Article

Comparative Evaluation of the TRIP Effect in Steels with Different Contents of Mn and Al

Mircea Cristian Pantilimon, Andrei Constantin Berbecaru, Ioana Arina Gherghescu *, George Coman, Sorin Ciucă *, Andrei Grecu, Mirela Gabriela Sohaciu , Ruxandra Elena Dumitrescu and Cristian Predescu

Faculty of Materials Science and Engineering, POLITEHNICA University of Bucharest, 313 Splaiul Independenței, 060042 Bucharest, Romania; mircea.pantilimon@upb.ro (M.C.P.); andrei.berbecaru@upb.ro (A.C.B.); george.coman@upb.ro (G.C.); andrei.grecu2611@upb.ro (A.G.); mirela.sohaciu@upb.ro (M.G.S.); ruxandra.dumitrescu@upb.ro (R.E.D.); cristian.predescu@upb.ro (C.P.)

* Correspondence: ioana.gherghescu@upb.ro or gherghescu_ioana@yahoo.com (I.A.G.); sorin.ciuca@upb.ro (S.C.)

Abstract: This paper presents a comparison between four TRIP steels, which belong to two groups with different chemical compositions. The first group is that of steels with a relatively low contents of Mn (1.5–2%), high Al (1–2%) and about 0.2% C, and the second includes steels with lower percentages of C (0.1%) and Al (max. 0.6%), but with high percentages of Mn (over 5%). The steels were heat treated by incomplete austenitization, isothermally cooled in salt baths at 400 °C, followed by air cooling. The heat-treated samples were subjected to the impact bending test. A comparative study was performed from the point of view of the intensity of the TRIP effect, the development of the retained austenite-to-martensite transformation under shock (studied by SEM), X-ray analysis and hardness measurements. It was found that appropriate and similar behaviors in terms of mechanical shock were shown by two steels belonging to different groups, with similar amounts of the retained austenite being turned into martensite fractions. The steel with the highest Mn percentage was distinguished by having the highest hardness (362 HV) and the highest retained austenite (obtained after heat treatment) and martensite fractions (caused by the TRIP effect) (10.63% and 2.17%, respectively).

Keywords: TRIP steel; retained austenite; scanning electron microscopy; X-ray diffraction; Vickers hardness; car body material

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1. Introduction

Nowadays, car manufacturers are aiming to use of parts that have high mechanical strength combined with great ductility and low-specific-weight materials. The main purpose of this is to increase the performance and safety of vehicles, with the passengers' protection being of utmost importance, as well as reducing the car weight, leading to fuel economy and low emission levels of engines.

The most important characteristics of TRIP steels are their strength and ductility as well as hardness, which is increased by the transformation of the retained austenite when an impact occurs. TRIP steels are supposed to have a maximum 15% volume fraction of retained austenite in their structures following a bainitic transformation [1,2]. In order to obtain the optimum volume fraction of retained austenite, as well as other constituents such as ferrite, bainite and even martensite, TRIP steels are submitted to a partial austenitization followed by an isothermal quenching for bainitic transformation [3,4].

Several TRIP steels' chemical compositions were studied to obtain better control of the retained austenite fraction, to enhance its stability and to increase the resistance properties [5–14].

In this regard, the present article proposes an evaluation of the TRIP effect in two groups of TRIP steels, with each group being represented by two steels. The first group is that of steels with a relatively low contents of Mn (1.5–2%) (close to those of conventional

TRIP steels), high Al (1–2%) and about 0.2% C, and the second includes steels with lower percentages of C (0.1%) and Al (max. 0.6%), but with higher percentages of Mn (of over 5%). One of the steels of the second group is proposed as a solution in this paper in order to intensify the TRIP effect through the rigorous choice of its new chemical composition.

Thus, all the studied steels are alloyed with Mn and Al at different contents, with their most important effects being summarized as follows:

Manganese is the main alloying element in TRIP steel. It has the advantage that it does not form independent carbides in the presence of iron, moderately increasing the hardenability. Most importantly, it is a gammageneous element, and also has a tendency to induce the retention of austenite. In addition, it does not worsen weldability, a very important characteristic in technological process of producing car body parts. In conventional TRIP steels, the percentage of Mn is up to 2.5%, a range in which the steels in our first group fell. The second group has a higher content of Mn, associated with TRIP steels. This was limited to 6.1% in order to avoid an overly high fraction of retained austenite.

