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# CCT diyagramları modellenmesiyle düşük ve yüksek karbonlu TRIP çeliklerinin üretimi, mikroyapı haritalarının dizaynı ve çekme özellikleri

*Manufacturing of low and high-carbon TRIP steels by modeling CCT diagrams, design of microstructure maps and tensile properties*

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# Manufacturing of Low and High-carbon TRIP Steels by Modeling CCT Diagrams, Design of Microstructure Maps and Tensile Properties

## Önemli noktalar (Highlights)

- ❖ The production chain of automotive high-strength TRIP steels has been established.
- ❖ Cooling route modeling and microstructure maps were produced.
- ❖ Superior tensile properties have been achieved by developing a low-cost alloy.

## Grafik Özet (Graphical Abstract)

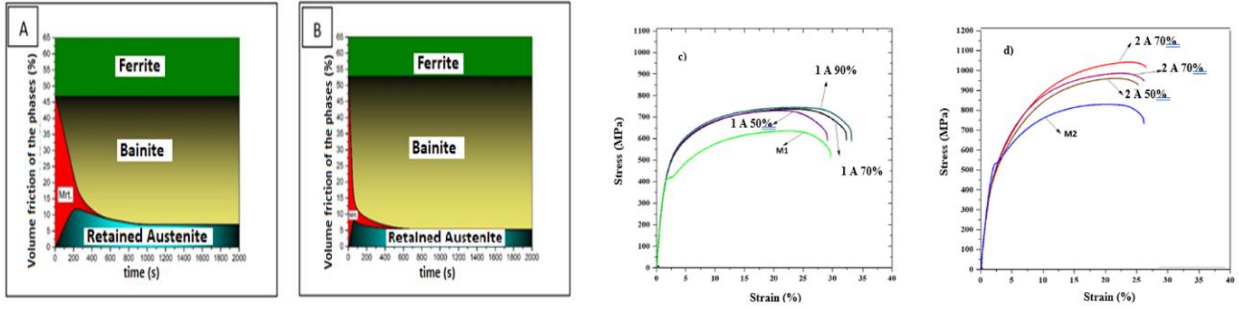


Figure. Graphical Abstract

## Aim

To examine the manufacturability of TRIP steels as an inexpensive alloy with superior properties

## Design & Methodology

Chemical and thermal modeling, microstructure and maps, tensile properties

## Originality

Microstructure mapping and modeling to create a rich context for the fabrication of literary steel.

## Findings

Superior tensile properties, microstructure maps, low and relatively high carbon productions of TRIP steel and alternatives

## Conclusion

The production of TRIP steel superior to both cost-effective alloys used in this study was achieved.

## Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

# Manufacturing of Low and High-carbon TRIP Steels by Modeling CCT Diagrams, Design of Microstructure Maps and Tensile

*Araştırma Makalesi / Research Article*

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## ABSTRACT

Although TRIP steels are the first-generation steel for the automotive industry, their high strength, formability, and strength after forming are versatile and widely used automotive steel. This study attempts to evaluate the automotive TRIP steels' manufacturing chains, thermal process, microstructure, and tensile properties via experimental modeling (CCT diagrams-microstructure maps) on two steel groups with low cost. The TRIP Steels manufacturing chains are chemical design, investment casting, hot rolling, and TRIP thermal processes modeling and applications. Experimental techniques performed on samples, meaning characterizations, are image analysis, XRD, hardness, and tensile tests. The results showed that a small amount of martensite transformation occurs during air cooling after the bainitic retention because of the low alloy content. As a result, modeling and microstructure maps have been successfully combined and studied in detail to design and manufacture the TRIP sheet steel.

**Anahtar Kelimeler:** TRIP çelikleri, Beynitik izotermal tutma, Mikroyapı haritaları, Soğuma diyagramları, Çekme özellikleri.

## Properties CCT Diyagramları Modellenmesiyle Düşük ve Yüksek Karbonlu TRIP Çeliklerinin Üretimi, Mikroyapı Haritalarının Dizaynı ve Çekme özellikleri

### ÖZ

TRIP çelikleri otomotiv endüstrisi için birinci nesil çelik olmasına rağmen yüksek mukavemeti, şekillendirilebilirliği ve şekillendirme sonrası mukavemeti çok yönlü ve yaygın olarak kullanılan otomotiv çeliğidir. Bu çalışma, otomotiv TRIP çeliklerinin üretim zincirlerini, ısı süreçlerini, mikro yapılarını ve çekme özelliklerini, düşük maliyetli iki çelik grubu üzerinde deneysel modelleme (CCT diyagramları-mikro yapı haritaları) yoluyla değerlendirmeyi amaçlamaktadır. TRIP çeliklerinin üretim zincirleri kimyasal tasarım, hassas döküm, sıcak haddelme ve TRIP termal proses modelleme ve uygulamalarıdır. Numuneler üzerinde gerçekleştirilen deneysel teknikler, yani karakterizasyonlar, görüntü analizi, XRD, sertlik ve çekme testleridir. Sonuçlar, beynitik tutmanın ardından havayla soğutma sırasında düşük alaşım içeriği nedeniyle az miktarda martenzit dönüşümünün meydana geldiğini gösterdi. Sonuç olarak, TRIP çelik sacın tasarımını ve üretimini gerçekleştirmek için modelleme ve mikro yapı haritaları başarıyla birleştirildi ve ayrıntılı olarak incelendi.

