**UNIVERSITY POLITEHNICA OF BUCHAREST**

**DOCTORAL SCHOOL**
**OF MATERIALS SCIENCE AND ENGINEERING**

# PHD THESIS
***SUMMARY***

# MODERN STEEL CONCEPTS FOR THE ROADWORTHINESS STRUCTURE OF ROAD VEHICLES

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- **TRIP**
- **Steel**
- **Scanning electron microscopy**
- **Retained austenite**
- **Mechanical tests**
- **XRD**
- **Optical microscopy**

# *Foreword*

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# INTRODUCTION

The use of steels with special properties in the automotive industry is conditioned by two major factors: fuel efficiency and increased passenger safety in the event of an accident.

Fuel efficiency is mainly dependent on the weight of the steel parts, which in turn are dictated by gauge and design.

Safety is determined by the energy absorption capacity of the steel elements of the vehicle's resistance structure, which deform during the impact of the accident.

Both factors are strong incentives for the use of advanced, high-strength steels (AHSS) in the construction of the strength structure of vehicles, replacing the conventional steels used in the manufacture of car parts. Slightly deformable steels are generally low carbon steels, completely or partially stabilized by alloying elements such as Ti or Nb.

The strict requirements set by the automotive industry for passive safety, weight reduction and energy saving, have led to the development of a new group of steels with improved properties. Recently, different types of high-strength steels have been developed to meet these requirements of the automotive industry. The main problem of these steels derives from the multiple defects associated with their lower deformability, so that strengthening the strength without deteriorating the deformability characteristics remains one of the most important objectives of the development of materials for the automotive industry.

AHSS is a general term used to describe different families of steels. The most common AHSS is duplex steel with ferrite-martensite microstructure.

An important class of AHSS is multiphase steel which has a complex microstructure consisting of different phase constituents and a high yield strength ratio. Transformation-induced plasticity steels (TRIPs) are the latest class of AHSS steels of growing interest to car manufacturers. These steels consist of a ferrite-bainite microstructure with a significant amount of retained austenitic phase and are distinguished by the best combination of strength and elongation among the AHSS steels in use. Martensitic steels with very high mechanical strengths are also used for certain parts of the vehicle body.

The use of these steels is classified into two major categories: exterior body panels and body structure elements coupled to the body.

In the case of exterior body panels, efforts to continuously reduce fuel consumption have resulted in reducing the weight of these elements. In addition to the bending strength, another requirement for exterior body panels is rigidity, and as a result, even in the case of steels with increased strength, the thickness cannot be reduced below a certain minimum that meets the rigidity requirement.

For bodywork elements coupled to the body, the major goal is weight reduction, with an increased emphasis on safety performance.

TRIP (Transformation Induced Plasticity) multiphase steels are a new generation of alloy steels, characterized by an improved combination of strength and ductility that meets the requirements of the automotive industry. The manufacture of steels uses the TRIP phenomenon, which consists in the transformation of retained austenite into martensite with plastic deformation, which is responsible for the remarkable resulting properties. These steels have high mechanical strength and have a considerable uniform elongation before breaking.

Therefore, in addition to strength, car safety requires alloys to be of considerable ductility. The deformability is necessary to allow the complex shapes of the car parts, the choice of materials must be suitable for the loading conditions and their operating environment.

Three elements ensure control over the mechanical properties of steel: its chemical composition, processing and heat treatment, all leading to the setting of its final microstructure.

The martensitic transformation induced by local stress has the effect of improving stress concentrations, increasing the speed of hardening by processing and promoting homogeneous deformation, with subsequent improvements in the strength, ductility and hardness of steels.

*The doctoral thesis aims to develop, process, treat and test a new TRIP steel, with superior properties compared to three other existing steels of the same type, with a microstructure that leads to an increase in mechanical strength without damaging ductility, offering very attractive combinations of strength and ductility, due to the coexistence of phases.*

The paper comprises **6** chapters, contains **160** pages, a chapter of original conclusions and contributions as well as a bibliography.

**Chapter 1** presents the current state of knowledge in the field at international level, compared to the latest references in the literature.

**Chapter 2** presents the heat treatment conditions present in the literature as well as the influence of each alloying element used in the compositions of TRIP steels that will be developed and studied in the doctoral thesis. Chapter 2 also has in its structure results from the specialized literature of the effects of impact tests both on the structure of TRIP steels and on the composition of their phases.

The research methodology and analysis techniques used to achieve the objectives are presented in **Chapter 3**. This chapter presents the general ideas that led to the experimental study of the new TRIP steel, as well as data on the raw materials used to make the steels. Also, the analyzes that were performed to determine the structure of the alloys, to demonstrate the presence of the TRIP effect on deformation as well as the equipment used for these tests and characterizations are highlighted.

**Chapter 4** presents the experimental research on the development of the 4 TRIP steels in the vacuum induction furnace and controlled atmosphere. Three known TRIP steels and self-designed TRIP steels were developed in a vacuum and controlled atmosphere. This chapter provides information on how to determine the new composition of processed steel TRIP, a breakdown of the influence of alloying elements introduced into the composition of steels, optical microscopy and hardness analyzes performed after processing, plastic deformation and regeneration of the structure, each processing step being detailed.