Aluminum was chosen in TRIP steel as an alternative to silicon [8,9,15]. It is an alphageneous element, with an important amount of ferrite being necessary for the essential property of the steel sheet for car body parts, namely high deformability. Instead, it shifts the A3 temperature to higher values, with all the known disadvantages. It does not have a significant influence on the hardenability. Aluminum is also added in order to obtain a bainite that has the lowest possible carbide content, as it is known to be a non-carbide-forming element. The carbon content of retained austenite is directly related with the aluminum content. Thus, aluminum stabilizes the carbon in the retained austenite [10]. In the new chemical composition, the highest Mn content among the studied steels (6.1%) is associated with a lower Al content (0.6%), making it possible to obtain the highest possible retained austenite volume fraction after unconventional heat treatment.

Regarding the carbon content, for the first steel group, the values of 0.2–0.25% are considered normal for the steel sheets used in mechanical constructions. For the second group the carbon content was limited to 0.1% for three reasons:

- Not to increase the hardness too much, with Mn being an element that still increases the hardenability;
- Not to form a large amount of complex carbides, such as FeMn_3C ;
- Carbon, a strong gammageneous element, should not negatively influence, together with Mn, the appearance of a quantity higher than the optimal value (10–15%) of retained austenite.

In this study, experimental research on the heat treatment of steels was carried out in order to obtain the TRIP effect. The study highlighted the parameters of unconventional heat treatment (bainitic hardening with partial austenitization) applied to obtain the required ferrite, but also bainite with the optimal amount of retained austenite. The results of scanning electron microscopy analyses, as well as hardness and X-ray diffraction tests, are presented in order to characterize the steels' structures, before and after the impact bending test.

The purpose of this paper was to obtain and characterize a new TRIP steel composition, by comparison with three other existing steels containing different percentages of C, Mn and Al [16–18]. Our study showed that the new steel exhibited better characteristics when compared to the three other steels. In this endeavor, the impact bending test was decisive for a qualitative assessment.

2. Materials and Methods

2.1. Production of Studied TRIP Steels

The four materials investigated in this paper were low-alloy steels, which are part of the advanced high-strength steels (AHSS) category, that exhibit the TRIP effect of Mn or Mn and Al steels and whose chemical compositions were chosen according to the existing data in the literature [16–19].

The raw materials used in the production of the four TRIP steels are presented in Table 1.

Table 1. The chemical compositions of the raw materials used in the production of the TRIP steels.

Raw Materials' Element Contents, wt%												
	C	Mn	Si	S	P	Cu	Al	Fe	Ca	Cr	Ni	Ti
ARMCO	0.005	0.047	0.043	0.02	0.006	0.01	0.004	bal.	-	0.006	0.01	-
FeSi	0	0.659	68.18	0.002	0.027	0.049	1.589	28.39	0.049	0.244	0.067	0.148
FeMn	1.2	78.22	1.832	0.004	0.187	0.093	0.056	17.97	0.017	0.197	0.147	0.019
Mn	-	99.8	-	-	-	-	-	-	-	-	-	-
Al	-	-	-	-	-	-	99.99	-	-	-	-	-

The alloys were made in an induction furnace, with vacuum and controlled atmosphere type Fives CELES ALU 600 (Fives, Lautenbach, France), and subsequently cast in cooled copper ingots with a cylindrical shape. Afterwards, the ingots were processed by cutting, polishing and plastic deformation. The chemical composition analysis of the steels was performed with a Leco GDS 500 A $10 \times 0.33 \mu\text{F}$ optical emission spectrometer (Leco Europe B.V., Geleen, The Netherlands). Comparative data (proposed and obtained) of the four TRIP steels' chemical compositions are presented in Table 2.

Table 2. The proposed and obtained chemical compositions of the four TRIP steels.