**Keywords:** TRIP steel, Microstructure maps, Bainitic isothermal holding, Cooling diagrams, Tensile properties.

### 1. INTRODUCTION

Although Ti and its many combinations exist, with new concepts to reduce part weight, steel is always an important structural and critical material. It is the subject of many interesting studies. In addition, steel is the basic building block in the automotive industry [1–4]. Over the last 70 years, harmonizing the weight reduction of car bodies with the improvement of crashworthiness has become one of the most important tasks of automobiles, particularly intending to reduce CO<sub>2</sub> gas emissions by improving fuel consumption [5]. Applications of high-strength steel sheets are expanding to meet these conflicting demands. Under the strong pressure of fuel

consumption, energy saving, and crashworthiness requirements, high-strength steels have been extensively used in automobile bodies to improve crashworthiness without increasing body weight [6]. Advanced high-strength steels (AHSS) have been developed on the high-strength low alloy steels (HSLA) concept and have made significant progress in the last four decades. Today's automotive sheet steel development started in the 1960s – 1970s with HSLA steel (Thermomechanical processing + micro-alloy additions). This development continued from the 1970s to the 1980s after the discovery of  $\alpha$ -phase steel [7–9]. Transformation plasticity (TRIP) steel was first introduced into the literature by General Motors and FORD in early studies in the 1990s. As before, this

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research was followed by the development of second and third-generation AHSS steels [10,11]. Also, today, steel, particularly AHSS, is one of the essential materials for the body in the white construction of the automobile [12]. Today, automobile manufacturers use advanced steels to achieve their range targets in increasing TRIP steel in AHSS, with Allotriomorphic ferrite, residual austenite, sometimes martensite phases, and deformation mechanisms in the microstructures, which has a vital role in weight reduction and formability of the part [11]. Moreover, medium and high alloy TRIP steels are possible today. However, conventional TRIP steels still have a significant advantage in their low alloying and low-cost improvement [12].

TRIP steels typically require an isothermal hold at an intermediate temperature, which produces some bainite. TRIP steels' silicon and carbon content can result in significant volume fractions of retained austenite in the final microstructure [5,13]. According to the general acceptance, Essential characteristics of TRIP steel arising from residual austenite play a key role [14–16].

Researchers reported [14,17,18] that adjusting the carbon content may control the strain level at which retained austenite begins to transform into martensite. At lower carbon levels, the retained austenite begins to transform almost immediately because of deformation, increased work hardening rate, formability during stamping, etc. The retained austenite is more stable at higher carbon contents and transforms only at strain levels beyond forming. At these carbon levels, the retained austenite stays in the final part. In various first and third-generation AHSSs, C, Si, Al, Mn, Cr, Mo, Ni, B, Nb, Ti, V, etc., are added to enhance various mechanical properties through the microstructural structure [5,19,20]. Microalloying elements such as are added. For TRIP steels, Al and Si are two important elements for the presence of residual austenite and the inhibition of carbide formation. Al is mainly added as an alternative to Si [21–23]. Al, a ferrite stabilizer like Si, is also insoluble in carbide.

Another advantage of Al over Si is a high driving force from austenite to bainite, which accelerates the bainite transformation kinetics resulting from the increased nucleation rate. It converts to martensite during subsequent deformation, such as a crash event. Therefore, TRIP steel is preferred for manufacturers' requirement of high strain value in the production of automotive parts such as frame rails, rail reinforcements, side rails, crash boxes, dash panels, roof rails, B-pillar upper, roof rail, engine cradle, front and rear rails, seat frame and so forth. Therefore, this study combined heat treatment with software modeling, giving better opportunities to design TRIP and other advanced steel such as DP and CP. Another essential scope of this study is microstructure maps. First, Lawson [7,24–26] recommended that microstructure maps be interpreted to achieve austenite transformation martensite, specifically hardenability information for various austenite substances. Even though TRIP steel has not been studied in detail, a microstructure map could help estimate the

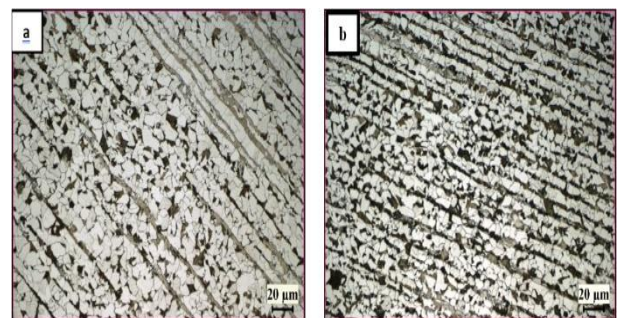
thermal process characterization [27,28]. Furthermore, the research presented herein constitutes the inaugural organization of detailed tensile results and microstructure maps created as particular annealing temperature vs. bainitic isothermal holding (BIH). This research employs a combination of modeling and experimental tests to develop a cost-effective method of producing TRIP steel.

Considering the above, this research is organized as the two-stage thermal process, which is annealing (intercritical annealing (IA) and bainitic isothermal holding (BIH) process. They were performed to produce different C-content TRIP steel structures and to improve mechanical properties. The hot-rolled steel structure was annealed and quenched at different intercritical temperatures. In the second stage, after intercritical annealing, it was kept in an isothermal salt bath at various times and then cooled in air. This stage has been modeled by combining the CCT&TTT diagrams using JMatPro software and perform experimental study [29,30].

Furthermore, it has produced microstructure maps that observe austenite transformation from critical temperature cooling and bainitic retention. Although these microstructural maps were rarely emphasized in previous studies, TRIP steel is helpful as a phenomenon for production chain and planning. Another feature of this study is the simultaneous evaluation of Al and Si alloys and low and high (relatively) -carbon alloys.

## 2. MATERIAL and METHOD

The chemical compositions of the two different steel group materials (labeled as M1 and M2) used in this study are given with the calculated [8] limit temperatures of the thermal process and martensite formation as AC1, AC3, and Ms in Table 1, respectively. The microstructures of the steels are shown in Figure 1. The design of these steel compositions aims to keep the other alloying elements constant while changing the amount of Carbon. These steel materials were produced as 40x40x400 mm blocks by investment casting method, and then, the size of blocks was reduced to 75x4 mm by hot rolling and left cooling at room temperature.