**Chapter 5** presents the experimental research on the heat treatment of steels performed in order to obtain the TRIP effect. This chapter focuses on highlighting the parameters of unconventional heat treatment applied to obtain retained austenite in the phase composition of steels as well as optical microscopy, scanning electron microscopy, hardness and X-ray diffraction analyzes performed to highlight the structure of elaborated alloys.

**Chapter 6** presents experimental research on the impact behavior of TRIP steels. Both the working method for performing the impact tests and the equipment used are presented. The experimental results from the tests show the existence of a deformation that allows immediately after the shock a high absorption of energy after the impact, followed by a significant hardening due to the structural transformation by transforming a significant part of the retained austenite into martensite. The analyzes performed on steels highlight the existence of the transformation following the mechanical shock of austenite into martensite.

**Chapter 7** presents the final conclusions, the original contributions and the new research directions.

# Chapter 1. CURRENT STATE OF KNOWLEDGE IN THE FIELD OF STEEL USED IN THE CONSTRUCTION OF THE ROADWORTHINESS STRUCTURE OF CARS

In order to satisfy as much as possible the requirements manifested towards the quality, performance, safety and cost of vehicles, the specialists' concerns converge in the direction of capitalizing in practice the latest technologies in metallurgy, automation and robotization of manufacturing and assembly processes.

Materials play an important role in the construction of vehicles. For future models, car manufacturers have extended the nomenclature of parts to be made of unconventional materials. Thus, the aim is to use as many parts as possible made of materials with low specific gravity, or small size, but with high mechanical strength.

## 1.1.Steels used in the strength structure of motor vehicles

Steel is still a basic material for car construction. The choice of steel for critical safety areas follows two general directions. These directions are based on the principle that, in a sudden deceleration as a result of an accident, the energy must be dissipated in a controlled manner so that the deceleration of the occupants does not exceed certain limits, maximizing survival and minimizing the risk of injury [1].

Figure 1.1 shows the steels used in the automotive industry.

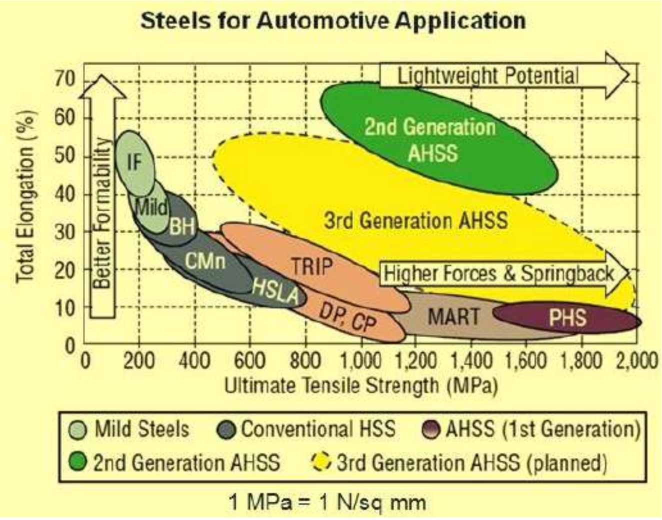

**Fig. 1. 1.** *Steels with applications in the automotive industry [2]*

The other direction for designing a secure vehicle structure is the so-called "safety cell" which requires the passenger compartment to withstand impact and maintain its integrity, thus protecting passengers. This allows engineers to design the interior of the car ensuring a safe position of passengers during possible events due to accidents [3]. Figure 1.2 shows the design of a body with the location of the steel elements in the resistance structure of a car.

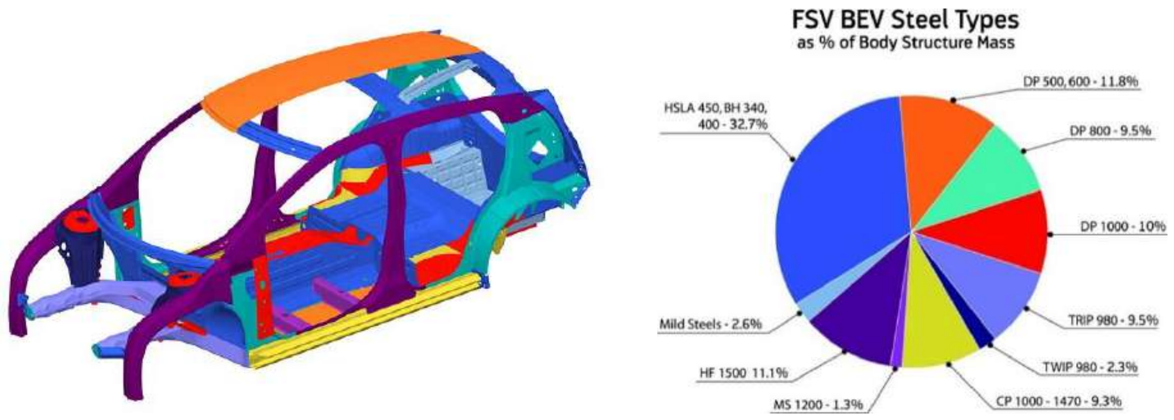

**Fig. 1. 2** *The location and weight of each type of steel in the construction elements of a car* - [4]

## Classification of steels used in the manufacture of motor vehicles

- Steels with high formability
- High strength IF steels
    - *High strength IF steels - HSIF*
    - *High-strength IF steels with hardening treatment - HSIF-BH*
- Advanced high-strength steels - AHSS
    - *Cold rolled duplex steels*
    - *Galvanized and standardized duplex steel*
    - *Galvanized duplex steels*
- Martensitic steels