		Element Contents, wt%											
Steel		C	Mn	Si	S	P	Cu	Al	B	Mo	Cr	Ni	Ti
TRIP 1	Ref. [10]	0.2	1.6	0.3	-	-	-	1.8	-	-	-	-	-
	Cast	0.199	1.58	0.281	0.035	0.023	0.020	1.77	0.003	0.002	0.016	0.024	0.014
TRIP 2	Ref. [11]	0.25	1.8	0.3	-	0.021	-	1.3	-	-	-	-	-
	Cast	0.251	1.81	0.307	0.029	0.024	0.033	1.29	0.003	0.005	0.028	0.030	0.080
TRIP 3	Ref. [12]	0.1	5.18	0.2	0.008	0.015	0.03	0.026	-	0.02	0.04	0.03	-
	Cast	0.105	5.20	0.213	0.007	0.019	0.016	0.002	0.002	0.001	0.012	0.020	0.008
TRIP 4	Ref. [13]	0.1	6.1	0.3	-	-	-	0.6	-	-	-	-	-
	Cast	0.097	6.11	0.324	0.028	0.022	0.016	0.616	0.002	0.001	0.012	0.018	0.009

2.2. Heat Treatments

After casting, the ingots were hot rolled at 1150°C , applying total of eight successive passes between the rolling mill cylinders. The total degree of deformation was 72%, as the initial thickness of the samples, prior to rolling, was 18 mm and the thickness after the eighth pass was 5 mm.

The preliminary heat treatment consisted of a normalization annealing applied in order to regenerate the structures obtained subsequently to the hot plastic deformation. The samples were heated in a vacuum Caloris furnace (Caloris Group, Bucharest, Romania) at 925°C for 0.5 h and cooled in air.

The final heat treatment involved heating in the biphasic range $\alpha + \gamma$ for 10 min and cooling in a salt bath (BaCl_2) down to 400°C , for 2 min holding time. Subsequently, cooling to room temperature was performed in air. Incomplete austenitization was performed in a Nabertherm furnace (Nabertherm, Lilienthal, Germany), at 13 kW power and a maximum operating temperature of 1600°C , and salt bath heating was performed simultaneously in a Caloris sintering furnace (Caloris Group, Bucharest, Romania) at 400°C .

The heating temperatures were established in correlation with the temperatures Ac_1 and Ac_3 of the four steels, with these being calculated according to the formulas given below [20]:

$$\text{Ac}_1 = 727 - 14 [\% \text{Mn} + \% \text{Ni}] + 22 [\% \text{Si} + \% \text{Cr} + \% \text{Al}] \quad (1)$$

$$\text{Ac}_3 = 855 - 180 [\% \text{C}] - 14 [\% \text{Mn}] - 18 [\% \text{Ni}] + 45 [\% \text{Si}] + 1.7 [\% \text{Cr} + \% \text{Al}] \quad (2)$$

The critical temperatures of the four TRIP steels as well as the heating temperatures for incomplete austenitization are shown in Table 3.

Table 3. Critical temperatures and final heat treatment temperatures of the studied TRIP steels.

Steel	Ac ₁ (°C)	Ac ₃ (°C)	T _T = (Ac ₁ + Ac ₃)/2 (°C)
TRIP 1	750	813	781.5
TRIP 2	737	800	768.5
TRIP 3	659	773	716
TRIP 4	661	766	713.5

2.3. TRIP Steels Testing

2.3.1. Impact Bending Test

This test is considered to be the one that most accurately reproduces a frontal impact car accident. In order to test the dynamic stress behavior of the four studied steels and to be able to comparatively evaluate the intensity of the TRIP effect, flat specimens with an impact surface of $10.4 \times 5 \text{ mm}^2$ were subjected to bending at three points. The test applied to steel samples after the final heat treatment was dynamic, with the impact being achieved with a speed of approximately 60 km/h and by applying a shock mass of 3.219 kg, which generated an impact energy of 18 J. These parameters were set so as to simulate a frontal accident of a 2000 kg car traveling at a speed of 60 km/h, with a contact surface at the time of impact of 0.8 m^2 .

The bending test was performed on an INSTRON Ceast 9340 (INSTRON, Norwood, MA, USA) equipped with the VisualIMPACT V.6 (INSTRON, Norwood, MA, USA) and CeastVIEW (INSTRON, Norwood, MA, USA) specialized data acquisition software modules.

2.3.2. Hardness Test

The Vickers hardness was determined using an Innovatest Falcon 500 (INNOVATEST, Maastricht, The Netherlands) device. The pressing force was 50 N for a duration of 10 s. The hardness measurements were performed both before (in heat-treated state) and after the mechanical shock test. Hardness was also tested on samples taken from cast and rolled material.