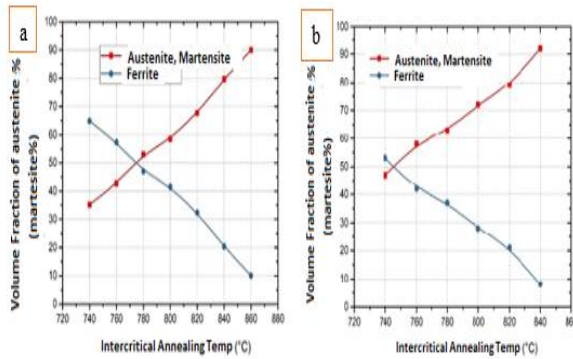
**Figure 1.** The initial microstructures of the designed steel, a) low C and b) high C steel

This study produced TRIP steel by two steel groups' intercritical annealing and isothermal holding. For this process, the first step was calculating intercritical annealing temp, the limit temp as Ac1 and Ac3 shown in Table 1.

**Table 1.** Chemical compositions of steel samples (wt %) with calculated intercritical temp

Materials groups	Chemical composition				Calculated Intercritical and Martensite start		
	C	Si	Mn	Al	Ac1 (°C)	Ac3 (°C)	Ms (°C)
Low Carbon, M <sub>1</sub>	0.14	0.62	1.62	0.08	726	863	430
High Carbon, M <sub>2</sub>	0.23	0.64	1.59	0.09	727	840	393

The second step was determining the change of austenite volume fraction with intercritical annealing and then cooling in cold water experimentally, as shown in Figure 2. As well known, TRIP steel production with heat treatment covers two steps: intercritical annealing and isothermal holding at bainitic temperatures over martensite start temperatures. Using this knowledge in Figure 2., intercritical annealing temperatures for producing TRIP steel have been determined.

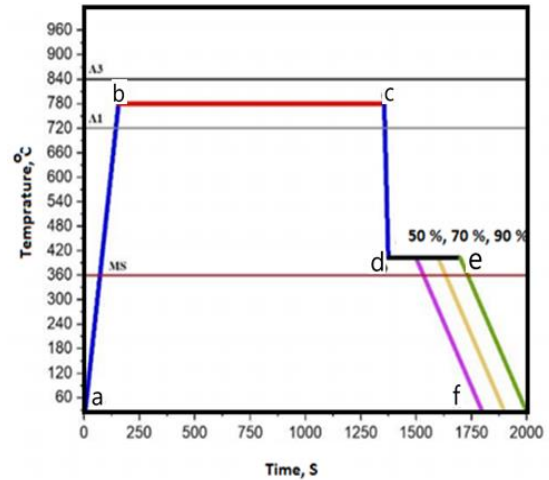


**Figure 2.** Changing of austenite volume fraction (martensite, VFM) with intercritical annealing temperatures for two groups, a) M1 b) M2

Another primary process after intercritical annealing is the bainitic holding (BIH) stage. Followed cooling map routes of the TRIP process were obtained by JMatPro software and classical formulas. The Thermal and time profile of the TRIP process used in this research is given in Figure 3.

The microstructures obtained after partial austenitization were evaluated, and temperatures with a volume ratio close to 50% Ferrite + 50% Martensite (austenite) were used. It is aimed to obtain conversion products (bainite + martensite + residual austenite) in different amounts from 45-55% austenite phase obtained in partial austenitization. Targeted amounts of bainite are 25%, 35%, and 45%. The XRD method determined the residual austenite content of the microstructure-mapped materials. XRD analysis condition: Cr-K $\alpha$  radiation was measured by four peak methods and evaluated according to the ASTM E975 standard (Measurement resolution = 0.05 °, Collimator diameter = 2mm). The measurement

time (excluding device movements and positioning) is 900 seconds per scan interval. Peak ranges: 1. Scan 1: 74.000° - 84.000°, 2. Scan 2: 102.000° - 108.000°, 3. Scan 3: 122.000° - 136.000°, 4. Scan 4: 149.000° - 163.000°



**Figure 3.** Schematic showing heat treatments, meaning partial austenitization and then isothermal holding

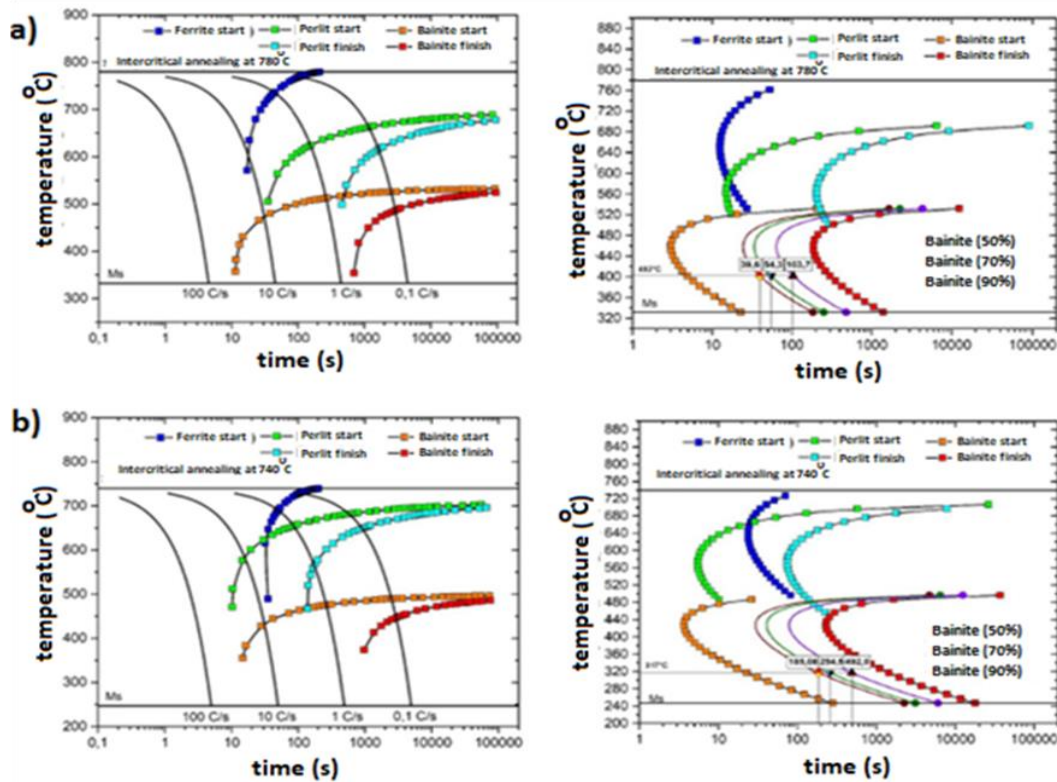
Sizes of the Tensile test samples were  $L_0 = 34$  mm,  $L_T = 77$ , and thickness = 3 mm (EN ISO 6892-1). Three tensile tests for each steel sample were conducted to ensure that the obtained tensile properties represent actual mechanical behavior. The tensile test speed was kept constant at  $57 \times 10^{-2}$  s $^{-1}$ .