# Chapter 2. TRIP STEELS USED IN THE MANUFACTURE OF MOTOR VEHICLES

Among the various steels belonging to the AHSS family, TRIP assisted steels possess the best mechanical properties in terms of a combination of high strength / elongation and the value of the stress hardening exponent [5]. This generates excellent formability in production and makes TRIP-assisted steels used in the manufacture of automotive structural components.e [6]. In addition, increased passenger safety is ensured by improving the quality of these steels [7].

The acronym TRIP for transformation-induced plasticity was originally given by Zackay et al. [8] to classify all alloys with a unique combination of high strength and improved deformability as a result of the deformation-induced transformation of austenite into martensite, resulting in increased hardening rate, leading to a delay in the onset of reversal (TRIP effect).

Figure 2.1 shows an illustration of the typical microstructures of the different types of AHSS steels.

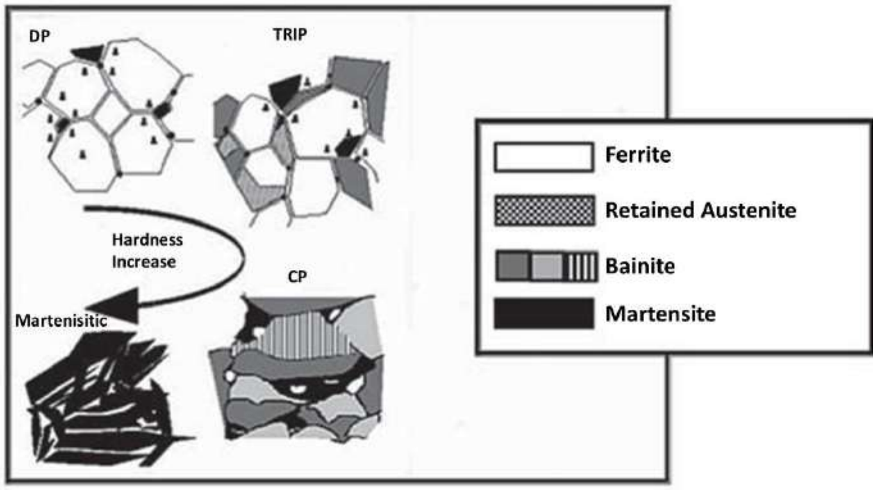

**Fig. 2. 1** *Illustration of typical microstructures of different AHSS. (DP: double phase steel, TRIP: assisted steel TRIP, CP: complex phase steel, MART: martensitic steel)[9].*

Table 2.1 show the typical dimensions of the different phases in the types of AHSS steels shown in Figure 3, and Table 2.2 shows the mechanical properties of TRIP steels.

**Table 2. 1** *Typical dimensions of the different phases* **[10]**

| **Steel** | **Ferrite (%)** | **Martensite (%)** | **Bainite (%)** | **Retained Austenite (%)** |
|---|---|---|---|---|
| **DP** | 0.80-0.85 | 0.15-0.20 | – | – |
| **TRIP** | 0.55-0.65 | – | 0.25-0.35 | 0.05-0.20 |
| **CP** | 0.05-0.10 | 0.05-0.10 | 0.80-0.90 | – |
| **MART** | – | 1.0 | – | – |

**Table 2. 2** *Mechanical properties of TRIP steels* **[10]**

| **Product** | **$Ts_{min}$ (MPa)** | **Y (MPa)** | **$Te_{min}$ (%)** |
|---|---|---|---|
| **590 TRIP** (laminat) | 590 | 350-495 | 31 |
| **780 TRIP** (laminat) | 780 | 410-500 | 21 |
| **590 TRIP** (galvanizat și calit) | 590 | 360-510 | 26 |
| **590 TRIP** (galvanizat) | 590 | 380-480 | 27 |
| **780 TRIP** (galvanizat și calit | 780 | 410-560 | 19 |
| **780 TRIP** (galvanizat) | 780 | 440-500 | 21 |

### 2.1.2. Alloy elements in TRIP steels

Carbon improves austenite by strengthening the interstitial solid solution and increases its stability, diffuses and can be enriched in austenite during bainitic transformation. The stress or stress level at which the retained austenite begins to turn to martensite can be controlled by adjusting the carbon content.