2.3.3. Microstructural Analysis

In order to perform the microscopic analysis, the samples were cut and embedded in hot resin (180 °C), resulting in samples with 30 mm diameter that were finally ground and polished. For these last stages, SiC emery paper with 220 µm graininess and abrasive solutions with 0.04–9 µm graininess were used.

The microstructures of the examined steels were observed using a Quanta 450 FEG field emission scanning electron microscope (FESEM) (FEI, Hillsboro, OR, USA) in the secondary electron (SE) and back scattered electron (BSE) modes. The working parameters of the field emission scanning electron microscope were an acceleration voltage of 30 KV under high vacuum, a working distance of 10 mm and a spot size of 5. The samples were also etched with NITAL 2% before SEM analysis.

The quantitative evaluation of the TRIP effect required the determination of the amount of retained austenite, which was performed by means of X-ray diffraction in accordance with ASTM E 975-03.

The equipment used was a Rigaku AUTOMATE II diffractometer (Rigaku Corporation, Tokyo, Japan) with the following characteristics:

- Cr K α radiation, ($\lambda = 2.29092 \text{ \AA}$);
- X radiation beam parameters: 40 kV, 40 mA, irradiated area = $1.15 \times 1.15 \text{ mm}^2$;
- Detector: D/teX Ultra 2000 silicon strip (Rigaku Corporation, Tokyo, Japan).

In order to perform the diffraction analysis, the samples were metallographically processed, with the surface being brought to a metallic luster. As a result of the quantitative analysis, at three points of the analyzed surface located approximately 2 mm apart, the following diffraction lines were found: $\alpha(211)$ ($2\theta = 156.40^\circ$, $t = 100$ s) and $\gamma(200)$ ($2\theta = 128.40^\circ$, $t = 300$ s).

For the impact tests, the analysis was performed in the sample's section, in the middle of the plastically deformed area and at 2 mm left/right of the central point. Integrated intensities were determined for each diffraction line, with corrections made according to ASTM E 975-03.

For the calculation of the retained austenite volume, the following formula (according to ASTM E 975-03) was used:

$$V_\gamma = \frac{\frac{I_\gamma}{R_\gamma}}{\left[\frac{I_\alpha}{R_\alpha} + \frac{I_\gamma}{R_\gamma} \right]} \quad (3)$$

where: I_α = the integrated intensity of the diffraction line $\alpha(211)$;

R_α = correction corresponding to the diffraction line $\alpha(211)$; $R_\alpha = 190.8$;

I_γ = integrated intensity of the diffraction line $\gamma(220)$;

R_γ = correction corresponding to the diffraction line $\gamma(220)$; $R_\gamma = 47.88$.

3. Results and Discussion

The TRIP effect in the studied steels was highlighted in the following ways:

- Qualitatively, using electron microscopy images of the samples before and after the impact bending test;
- Quantitatively, by establishing the volume of retained austenite (also before and after the impact bending test).

The hardness determinations performed on the heat-treated samples before and after the impact bending test also provided information on the intensity of TRIP effect produced in the analyzed steels.

3.1. Scanning Electron Microscopy (SEM)

Figures 1–4 show the electron microscopy images of the TRIP 1–TRIP 4 samples after heat treatment and Figures 5–8 show the steels microstructural aspects after the impact bending test.

In Figure 1, it can be seen that the TRIP 1 steel had a predominantly ferritic structure, with the proeutectoid ferrite having an allotriomorphic appearance, along with bainite (bainitic ferrite and carbides) exhibiting a rod-like form that surrounded the ferritic zones. Within the bainite areas, austenite islands that were slightly differently shaded than the ferrite were observed, as shown in the figure (austenite was also identified by X-ray diffraction).

Figure 2 shows that the TRIP 2 steel had a lower fraction of proeutectoid ferrite, due to their being a slightly increased amount of carbon, which led to a restriction in the area of proeutectoid ferrite in favor of bainite, the rod-like morphology of which is more clearly highlighted in the figure (TRIP 2b).

However, there was also a slight restriction of the retained austenite areas, as highlighted also by diffraction analysis. The explanation for this decrease was found in the slightly lower Al content in TRIP 2 steel as compared to TRIP 1 steel: 1.3% vs. 1.8%. As already known, Al is introduced into TRIP steels because it prevents carbides' precipitation, a process that accompanies the bainitic transformation. The excess carbon will be expelled from bainitic ferrite into untransformed austenite, stabilizing it [21]. The Al concentration from which it becomes "effective" in terms of increasing the fraction of retained austenite is at least 0.5%, and the higher the amount of Al, the higher the fraction of retained austenite stabilized by carbon enrichment [22].