### 3. RESULTS AND DISCUSSION

#### 3.1. Microstructure and Cooling Transformation Diagrams

Using the information in Figure 2, which shows the variation of the intercritical annealing temperature with austenite (martensite), the critical annealing temperatures at which the TRIP samples of both groups could be produced have been obtained. For desired phase volume fractions at austempering-BIH, as essential annealing temperatures, 780 oC and 740 oC were selected for M1 and M2 to receive 47% VFM and 53% VFM, respectively. These temperatures are relatively low critical annealing temperatures. In critical annealing, the carbon content of the partial austenite is high by the lever rule. It thus increases the stability of the austenite during the second stage of the thermal process BIH [31]. In order to create a TRIP structure with both steel groups, the samples underwent thermal procedures following the profile depicted in Figure 3. Here, the cooling route of TRIP and so holding BIH temperatures and times were obtained via Using all the above, the dissociation-transformation product of three different partial austenite, 50%, 70%, and 90% by volume, was obtained with three BIH holding times. These percentages were also used to code the samples produced.





**Figure 4.** Intercritically annealed and then fast-cooled samples microstructures of both steel groups a) 1S 780°C samples of M1 (a) 2 S 740°C samples of M2

Experimental results have also shown that the phase volume fractions obtained have been approximately in amounts compatible with previous knowledge (Figure 2) and modeling of the cooling diagram (Figure 4). The sample microstructure and identification of the TRIP steels produced in this study are shown in Figures 5 and 6. However, the state of the residual austenite from these phases is somewhat different from the others. The ferrite, bainitic ferrite retained austenite, and martensite phases could be clearly understood. Although it is possible to show residual austenite, it is challenging to view the whole and determine the exact amount with an optic microscope or SEM [25,33]. Therefore, a realistic measurement and determination were made exclusively with X-RAY diffraction, and the retained austenite volume ratio was determined as shown in Table 2. As

given in Table 2, the reference sample (inter-critical annealed) of the first group has shown 53% ferrite + 47% austenite, and the reference sample of M2 (inter-critical annealed) has the Modelling of CCT and TTT diagrams by JMatPro software, which is based on thermodynamic modeling [29,30,32] as seen in Figure 4. shown 47% ferrite + 53% austenite. These samples were etched with 2% Nital + Sodium metabisulfite [7] Microstructures consisting of ferrite (off-white), bainite + martensite (black), and retained austenite (white) could be easily distinguished as described on the microstructure in optical microscopy, and a multiphase structure has been obtained. Retained austenite is homogeneously distributed throughout the microstructure along with martensite and is connected to neighboring ferrite or bainite. Containing residual austenite was produced; in

**Table 2.** Phase's volume fractions, after BIH, obtained by a combination of X-RAY diffraction RA and image analysis (Ferrite, Martensite, and bainite)

Samples groups	Volume Fractions of Phases (%) *(±2) tolerance				BIH time (s)
	Ferrite*	Martensite*	Bainite*	RA	
M1 A 50%	53	20.1	20	6.9 (+0.8 / -0.7)	40
M1 A 70%	53	6.3	31.8	8.9 (+2.5 / -2.3)	54
M1 A 90%	53	2	38.5	6.5 (+1.4 / -1.3)	104
M2 A 50%	47	16.1	24.5	12.4 (+7 / -5.7)	185
M2 A 70%	47	5.3	35.7	12.0 (+5.7 / -5.0)	255
M2 A 90%	47	2.3	41.4	9.3 (+2.6 / -2.3)	492

other words, it could be said that TRIP multiphase steels were accomplished [34]. BIH temperatures were 402 ° C for M1 and 347 ° C for M2 in this research. In the open literature, reported BIH temperatures are generally typically between ~350 and 450 °C. However, holding time is also very effective in the transformation of austenite. As indicated by Sugimoto et al., RA volume

fraction decreases at longer BIH times [35]. Also, in this study, the effect of time easily could be understood from the microstructure maps in Figure 7. and Table 2.: we see that RA increases in M1 with a 50 percent conversion rate (50% and 70%) and decreases at 90%, while M2 tends to decrease continuously. Jacques et al. [31] reported the increased RA value up to saturation value in 1.5Si and

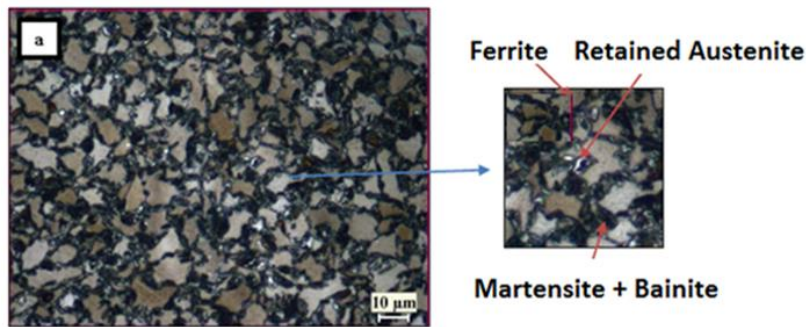


Figure 5. Microstructures of the TRIP steel, which have been produced in M1 steel