Austenite can be stabilized by carbon only if it is not consumed by the formation of cementite. Silicon is added to inhibit the formation of cementite during bainitic transformation. The minimum level of silicon required to effectively suppress the formation of cementite is ~ 0.8%. Aluminum has a lower influence than silicon to delay the formation of cementite at the same weight concentration. The presence of aluminum in steel contributes to a remarkable TRIP effect during tensile tests due to the large amount of retained austenite.

Manganese from TRIP steel is required to obtain a high hardness and has no adverse effects on reactive wetting during coating. Niobium in solid solution lowers the starting temperature of martensite and delays the precipitation of carbides during the transformation of bainite, thus increasing the amount of retained austenite. [11-12].

Molybdenum is a hardening agent of the solid ferrite solution and strongly delays the formation of perlite, decreasing both the rate of nucleation and the rate of growth. These phenomena are the most effective elements in suppressing the formation of perlite and, therefore, Molybdenum is particularly good in reducing the critical cooling rate for the formation of bainites. [13].

Copper, being an austenitic stabilizer, helps maintain austenite. In addition to consolidating the solid solution, fine precipitation of copper from ferrite can increase the overall strength. Thus, it is possible to consider the replacement of silicon with copper both in the roles of austenite retention and in increasing the resistance of ferrite.[14]

**Tabel 2. 3** *Typical chemical compositions (% by weight) of TRIP-assisted steels* [11, 15-16]

| C | Si | Mn | Al | P | Nb | Mo | Cu | Cr | Ni |
|---|---|---|---|---|---|---|---|---|---|
| 0.38 | 1.53 | 0.83 |  | 0.007 |  |  |  |  |  |
| 0.18 | 2.0 | 1.5 | 0.037 | 0.015 |  |  |  |  |  |
| 0.19 | 2.48 | 1.49 | 0.036 | 0.014 |  |  |  |  |  |
| 0.11 | 0.59 | 1.55 | 1.5 | 0.012 |  |  |  |  |  |
| 0.14 | 0.53 | 1.57 |  | 0.204 |  |  |  |  |  |
| 0.22 | 1.55 | 1.55 | 0.028 |  | 0.035 |  |  |  |  |
| 0.20 | 1.48 | 1.44 | 0.04 | 0.004 | 0.109 |  |  |  |  |
| 0.20 | 1.47 | 1.51 | 0.028 | 0.004 | 0.047 | 0.2 |  |  |  |
| 0.20 | 1.6 | 1.6 | 0.028 |  | 0.041 | 0.3 |  |  |  |
| 0.21 | 1.49 | 1.49 | 0.028 | 0.005 | 0.017 | 0.1 |  |  |  |
| 0.14 | 1.49 | 1.51 | 0.04 | 0.0012 |  |  | 0.51 |  |  |
| 0.15 | 1.52 | 1.51 |  |  |  |  | 0.51 | 0.39 |  |
| 0.15 | 1.55 | 1.50 |  |  |  |  | 0.51 |  | 0.41 |

## 2.2. Steps for processing TRIP steels

The microstructure of TRIP steels currently usually consists of a continuous ferrite matrix with bainite and a volume fraction of metastable retained austenite as other phases.

Generally, a two-stage heat treatment is used. The first stage of heat treatment is performed in the region of ferrite (α) austenite (γ) in two phases and is called interleaving treatment (IA). During this treatment the cold rolled structure is recrystallized, the dissolution of perlite and carbide particles and the formation of austenite takes place.

The microstructural development in different stages of the heat treatment was elucidated by Chen et al. [17]. The various phase transformations that take place during the various processing steps are clearly highlighted. TRIP steels, as described above, can be produced by either cold rolling (CR) or hot rolling (HR), but most modern TRIP steels are produced by cold rolling.

## 2.5. Heat treatments for the formation of TRIP steels

The microstructure of TRIP-assisted steels is obtained by performing a two-stage heat treatment after cold rolling as can be seen in Figure 2.6.