Figure 1. BSE microstructure of TRIP 1 steel after heat treatment.

Figure 2. Microstructures (BSE—(a); SE—(b)) of TRIP 2 steel after heat treatment.

Figure 3. Microstructures (BSE—(a); SE—(b)) of TRIP 3 after heat treatment.

Similar to Figure 2, Figure 3 similarly shows a smaller amount of ferrite. Although the sample's carbon content was low, the areas of proeutectoid ferrite (fixed by intercritical heating in the applied treatment) were quite small. It can be stated that the presence of manganese in a significant amount led to increased steel hardness, so that the proeutectoid ferrite merged with the bainitic ferrite. Indeed, the structure was mostly bainitic, highlighted in the micrograph by the upper bainite with a typical rod-like morphology.

Figure 4. BSE microstructures ((a,b) at different magnifications) of TRIP 4 steel after heat treatment.

Figure 5. BSE microstructures of TRIP 1 steel ((a,b) at different magnifications) after impact bending test.

Figure 6. BSE microstructures of TRIP 2 steel ((a,b) at different magnifications) after impact bending test.

Figure 7. BSE microstructures of TRIP 3 steel ((a,b) at different magnifications) after impact bending test.

Figure 8. BSE microstructures of TRIP 4 steel ((a,b) at different magnifications) after impact bending test.

There were also small areas of retained austenite, in the form of islands with a slightly higher brightness (TRIP 3b). Parallel acicular formations of cryptocrystalline martensite specific to low-carbon steels also appeared. They were probably the result of austenite that had not completely turned into bainite during isothermal holding. On continuous cooling, it is possible that austenite turns into the mentioned martensite. Having little carbon, the latter does not bring a significant increase in hardness, so it will not negatively affect the cold plastic deformability.

Figure 4 shows that the proeutectoid ferrite and the bainitic ferrite were seen as a whole, with the structure being mainly composed of upper bainite, with a clearly highlighted rod-like distribution.

In Figure 4b, at the bottom, one can see precipitated carbides inside the ferrite plate, a morphological aspect that is specific to the upper bainite.

A more visible structural detail in this sample is related to the areas where retained austenite was identified. Being wider, an insular distribution between the bainitic ferrite plates was observed. This distribution clearly explains the retained austenite-preserving mechanism in the bainitic transformation process. Thus, according to Bhadeshia's theory [23], a quantity of carbon, but also of alloying elements, is expelled at the top of the bainitic ferrite plate because the bainitic ferrite dissolves a very small amount of these elements. The still untransformed area of austenite suddenly has a different local chemical composition; it becomes more stable and remains in the structure as retained austenite. This process explains why the bainitic transformation will always be accompanied by a certain amount of untransformed austenite (retained austenite). In this case, too, acicular formations of cryptocrystalline martensite were identified, but in an increased amount when compared to the previous case, that of TRIP 3. TRIP 4 was considered to have a higher amount of manganese, and thus, an increased hardenability. The presence of martensite was justified by the same reasoning as in the case of TRIP 3 steel.

The micrograph in Figure 5 reveals the microstructure that was obtained after heat treatment and plastic deformation, which was caused by mechanical shock involving ferrite, bainite, retained austenite and martensite that occurred as the result of the partial transformation of austenite following dynamic stress.

As they are phases that are characterized by low hardness and high plasticity, both proeutectoid ferrite and bainitic ferrite were found to have grains oriented along the deformation direction, thus favoring the hardening effect caused by the cold working of the steel. The martensite produced by the transformation of metastable austenite during plastic deformation was disposed inside the austenite islands.

Figure 6 shows the microstructure of TRIP 2. It was observed to be similar to that of the TRIP 1 sample: their chemical compositions were close to one another; they had the same structural transformations during thermal and mechanical processing, which led to the formation of identical constituents without noticeable changes in their fractions.

The chemical compositions of TRIP 3 and TRIP 4 steels had considerably increased contents of manganese. Through its austenite-stabilizing effect, manganese influenced

the initial microstructures of both of these steels as well as the structural transformations produced by heat treatment, respectively, by means of the subsequent plastic deformation (mechanical impact).