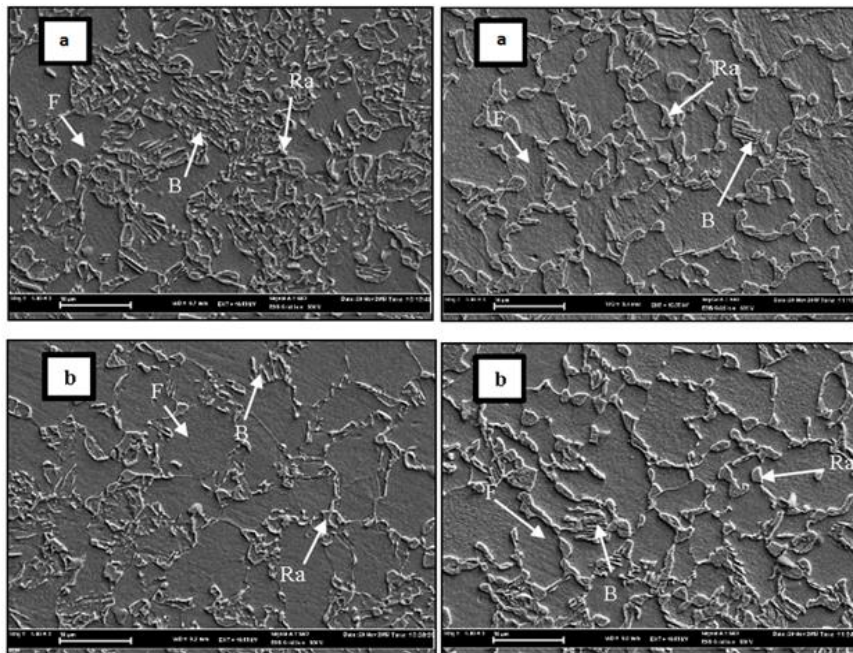


Figure 6. Microstructures of the TRIP steel, which have been produced in M1 steel

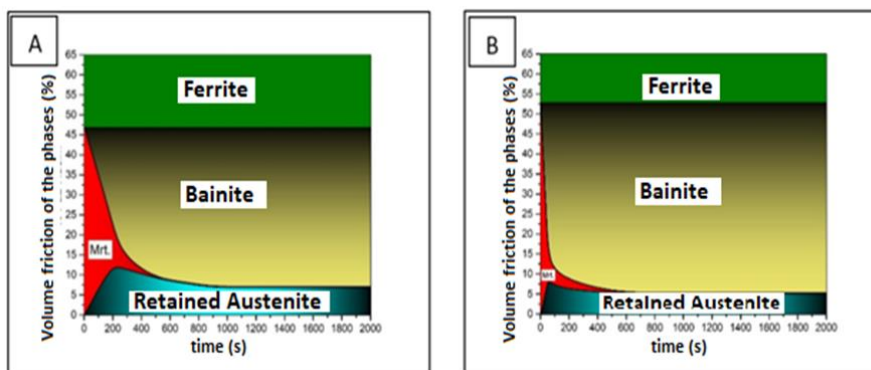


Figure 7. Microstructure Maps of the Austenite transformation A) M1 and B) M2

**Table 3.** Phase's volume fractions, after BIH, obtained by a combination of X-RAY diffraction RA and image analysis (Ferrite, Martensite, and bainite)

Samples group and decomposition of Austenite via BIT	Mechanical Properties					
	Hardness (HV0,5)	YS (MPa)	UTS (MPa)	Fracture elongation (%)	Uniform elongation (%)	Yield ratio, YS/UTS
M1 base steel	182	413	636	29,7	22.5	0.649
A 50%	217	375	731	29	20.7	0.512
M1 A 70%	207	366	739	32.4	23.6	0.495
M1 A 90%	198	356	746	33.7	23.9	0.477
M2 base steel	191	532	830	26.1	20.4	0.640
M2 A 50%	307	455	961	26.5	21.8	0.473
M2 A 70%	298	423	1042	26.4	24	0.405
M2 A 90%	280	359	986	26.2	22.8	0.364

1.5Al TRIP steels. They reported that RA peaked in 0.4 Si steel and decreased due to low carbon levels. Therefore, through this knowledge, the minus tolerances given in the XRD results were used as the minus tolerance before and after the start and end times as the RA volume ratio when creating the microstructure maps. The Image Analysis method calculated bainite and martensite volume fractions by preliminary studies (Table 2).

### 3.1. Hardness and Tensile Properties

The hardness results for the M1 and M2 groups are in Table 3, along with the tensile test results. When we examine the Tables, when we compare the percent conversion amounts of the materials, we see that it is higher for the M2 group (307 HV0.5 at the highest 50% conversion) and decreases in both fabrics with the increased amount of bainitic percent conversion. It is assumed that low BIH and carbon ratios cause the hardness of the M2 group. Researchers [36,37], reported that temperature increases hardness during the isothermal bainite transformation, so the strength of the bainite structure decreases. In this case, austenite, exiting the surrounding matrix phase and referred to as "matrix constraints," may reduce grain stability, resulting in a lower RA. The decrease in residual austenite can lessen TRIP steel's final ultimate tensile strength (UTS) [16,22].

Suikkanen et al. [38], stated that TRIP steel properties depend on the cooling path and carbon content for ultra-high-strength TRIP steel, except for samples kept at 450 ° C, noting that carbon content hasn't had much more effect on yield strength. However, yield strength increased with decreasing isothermal holding temperature (BIHT). In addition, decelerated that Independent of quenching and isothermal retention temperature, tensile strength increases with increasing carbon content. Moreover, they said uniform elongation increases with increasing carbon content at  $\leq 350$  ° C holding temperatures. The isothermal retention temperature does not significantly affect uniform elongation. As a result, they claim that carbon content or controlling temperature has no definite impact on total extension. Related to their study, a similar approach may

be used, according to Table 3, for this research, which shows the tensile and hardness test results of the M1 and M2 groups samples. Yield strength appears to decrease with BIH and BIH processes compared to original materials, as seen in Table 3. What are the changes by BIH and, therefore, especially on RA? It can be estimated that the flowing starts at lower tensions in the austenite phase, which is softer than protectoit ferrite, bainite, or martensite. However, austenite particles are tiny in size and lower in volume. Its softening effects could depend on RA percent volume and grain size. Tensile strength is independent of the proportion of residual austenite, meaning that a higher proportion of residual austenite probably results in a higher rate of deformation hardening through the TRIP effect [35,37].