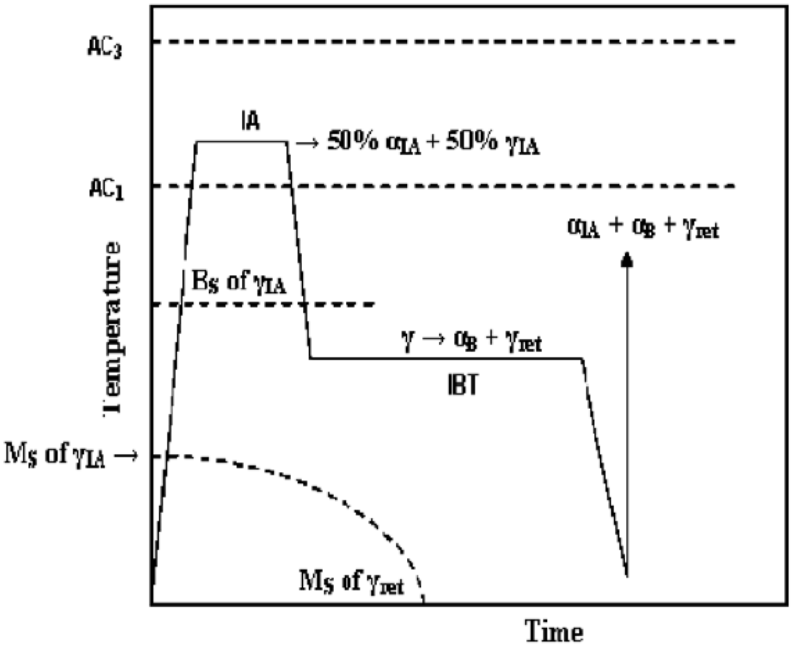

**Fig. 2. 2** *Schematic representation of the thermal cycle used to obtain typical TRIP microstructure.[18]*

The first stage of the heat treatment is performed at a slightly higher temperature in the bidirectional region α + γ, leading to a microstructure of about 50% austenite and 50% ferrite. A rapid cooling rate after annealing is used to avoid any major ferrite formation, and the final transformation is performed isothermally in the bainite region (heat treatment in the second stage). During bainite formation, carbon diffuses into the austenitic islands. Enriching carbon austenite increases thermal stability and, as a result, austenite can be maintained at cooling to room temperature.

## 2.6. Mechanical tests for characterization of TRIP steels

Most of the published data refer to the reliability of a steel that shows energy absorption during a dynamic test; usually, tensile tests [2, 4, 19] or compression tests [20]. Some documents [2, 4, 20] have a mechanical point of view, presenting interesting results of dynamic tests, which often include the method of strong finishing (FEM) to simulate the results.

However, these studies never perform metallographic analyzes of the tested steels, except for a brief comment on the present microconstituents, annotated by "hot rolling" or "cold rolling".

In the case of TRIP steels, they must be extensively analyzed before testing to determine their possibility of use in the field of motor vehicle construction.

For fully austenitic TRIP steels, the mechanical response of TRIP-assisted multiphase steels depends very much on the hydrostatic stress due to the transformation stress expansion component. [21].

TRIP-type multiphase steels and fully austenitic TRIP steels also differ in the quantities of alloying elements, which strongly influence the energy of the austenite network defects and therefore the way austenite is transformed.

# Chapter. 3. RESEARCH METHODOLOGY AND ANALYSIS TECHNIQUES USED TO ACHIEVE THE OBJECTIVES

## 3.1. The purpose and objectives of the research

The main purpose and objective of the research is to design and manufacture a TRIP steel with a new chemical composition with superior characteristics, to be used in the strength structure of the car body. In this sense, the research direction goes through the following steps:

- - evaluation of data from the literature on TRIP steels used in the construction of motor vehicles;
- - development of three types of existing TRIP steels in current technologies and development of a new TRIP steel;
- - mechanical machining of rolled steels;
- - carrying out heat treatments of processed steels;
- - determination of the shock behavior of the made TRIP steels; for the experiment a speed of 60 km / h was chosen as the one used in the Euro NCAP tests;
- - physical-mechanical characterization of the new steel compared to the three existing steels, in all phases: development, rolling, heat treatment, shock;
- - determination of the amount of retained austenite converted to martensite after impact;
- - dissemination of research results in order to ensure the practical use of designed steels.

## 3.2. Research methodology

The research methodology was based on the current state of research in the field, found after studying the literature. Thus, the influence of the impact on the transformation of retained austenite into martensite on TRIP steels and the increase of their mechanical strength is not yet fully scientifically substantiated. The need for further research derives from the effect of reducing the impact of traffic accidents on human integrity. In order to achieve this goal, immediate solutions and interventions are needed regarding the quality of the metallic materials used in the resistance structure of the vehicles and the technology of their realization, in order to take over the impact energy followed by the increase of the mechanical resistance.

Based on those presented, the research plan was prepared taking into account the following aspects:

**1) Justification of the need to approach the research topic,** as a major subject of materials science, with emphasis on the impact behavior of TRIP steels in the strength structure of vehicles;

**2) Contributions to the development and improvement of technologies for the development and processing of TRIP steels used in the manufacture of motor vehicles.**

This objective scientifically substantiates the possibilities of defining, elaborating and mechanically processing some TRIP steels used in the resistance structure of motor vehicles in order to improve their quality. Thus, topics such as:

a) The current state of knowledge in the field of TRIP steels at international level, compared to the references in the specialized literature;

b) The mechanism of the process of formation of retained austenite in TRIP steels;

c) Making a new TRIP steel with specified composition and improved properties;

d) Comparative critical analysis of research results.

**3) Contributions to the development of technologies and techniques for obtaining elements from the resistance structure of motor vehicles,** aiming at the following concrete aspects:

a) Experimental research on improving the quality of steels used in the strength structure of vehicles;

b) Experimental research on the impact behavior of TRIP steels.

In figure 3.1. the structure of the research plan of the doctoral thesis is presented schematically.