The microstructural aspects specific to TRIP 3 steel are presented in Figure 7.

The microstructures showed the same constituents as in the TRIP 1 and TRIP 2 samples, with the differences being:

- Accentuation of the ferrite oriented disposition, especially the bainitic one;
- The trend of orderly disposal of lath martensite inside austenite islands.

The TRIP 4 steel microstructure (Figure 8) had the highest manganese content. The highest amounts of austenite and martensite were retained as a result of the transformation produced during the impact bending test. Along with the martensite formed as a result of the heat treatment, a new quantity of martensite was formed after the impact bending test. A distinction between the two generations of martensite could be made based on the regions in which they were formed, with the new one appearing right in the interior of the retained austenite islands, clearly suggesting the affiliation.

The oriented arrangement of the ferritic phase increased the tendency of cold-working hardening, but the major role in the increasing of the hardness was played by martensite. In this phase, it was possible to observe the presence of differently sized features: long and thick laths (8–9 μm) were formed, with these being induced by the beginning of mechanical shock transformation, and shorter and thinner laths (1–2 μm) were formed at the structural transformation end. Their orientation allowed the identification of the main direction of plastic deformation produced by mechanical shock.

3.2. Determination of Retained Austenite by X-ray Diffraction

In order to evaluate the fraction of retained austenite using X-ray diffraction, only the peaks that needed to be submitted to quantitative analysis, α (211) and γ (220), were investigated for each steel; this analysis was conducted after heat treatment and after the impact bending test that followed heat treatment.

The full intensity of the selected peaks was computed using the integrated retained austenite calculation program developed by Rigaku for the AUTOMATE II equipment used in the data acquisition.

Figures 9 and 10 show the diffraction peaks of the two phases, ferrite and austenite, for TRIP 4 steel in a heat-treated state.

Figure 9. Ferrite peaks (211) measured at three points for the TRIP 4 steel sample after heat treatment.

Figure 10. Austenite peaks (220) measured at three points for the TRIP 4 steel sample after heat treatment.

The computed retained austenite fractions for all four heat-treated steel samples are shown in Table 4.

Table 4. Retained austenite fraction in heat-treated samples, V_{γ_1} .

Sample Code	Retained Austenite Fraction, V_{γ_1} (%)
TRIP 1	9.29
TRIP 2	7.40
TRIP 3	4.63
TRIP 4	10.63

After analyzing the results presented in Table 4, the following could be concluded:

- The highest amount of retained austenite was found in TRIP 4 steel (10.63%) due to it having the highest percentage of Mn and an Al content of 0.6%. Manganese was gammageneous and determined the improvement of the hardenability, which, at the same time, was correlated with the presence of an important fraction of retained austenite. The stabilization of austenite was thus due to alloying with both Mn and Al and was also achieved according to Bhadeshia's theory [23];
- A similar amount of retained austenite was also noticeable in TRIP 1 steel, probably due to it having a doubled percentage of C (0.2% vs. 0.1%) as well as the highest percentage of Al (1.8%). All alloying elements acted synergistically in terms of stabilizing austenite, with the high amount of Al causing the Mn deficiency of this steel (1.6%) as compared to the TRIP 4 sample (Mn = 6.1%);
- A lower fraction of retained austenite was found in TRIP 2 steel, which, despite having a C content almost identical to that of TRIP 1 steel, had a lower amount of Al (1.3%), which was correlated with a slightly higher percentage of Mn (1.8%). It can be stated in this case that increasing the amount of Mn by 0.2% did not have the expected effect on the austenite stabilization (counteracting the Al decrease by 0.5%);
- The lowest fraction of retained austenite was observed, as expected, in TRIP 3 steel, which had a low C content (0.1%) as well as the lowest percentage of Al (negligible when compared to the other steels). The high content of Mn (5.18%) led to the predominance of the bainite fraction, but could not stabilize higher fractions of austenite at the top of the ferrite laths, most likely due to the steel's small number of alloying elements (including C).

One can see that the quantitative determinations of retained austenite were in full accordance with the qualitative observations made by SEM.

Figures 11 and 12 show the X-ray diffractions made on the heat-treated and impact-bent TRIP 4 steel samples in the angular intervals corresponding to the (211) peak of the supersaturated ferrite (martensite) and the (220) austenite peak.