While total elongation is insensitive, homogenous extension is sensitive to changes in the volume ratio of residual austenite. That is remarkably consistent with Barbacki's [39] which found that homogenous elongation depends on the volume ratio of residual austenite in bainitic TRIP steels, but tensile elongation does not. It is known that the effect of TRIP relies not only on the residual austenite ratio but also on its morphology, distribution, and chemical composition play essential roles. As a result, the TRIP effect depends on the stability of residual austenite, and a gradual transformation of martensite is desired in deformation. Austenite is found in two morphologies in the steels studied: granular islands and thin films. The volume ratio of residual austenite increases the homogeneity and total elongation if the residual austenite is distributed uniformly between the bainitic sheets. However, granular islands should be avoided. It should also be remembered that the TRIP effect is not the only factor affecting homogeneous and total elongation because it contributes to inclusions, microstructural banding, and matrix microstructure [40].

Suikkanen P.P. et al. [38] stated that the carbon content strongly affects tensile strength. They said that while the yield strength increased with decreasing isothermal retention temperature, the tensile strength increased enormously with the increasing carbon content. Residual tends to improve austenite homogenous elongation, but has said that it has no significant effect on total



elongation. TRIP steels are C-Mn-Si / Al steels. Carbon is a crucial element that keeps austenite stable and determines the martensite transformation characteristic during deformation. In addition, the carbon increases the strength of the austenite by interfering with austenite. During isothermal holding, especially ferrite formation, austenite is enriched with Carbon by austenite carbon fusion. In the case of the deformation, the low carbon level causes the transformation of residual austenite to martensite, increasing the hardening speed and formability during the forming process. If the carbon content in the residual austenite is high, austenite becomes much more stable, and transformation occurs at a significantly prolonged deformation stage. As with other and general steel logic, the element must be primarily for sulfur stabilization, strength and hardenability, and general steel characteristics. In addition, being an austenite-forming element, stabilizing austenite makes an essential contribution to isothermal retention [7,41].

Unlike other high-strength steels, TRIP steels silicon, one of the main elements; Silicon delays the formation of cementite during the bainitic transformation and contributes to increasing the stability of the residual austenite. A high dissipation force is required for the solubility of the Silicon in the cementite phase to be relatively low to enter or remove the cementite phase. Silicon atoms accumulating around cementite nuclei increase the activity of carbon atoms and prevent them from diffusing into cementite grains [31,42]. The minimum amount of Silicon required to delay the formation of cementite would be ~ 0.7% by weight. However, high silicon content can cause a high oxide layer, low surface quality, and low coating during steel production. That poses a problem, especially in galvanizing steel. To prevent such issues, while the amount of Silicon is reduced, the features can be improved by adding some Aluminum. If how much lower alloying elements have been added, so much it is better. This study aimed to do so. The tensile test results show that compatibility was achieved according to the literature.

Another important alloy for TRIP steel is aluminum. Like Silicon, aluminum delays cementite formation during isothermal retention and conversion. However, aluminum has a lower potential to prevent cementite formation at the same weight ratio as Silicon [31]. Since steels containing aluminum have a large amount of austenite, more TRIP effects can be observed during the tensile test. However, aluminum does not increase the strength of the ferrite phase as much as Silicon. That significantly changes the overall strength of the material. In recent years, it has been possible to maintain the welding ability and formability by increasing resistance with microalloying elements such as Nb, Ti, and V, which decrease the martensite formation temperature in TRIP steels and delay the carbide formation in the internal structure during the bainitic transformation.

These microalloying elements are essential for high-strength and high-strength steels and are also used commercially. Materials used in this study also include minor microalloying elements, as mentioned in related literature. Therefore, it could be said that the samples' achieved tensile properties and strength were also by these elements.

Moreover, in literature, High Strength Low Alloy (HSLA), AHSS, or microalloyed steels stand out with their high strength, superior mechanical properties, and corrosion resistance steels show much higher strength and toughness than the structural steels in which they are developed [36]. Different names are known for microalloyed steels in the market or the literature, such as microalloying steel, perlite poor steels, fine grain steels, High strength low alloy steels (High strength low alloys steel), etc. [29]. For example, high-strength and lightweight parts are desired in the automotive industry. Despite the low C-ratio, the flow rate of the microalloying elements Nb, V, and Ti can reach 500 N / mm<sup>2</sup> with controlled rolling and grain thinning and hardening effects. Development objectives [37] Development of weldability, the primary production technique, improves strength and toughness, reduces weight, and reduces cost. Micro-alloy steels are produced in four steps [9,43,44]. Microalloying, austenitization, hot rolling, and controlled cooling. These steps can be applied individually or in combination to produce the desired features. Many low-alloy, high-strength steels can be ferrite + perlite, while some may be ferrite + bainite and tempered martensite or bainitic structure. Microalloying elements control the microstructures of steels with various mechanisms, and these mechanisms vary with microalloying. Steel production has a double function as a deoxidizing agent and micro-alloy element. In fully stagnant steels, dissolved aluminum acts as an element. That prevents austenite grain growth and accelerates austenite transformation. Tensile test curves of the samples were given using different combinations in Figure 8. As observed, the original steel sheet has shown discontinuous yielding. However, the TRIP samples of both groups have demonstrated continuous yielding. That is good information for gaining the best surface after the stamping process. All TRIP samples have shown better strength and similar or more elongation than the original steel samples. All these results of the TRIP structure and its deformation arise from their microstructures and multiphases. Increasing the austenite transformation volume has increased tensile strength but causes decreasing elongation. However, all successful relations of strength–elongation value are better and usable when compared with original materials. When compiling the M1 group and M2 group results, the M1 groups have shown higher strength but lower elongation than M2. As explained before, alloy contamination and phase structure are dominant.