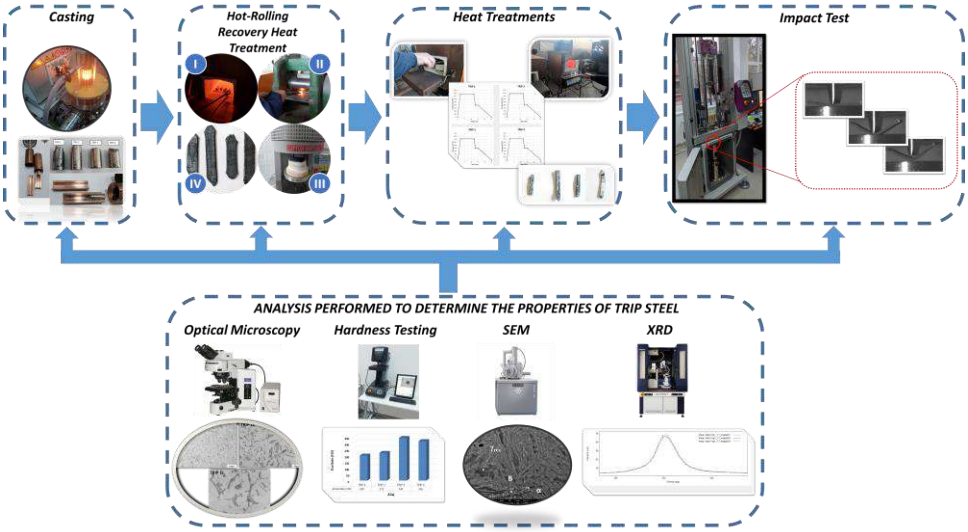

**Fig. 3. 1** *Schematic of the process of development and testing of the researched TRIP steels*

# Chapter. 4. DEVELOPMENT OF TRIP STEEL IN A VACUUM INDUCTION OVEN WITH CONTROLLED ATMOSPHERE

For the experimental research, 4 types of TRIP steels were made, steels that were subjected to processing, heat treatment, shock and physical-structural characterization.

## 4.1. Selection of the optimal chemical composition for TRIP steels

The alloying elements present in the chemical composition of the 4 steels proposed for experiments - Mn, Si, Al were chosen with much reasoning. On the one hand, they must ensure the classic technological characteristics for which they have been developed and, on the other hand, complement the operating characteristics in a modern way.

In the category of technological characteristics, Mn, Si and Al must not negatively affect the plastic deformability (especially cold) to which the sheets from which the constituent parts of a car body are made are subjected.

## 4.3. Development of TRIP steels

The development of the steels was performed in an induction, vacuum and controlled atmosphere furnace type Five CELES (model ALU 600), presented in fig.4.1. The use of this type of processing furnace allows the elimination of possible contaminations and oxidations of the metal melt and also ensures the casting in conditions of structural and compositional homogeneity of the batch.

**Fig. 4. 1** *Induction furnace with cold crucible, vacuum and argon atmosphere*

4 TRIP alloys were elaborated, 3 of them having chemical compositions studied in the specialized literature, but elaborated using other types of furnaces, and a TRIP steel of new

composition. The compositions of these steels are shown in Table 4.1.

**Tabel 4. 1** *Composition of processed TRIP steels*

| ***Material*** | | ***C (%)*** | ***Mn (%)*** | ***Si (%)*** | ***S (%)*** | ***P (%)*** | ***Cu (%)*** | ***Al (%)*** | ***B (%)*** | ***Mo (%)*** | ***Cr (%)*** | ***Ni (%)*** | ***Ti (%)*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***TRIP 1*** | *Reference1* | *0,2* | *1,6* | *0,3* | *N/A* | *N/A* | *N/A* | *1,8* | *N/A* | *N/A* | *N/A* | *N/A* | *N/A* |
| | *Developed* | *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*** | *Reference2* | *0,25* | *1,8* | *0,3* | *N/A* | *0.021* | *N/A* | *1,3* | *N/A* | *N/A* | *N/A* | *N/A* | *N/A* |
| | *Developed* | *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*** | *Reference3* | *0,1* | *5.18* | *0,2* | *0.008* | *0.015* | *0.03* | *0.026* | *N/A-* | *0.02* | *0.04* | *0.03* | *N/A* |
| | *Developed* | *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*** | *Calculated* | *0,1* | *6,1* | *0,3* | | | | *0,6* | | | | | |
| | ***Developed*** | ***0,097*** | ***6,11*** | ***0,324*** | ***0,028*** | ***0,022*** | ***0,016*** | ***0,616*** | ***0,002*** | ***0,001*** | ***0,012*** | ***0,018*** | ***0,009*** |

*Reference1:* Kruijver, Zhao et al. 2003
*Reference2:* Srivastava, Jha et al. 2006
*Reference3:* Merwîn 2007

### Metallographic analysis by optical microscopy after casting of elaborated steels

Following the development of the steels, they were prepared for metallographic examination and for performing hardness tests.

For the preparation of the 4 experimental samples, TRIP 1, TRIP 2, TRIP 3 and TRIP 4, a complete Struers training line (cutting, embedding, grinding) from the ECOMET Center equipment was used. A cylindrical part of about 4 mm was cut from each steel. These were subsequently embedded in the resin and sanded to a metallic luster level. For the purpose of the metallographic analysis, the samples were attacked with 2% NITAL to highlight the grains and the structure, then they were examined using an Olympus type metallographic microscope (BX 51 M), equipped with the possibility of light or dark field investigations and a magnification field. up to 1000x.