Figure 11. Ferrite peaks (211) measured at three points for the TRIP 4 sample after impact bending test.

Figure 12. Austenite peaks (220) measured at three points for the TRIP 4 sample after impact bending test.

Table 5 lists the fractions of retained austenite computed according to Formula (1) for all four heat-treated and impact-bent steels.

Table 5. Fractions of retained austenite in samples submitted to impact bending tests, V_{γ_2} .

Sample Code	Retained Austenite Fraction, V_{γ_2} (%)
TRIP 1	7.33
TRIP 2	5.32
TRIP 3	3.69
TRIP 4	8.46

The amount of austenite converted to martensite (V_M) by the TRIP effect in each studied sample was equal to the difference between the fractions of retained austenite (ΔV) calculated before and after the impact bending test, respectively:

$$V_M = \Delta V = V_{\gamma_1} - V_{\gamma_2} \quad (4)$$

The amounts of martensite in each sample, as well as the comparative appraisal of differences between the martensite volumes in samples with similar chemical compositions, are summarized in Table 6.

Table 6. Martensite fractions V_M in the investigated samples and differences between them in steels with similar chemical compositions.

Sample Code	Martensite Fraction, V_M (%)	The Difference between the Martensite Fractions, ΔV_M (%)
TRIP 1	1.96	0.12
TRIP 2	2.08	
TRIP 3	0.94	1.23
TRIP 4	2.17	

After analyzing Tables 4 and 5 comparatively, the following observations could be made:

- Regarding the steels belonging to the first compositional group, characterized by lower percentages of Mn and higher percentages of Al and C, the highest amount of martensite obtained by the TRIP effect was found in the TRIP 2 sample (2.08%), although it did not have the highest amount of retained austenite after heat treatment; on the other hand, the TRIP 1 sample, which had a similar chemical composition and a higher amount of austenite prior to the test, showed a slightly lower fraction of martensite. A possible explanation could be a better chemical homogeneity of austenite in the TRIP 2 sample when compared to TRIP 1 steel: the segregation of Al in austenite is known to be influenced by the presence of other chemical elements and is even more pronounced when the percentage of Mn is lower [24].

Thus, it can be stated that there was a higher chemical inhomogeneity in the TRIP 1 sample when compared to the TRIP 2 sample. As is well known, the temperature M_d is the temperature above which the driving force becomes far too low, such that the germination of martensite is impossible to be induced mechanically, and austenite will only deform plastically and not turn into martensite. The temperature M_d is strongly dependent on the chemical composition of austenite. Thus, the existence, in a certain volume of austenite, of extensive more chemically homogeneous areas will ensure the obtaining of slightly higher volumes of martensite than in cases of higher fractions of austenite, but with a more accentuated chemical inhomogeneity. However, the difference ΔV_M was very small (0.12%); thus, a similar TRIP effect could be seen in the case of the TRIP 1 and TRIP 2 steels (see Table 6):

- The TRIP effect was most pronounced in the case of TRIP 4 steel, from the second compositional group, characterized by high Mn and low Al and C contents, respectively. This steel had the highest percentage of Mn (6.1%). This was correlated with a sufficient amount of Al (0.6%) to stabilize the highest fraction of retained austenite (10.63%), which, following the mechanical shock, had the best transformation ratio. Thus, the amount of martensite obtained after the impact bending test (2.17%) was higher than in all the other analyzed steels, regardless of the compositional group. It can be stated that percentages of Mn of over 6% were associated with amounts of Al that were slightly higher than 0.5%, even when the C percentage was low, ensuring an optimal fraction of retained austenite, characterized by a good chemical homogeneity and an appropriate ratio of austenite-to-martensite transformation by plastic deformation. In addition, the low C content ensured high plasticity and superior weldability to the steels of the first compositional group, both of which are requirements that are imposed on TRIP steels;
- TRIP 3 had the lowest fraction of martensite obtained by the transformation induced by plastic deformation, and also had the lowest amount of retained austenite. In the case of steels belonging to the second compositional group, TRIP 3 and TRIP 4, it can be stated that the TRIP effect was enhanced only by the presence of an Al percentage of more than 0.5%. In fact, Table 6 shows that the highest values of ΔV_M were recorded for the TRIP 3 and TRIP 4 steels (1.23%). Only relatively high amounts of Mn (over 5%), without being associated with a percentage of over 0.5% Al and/or with a higher percentage of C, were sufficient neither to obtain a high fraction of retained austenite nor for its transformation into martensite in a significant amount.

