth via simulation studies. The purpose of this modelling and simulation study is to elucidate the impact of intercritical annealing temperature on the final microstructure and hardness of DP steel via CALPHAD methodology and Finite Element Method (FEM).

2. Materials and Method

In this modelling and simulation study, commercial St52 (heat treatment of unalloyed structural steels is more suitable for Simheat NxT 1.2 software) steel is used and the alloy chemistry of the steel is given in Table 1. Thermodynamic analyses of St52 steel according to its chemical composition were made according to the CALPHAD method. Thermo-Calc software version 2023a TCFE12 database was used. The temperature-dependent phase fractions were calculated based on the chemical composition. The critical transformation temperatures (CTT) of the phases forming the steel were determined and the A_1 and A_3 temperatures were calculated in terms of obtaining the intercritical annealing region.

Table 1. Chemical composition (wt.%) of St52 steel [16]

C	Si	Mn	P	S	Cr	Mo	Cu
0.12	0.58	1.34	0.01	0.004	0.1	0.02	0.19

Intercritical annealing temperature ranges were determined by determining A_1 and A_3 temperatures with Thermo-Calc software. Three different temperatures, 730, 780 and 830°C were determined for intercritical annealing. In addition, in this study, Simheat NxT 1.2 software was used for geometric-based modelling and simulation analysis. Simheat NxT is a finite element method software developed for heat treatment processes. For the analysis of intercritical annealing, a rectangular geometry (2x1x1 cm^3) was chosen, and water quenching processes were modelled after an intercritical annealing treatment at 3 different temperatures for 30 minutes. As a result of the modelling, the annealing temperature impact on the final microstructure and hardness of DP steel was investigated.

3. Results and Discussion

Phase fractions of St52 steel as a function of temperature were calculated via Thermo-Calc and shown in Figure 1. In hypo-eutectoid steels, the pro-eutectoid ferrite phase is first formed from the austenite phase. The point at which pro-eutectoid ferrite begins to form determines the A_3 temperature. A_3 temperature was calculated as 842°C for St52 steel. A_{1e} and A_{1b} temperatures were calculated as 702 and 688°C, respectively. The intercritical annealing has to be between the A_{1e} and A_3 temperatures to obtain a ferrite-austenite mixture, and it was determined as 730, 780 and 830°C.

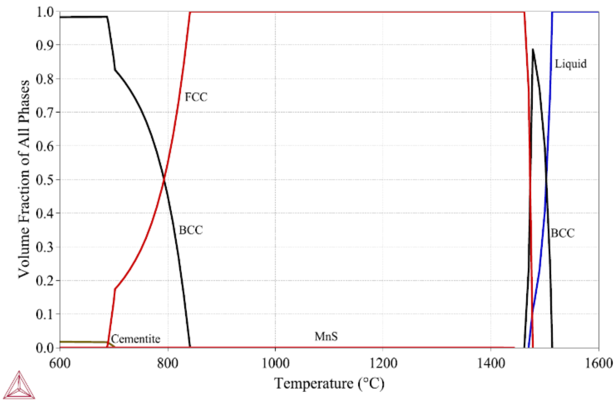

Figure 1. Phase fractions of St52 steel as a function of temperature

In terms of microstructural development, dual-phase (ferrite and martensite) microstructures were obtained with the absence of carbides via subsequent water quenching to room temperature from the intercritical annealing region, as shown in Figure 2. The fraction of martensite increases (ferrite fraction decreases) with the increase in annealing temperature, as seen in Table 2. As the intercritical annealing temperature increases, the amount of martensite increases up to 90% after water quenching. Bidmeshki et al. studied the dual-phase formation of St52 steel is used in this study by applying 780°C intercritical annealing for 30 minutes and the martensite fraction was calculated as 53% [16]. In this work, the martensite fraction was calculated as 54% by applying 780°C intercritical annealing. However, it was not possible to make comments about the morphology of the phases since it is a modelling and simulation study.

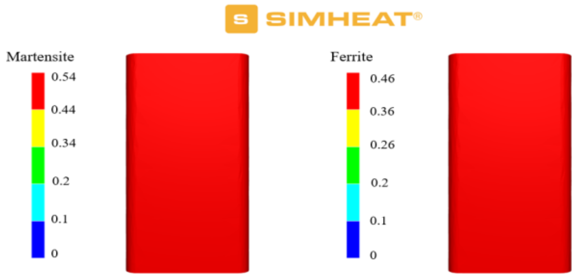

Figure 2. Fractions of martensite and ferrite for DP steel annealed at 780°C

Table 2. Selected annealing temperatures and phase fractions of DP steels

Intercritical Annealing Temperature (°C)	Martensite Volume Fraction (%)	Ferrite Volume Fraction (%)
730	21	79
780	54	46
830	90	10

In addition, the hardness values of the samples were taken from the Simheat NxT software after the annealing treatment. The hardness value of the alloys is influenced by the change in annealing temperature. As the annealing treatment temperature rises from 730 to 830°C, the hardness of the DP steel increases from 172 HV to 360 HV as given in Table 3. As a result, the hardness values of the DP steels increase with higher intercritical annealing temperatures, due to an increment in the martensite fraction.

Table 3. Selected annealing temperatures and hardness of DP steels

Intercritical Annealing Temperature (°C)	Hardness (HV)
730	172
780	261
830	360

4. Conclusions

This modelling and simulation study aimed to obtain a ferrite and martensite (dual-phase) microstructure via intercritical annealing of St52. The impact of the annealing temperature on the microstructural features and hardness was investigated by thermodynamic and FEM analysis.

In this work, the CALPHAD methodology was used to calculate the critical transformation temperatures of St52 steel. A_3, A_{1e}, and A_{1b} temperatures were calculated as 842, 702 and 668°C, respectively.

Thermodynamic analysis of the alloy was performed by using Thermo-Calc software and reliable parameters for the heat treatment process were determined.

The dual-phase microstructure is made of a matrix of soft ferrite to provide ductility and finely dispersed hard martensite islands to provide strength. The strength of DP steel is directly correlated with the volume fraction of martensite, and the martensite fraction can be arranged via intercritical annealing.

The martensite volume fraction increased from 21% to 90% by increasing the annealing temperature from 730 to 830°C.

The hardness of the DP steels increases by increasing the annealing temperature, in other words, increasing the martensite volume fraction. The hardness value increased from 172 HV to 360 HV.

In the end, a reliable process design of intercritical annealing can be modelled with Simheat NxT 1.2 software.

Declaration of Ethical Code

In this study, we undertake that all the rules required to be followed within the scope of the "Higher Education Institutions Scientific Research and Publication Ethics Directive" are complied with and that none of the actions stated under the heading "Actions Against Scientific Research and Publication Ethics" are not carried out.

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