Overall, the structure of the TRIP 4 sample is quite similar to that of the TRIP 3 sample. The same overheating trend associated with the increase in calcification is also determined by the presence of Mn in the structure; and the value of the average hardness of 366HV is close to that of the TRIP 3 sample. The peculiarity can be noticed by studies at higher magnification powers (M = 500x). Along with the upper and lower bainite, which are structurally predominant, it is possible to highlight light regions in greater quantity, in which the presence of ferrite is observed. The increased amount of ferrite is due to the presence in the structure of Al (0.6%), known as the alpha element.

Studies at maximum magnification powers (M = 1000x) allow highlighting another structural detail, represented by the existence of polyhedral, bright micro-regions, which are attributed to retained austenite. The existence of these formations is also related to the presence of a significant amount of Mn, known as a factor that determines the retention in the structure of untransformed austenite, also called retained asthenite.

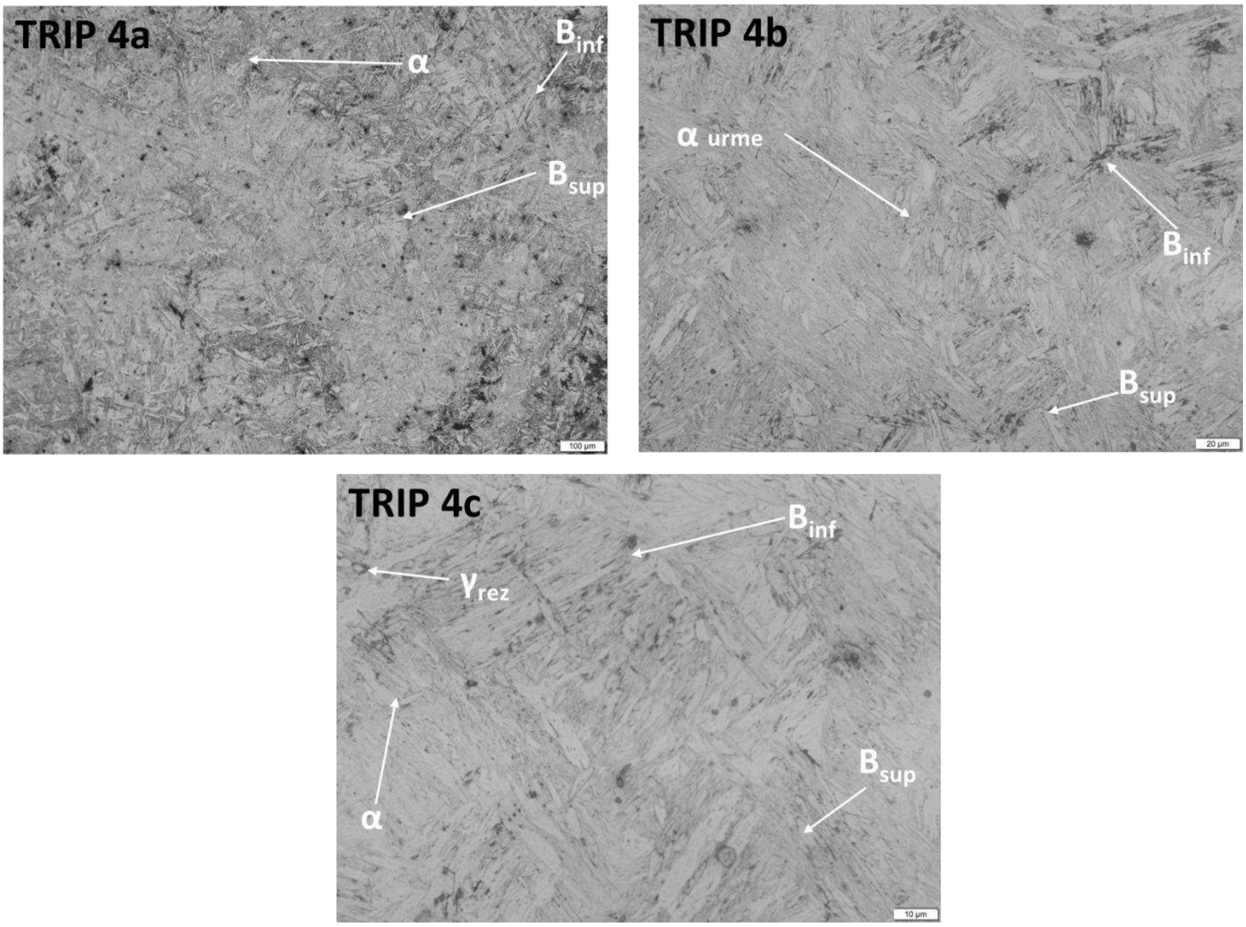

**Fig. 4. 2** *Optical microscopy images of the TRIP 4 sample, NITAL attack 2%,*

*a) M = 100x; b) M = 500x; c) M = 1000 x*

### Hardness tests after casting TRIP steels

Hardness tests can provide useful information about the metallographic structure of the analyzed material. In the case of metallic materials, the hardness may indicate the presence in a higher proportion of one phase than the others. The descending order of the hardness of the phases of a steel is the following: Martensite  Bathed  Ferrite  Austenite.