#### 4. CONCLUSIONS

As a result of the modeling of the cooling diagrams applied in this study, heat treatment applications, microstructure maps, and material characterization studies, the following critical evaluations can be made about the production chain, materials characterizations, and tensile properties of TRIP steels.

1. The production of TRIP steel, which is superior to both cost-effective alloys used in this study, was achieved.
2. As with dual-phase steels, microstructure maps and cooling diagram modeling are very useful for producing the desired multiphase structures of TRIP steels.
3. The TRIP steels produced have high elongation values and very high strength compared to the original properties of the steel produced.
4. The C ratio in partial austenite appears to increase the amount of residual austenite. However, BIH influences the characteristic of residual austenite, while the part of residual austenite has had a definite effect on homogenous elongation.
5. With increasing BIH, the yield strength decreased, regardless of C, and higher values were obtained in the material with higher C (M2).

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#### AUTHORS' CONTRIBUTIONS

**Samet ŞERAS:** Performed the experiments and analyse the results. Performed the writing process of the article.

**Bilge DEMİR:** Concept design, Performed the writing process of the article.

#### CONFLICT OF INTEREST

There is no conflict of interest in this study.

#### REFERENCES

- [1] Ö. Pamuk, A. Durgutlu, Patlama Kaynağı Yöntemi ile Birleştirilen Östenitik Paslanmaz Çelik (AISI 316L) – S235JR Kompozit Malzemelerde Patlayıcı Oranın Mikroyapı ve Yorulma Özelliklerine Etkisi, *Politeknik Dergisi*, 21, 527–534, (2018).
- [2] A. Durgutlu, B. Gülenç, Patlama Kaynağıyla Paslanmaz Çelik – Bakır Levhaların Kaynaklanabilirliği Ve Patlayıcı Oranın Birleşme Arayüzeyine Etkisi, *Politeknik Dergisi*, 5, 243–248, (2002).
- [3] M.S. Yıldırım, Y. Kaya, Investigation of The Joining Interface of Copper-Titanium Bimetallic Composite Materials Manufactured Using Explosive Welding Method, *Journal of Polytechnic*, (2022).
- [4] B. Demir, An Investigation Of Producability Of Dual-Phase - PhD thesis, *Gazi University*, Ankara., (2003).
- [5] D.K. Matlock, J.G. Speer, Third Generation of AHSS: Microstructure Design Concepts, *Microstructure and Texture in Steels*, 185–205, (2009).
- [6] J.-H. Schmitt, T. Jung, New developments of advanced high-strength steels for automotive applications, *C R Phys*, 19, 641–656, (2018).
- [7] B. Demir, M. Erdoğan, The hardenability of austenite with different alloy content and dispersion in dual-phase steels, *J Mater Process Technol*, 208, 75–84, (2008).
- [8] B. Demir, M Erdoğan, Çift-Fazlı Çeliklerde Martensit Hacim Oranı Ve Morfolojisinin Çekme Özellikleri Üzerine Etkisi, *Gazi Üniv. Fen Bil. Dergisi*, vol: 11 no 4 s. 727, Ekim (1998).
- [9] B. Demir, An investigation on the production of dual-phase steel from AISI4140 and its impact strength at different martensite volume fractions, *Metallofizika i Noveishie Tekhnologii* 29, (9), pp.1159 - 1166 (2007).
- [10] B.C. De Cooman, Structure–properties relationship in TRIP steels containing carbide-free bainite, *Curr Opin Solid State Mater Sci*, 8, 285–303, (2004).
- [11] A. Eres-Castellanos, C. Garcia-Mateo, F.G. Caballero, Future trends on displacive stress and strain induced transformations in steels, *Metals*, 11, 1–19, (2021).
- [12] Y. Wang, Y. Xu, Y. Wang, J. Zhang, C. Guo, X. Wang, W. Zhao, H. Liu, Enhanced stretch flangeability and crack propagation behavior of an 1100 MPa grade TRIP-aided bainitic ferrite steel, *Journal of Materials Research and Technology*, 26, 5503–5517, (2023).
- [13] D.K. Matlock, J.G. Speer, E. De Moor, P.J. Gibbs, Recent Developments In Advanced High Strength Sheet Steels For Automotive Applications: An Overview, *JESTECH*, 15, 1–12, (2012).
- [14] J. Wang, S. Van der Zwaag, Stabilization mechanisms of retained austenite in transformation-induced plasticity steel, *Metallurgical and Materials Transactions A*, 2001, 32:6, 32, 1527–1539, (2001).
- [15] G.N. Haidemenopoulos, A.N. Vasilakos, Modelling of austenite stability in low-alloy triple-phase steels, *Steel Research*, 67, 513–519, (1996).
- [16] J. Chiang, B. Lawrence, J.D. Boyd, A.K. Pilkey, Effect of microstructure on retained austenite stability and work hardening of TRIP steels, *Materials Science and Engineering: A*, 528, 4516–4521, (2011).