3.3. Hardness Tests

The evaluation of the TRIP effect's intensity could also be conducted by highlighting the steels' hardness variations after the final heat treatments and after the impact bending tests.

The hardness values determined for the samples studied before and after impact are shown in Table 7. Each hardness value represents the average value of three measurements.

Table 7. TRIP steels' Vickers hardness determined before and after impact bending test.

TRIP Steel	Vickers Hardness			
	HV ₁	Stdev 1	HV ₂	Stdev 2
TRIP 1	200	3	211	26
TRIP 2	221	4	240	29
TRIP 3	341	11	347	25
TRIP 4	329	2	362	20

Note: HV₁ is the hardness measured after the heat treatment; HV₂ is the hardness measured after the impact bending test.

Graphical representations of hardness values obtained for all the studied steels are shown in Figure 13.

Figure 13. Graphical representation of average Vickers hardness values for TRIP steels after heat treatment and after impact bending test.

For all TRIP steels studied, it was found that after the plastic deformation caused by mechanical shock, a hardening process occurred.

Following the hardness tests conducted after the salt bath quenching heat treatment, the hardness average values of the steels showed an increase as compared to those obtained after the previous processing (rolling and normalization), except for TRIP 4 steel. In this case, the hardness decreased by approximately 20 units, which gave it a better plasticity. The hardness decrease was strictly related to the fact that this steel contained the largest amount of retained austenite after heat treatment.

The hardness values for steels belonging to the same compositional group were close, which demonstrates the reproducibility of the steel structures tested after the heat treatment.

The steels' hardness values increased after the impact bending test had occurred as a result of two mechanisms:

- Cold-working, produced by plastic deformation in the impact bending test;
- Structural hardening, which occurred as a result of obtaining martensite via the $\gamma_{\text{ret}} \rightarrow \text{M}$ phase transformation.

The volume of retained austenite in each sample subjected to the impact bending test allowed the appropriate appraisal of the amount of martensite formed as a result of plastic deformation, which had a direct effect on the hardness increase. The production of the martensitic transformation in the impact bending test resulted in a remarkable hardness increase for the TRIP 4 and TRIP 2 steels, as shown in Table 8. In addition, the tripling of the Mn content in the TRIP 4 sample, which was correlated with a lower C amount, hardened the newly obtained phase (martensite) as a result of the Mn hardening effect that manifested in low-carbon steels following the martensitic transformation.

Table 8. Correlation of the hardness increase with the martensite fraction resulting from the impact bending test.

TRIP Steel	γ_{ret} Volume Transformed in M (%)	Vickers Hardness Increase (ΔHV)
TRIP 1	1.96	11
TRIP 2	2.08	19
TRIP 3	0.94	6
TRIP 4	2.17	33

4. Conclusions

The comparative assessment of the TRIP effect in the four studied steels led to the following conclusions:

1. The highest fraction of retained austenite after heat treatment was found in the TRIP 4 steel (10.63%); a close value (9.29%) was determined in the TRIP 1 steel, while smaller amounts were found in the TRIP 2 (7.40%) and TRIP 3 (4.63%) steels. Therefore, TRIP 4 steel is the most promising in terms of the extent of the transformation underlying the TRIP effect. The highest content of Mn (6.1%), which was correlated with an Al percentage of 0.6%, contributed to the stabilization of austenite and, thus, to the obtaining of the highest fraction of retained phase that was able to be transformed after impact.
2. The deformation-induced martensite fractions were: TRIP 1—1.96%; TRIP 2—2.08%; TRIP 3—0.94%; TRIP 4—2.17%. Given that the highest amount of martensite was obtained in TRIP 4, this steel is the optimal solution in impact situations.
3. The increases in hardness after impact were correlated with the martensite fractions obtained after the impact bending test. In this respect, the highest hardness was recorded in TRIP 4 steel (362 HV).

Thus, based on the experimental results, namely the highest amount of retained austenite obtained after unconventional heat treatment, the highest fraction of martensite resulting from shock and the highest hardness after the impact bending test, one may state that TRIP 4 steel has the best impact behavior of all four analyzed steels.

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