- [17] S.J. Kim, C.G. Lee, I. Choi, S. Lee, Effects of heat treatment and alloying elements on the microstructures and mechanical properties of 0.15 wt pct C transformation-induced plasticity-aided cold-rolled steel sheets, *Metall Mater Trans A Phys Metall Mater Sci*, 32, 505–514, (2001).
- [18] A. Ramazani, K. Mukherjee, U. Prahl, W. Bleck, Transformation-induced, geometrically necessary, dislocation-based flow curve modeling of dual-phase steels: Effect of grain size, *Metall Mater Trans A Phys Metall Mater Sci*, 43, 3850–3869, (2012)
- [19] Keele Stuart and Kimchi Manachem, AHSS\_Guidelines V5.0 20140514, *WorldAutoSteel*, 2014.
- [20] Sugimoto, K. I., Nakashima, Y., Kobayashi, J., & Hojo, T. (2023). Effects of Partial Replacement of Si by Al on Impact Toughness of 0.2% C-Si-Mn-Cr-B TRIP-Aided Martensitic Steel. *Metals*, 13, (7), 1206, (2023).
- [21] K.S. Choi, A. Soulam, W.N. Liu, X. Sun, M.A. Khaleel, Influence of various material design parameters on deformation behaviors of TRIP steels, *Comput Mater Sci*, 50, 720–730, (2010).
- [22] X.D. Wang, B.X. Huang, Y.H. Rong, L. Wang, Microstructures and stability of retained austenite in TRIP steels, *Materials Science and Engineering: A*, 438–440, 300–305, (2006).
- [23] O. Graè Ssel, L. Kruè Ger, G. Frommeyer, L.W. Meyer, High strength Fe-Mn-(Al, Si) TRIP/TWIP steels development of properties of application, *International Journal of plasticity*, 16.10-11: 1391-1409, (2000)
- [24] M. Erdogan, R. Priestner, Effect of epitaxial ferrite on yielding and plastic flow in dual phase steel in tension and compression, *Materials Science and Technology* 15 (1999) 1273–1284.
- [25] B. Demir, M. Erdogan, Tensile Properties Of The Hardenable Dual Phase Steel With Different Martensite Dispersion, *JESTECH*, 15, 13–19, (2012).
- [26] B. Demir, M. Erdogan, Fracture Behaviour Of The Hardenable Dual Phase Steel With Different Martensite Dispersions, *JESTECH*, 15, 97–103, (2012).
- [27] M. Zhang, L. Li, R.Y. Fu, D. Krizan, B.C. De Cooman, Continuous cooling transformation diagrams and properties of micro-alloyed TRIP steels, *Materials Science and Engineering: A*, 438–440, 296–299, (2006).
- [28] S. Chatterjee, Transformations in TRIP-assisted Steels: Microstructure and Properties, *PhD Thesis* (2006).
- [29] Xie, Hao-jie, Xiao-chun Wu, and Yong-an Min. "Influence of chemical composition on phase transformation temperature and thermal expansion coefficient of hot work die steel." *Journal of Iron and Steel Research International*, 15, 6. 56-61, (2008).
- [30] S.H. Atapek, E. Erişir, S. Gümüş, Modeling and thermal analysis of solidification in a low alloy steel, *J Therm Anal Calorim*, 114, 179–183, (2013).
- [31] P.J. Jacques, E. Girault, P. Harlet, F. Delannay, The developments of cold-rolled TRIP-assisted multiphase steels. Low silicon TRIP-assisted multiphase steels, *ISIJ International*, 41, 1061–1067, (2001).
- [32] A. Kozłowska, A. Grajcar, J. Opara, J. Kaczmarczyk, A. Janik, K. Radwański, Mechanical behaviour and micromechanical modelling of medium-Mn steel microstructure evolution, *Int J Mech Sci* 220 (2022).
- [33] M. Erdogan, Effect of austenite dispersion on phase transformation in dual phase steel, *Scr Mater*, 48, 501–506, (2003).
- [34] P.J. Jacques, E. Girault, A. Mertens, B. Verlinden, J. Van Humbeeck, F. Delannay, The developments of cold-rolled TRIP-assisted multiphase steels. Al-alloyed TRIP-assisted multiphase steels, *ISIJ International*, 41, 1068–1074, (2001).
- [35] K.I. Sugimoto, D. Fiji, N. Yoshikawa, Fatigue strength of newly developed high-strength low alloy TRIP-aided steels with good hardenability, in: *Procedia Eng*, pp. 359–362, (2010).
- [36] De Meyer, Marijke, Jan Mahieu, and B. C. De Cooman. "Empirical microstructure prediction method for combined intercritical annealing and bainitic transformation of TRIP steel.", *Materials science and technology*, 18, 10, 1121-1132, (2002).
- [37] H. tao Jiang, W. Ding, D. Tang, W. Huang, Mechanical Property and Microstructural Characterization of C-Mn-Al-Si Hot Dip Galvanizing TRIP Steel, *Journal of Iron and Steel Research International*, 19, 29–36, (2012).
- [38] P.P. Suikkanen, A.-J. Ristola, A.M. Hirvi, P. Sahu, Mahesh, C. Somani, D. Arthur, L.P. Karjalainen, Effects of carbon content and cooling path on the microstructure and properties of TRIP-aided ultra-high strength steels, *ISIJ International*, 53, 337–346, (2013).
- [39] A Barbacki, "The role of bainite in shaping mechanical properties of steels." *Journal of Materials Processing Technology*, 53, 1-2, 57-63, (1995).
- [40] C. Wang, H. Ding, M. Cai, B. Rolfe, Characterization of microstructures and tensile properties of TRIP-aided steels with different matrix microstructure, *Materials Science and Engineering: A*, 610, 65–75, (2014).
- [41] M. De Meyer, L. Kestens, B.C. De Cooman, Texture development in cold rolled and annealed C-Mn-Si and C-Mn-Al-Si TRIP steels, *Materials*

- Science and Technology*, 17, 1353–1359, (2001).
- [42] S. Chatterjee, H.K.D.H. Bhadeshia, Stretch-flangeability of strong multiphase steels, *Materials Science and Technology*, 23, 606–609, (2007).
- [43] Garcia, C. I., and A. J. Deardo. "Formation of austenite in 1.5 pct Mn steels." *Metallurgical Transactions A*, 12: 521-530, (1981).
- [44] D.Z. Yang, E.L. Brown, D.K. Matlock, G. Krauss, The formation of austenite at low intercritical annealing temperatures in a normalized 0.08C-1.45Mn-0.21Si steel, *Metallurgical Transactions A*, 16, 1523–1526, (1985).
- [45] S. Şeras, Investigation of The Mechanical Properties Of TRIP Steels Containing 0,14% - 0,23% C, Msci thesis, *Karabük Univ.*, (2018).