The hardness tests were performed on the Innovatest Falcon 500 hardness tester, with an intelligent load application system, a load ranging between 1g and 31 kgf and the possibility of performing Vickers, Brinell and Knoop hardnesses. The steels were tested at a load of 5kgf, the results being presented in table 4.2 where are the values for each test as well as the average hardness value after 3 measurements.

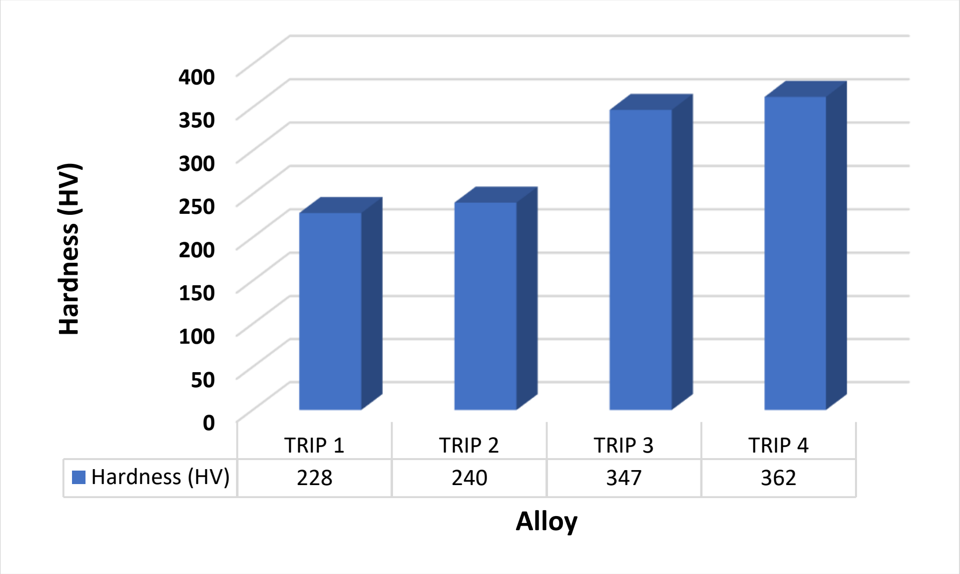

**Fig. 4. 3** *Graphical representation of the average hardness recorded in the analysis of TRIP alloys after casting*

## 4.6. Rolling and heat treatment of processed TRIP steels

In order to form a homogeneous structure, with high compactness, without internal stresses and with the constituents necessary to achieve the imposed mechanical properties, the samples were laminated. The process offers the advantage of an efficient processing of the metallic material in its entire volume, in the conditions of ensuring a good dimensional precision and a good quality surface.

In the experiment, the same heating temperature was used for all processed steels (1150 ° C). Using a Caloris 1206 oven (electric oven with resistance) and without controlled atmosphere, figure 4.12. The holding time for each sample was 10 minutes.

**Fig. 4. 4** *Heating the samples in the furnace to 1150°C*

**Table 4. 2** *Changing the thickness of the samples during the rolling process*

| *Pass* | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | *8* |
|---|---|---|---|---|---|---|---|---|---|
| *Thickness [mm]* | *18* | *15* | 13 | 11 | 9 | 7,6 | 6,9 | 5,9 | 5 |

Following the rolling process, the samples were heat treated by normalization annealing. Annealing is a heat treatment that modifies the physical and sometimes chemical properties of a material to increase its ductility and reduce its hardness, making it more viable. Annealing involves heating a material above the recrystallization temperature, maintaining a suitable temperature for an appropriate period of time, and then cooling in air. This annealing was performed in a Caloris heating furnace at a temperature of 1200 ° C in vacuum, figure 4.11.

**Fig. 4. 5** *Inserting rolled steels into the vacuum heating furnace*

### 4.7. Metallographic analysis by optical microscopy of laminated and standardized samples

In all cases analyzed, solidification after casting led to overheating structures, incorrect in terms of all technological characteristics (behavior during processing) and operation. Therefore, a regeneration annealing heat treatment was subsequently applied. This was in fact a normalization, at which, as mentioned in the thesis work plan, the temperature was set at 925 ° C, $t_{ment}$ = 0.5h, and cooling in air. It is specified that the thermal and temporal parameters, covering for all samples (TRIP 1, TRIP 2, TRIP 3 and TRIP 4) have been established according to the principles of heat treatments.:

- The temperature should be slightly higher than the temperature for austenite formation;
- Maintenance times (correlated with sample size) to be appropriate;
- Cooling freely in the air, according to the definition of normalization.

**Optical microscopy of the TRIP sample 4** (0.1% C, 6.1% Mn, 0.6% Al, 0.3% Si, rest Fe)

The analysis of the micrographs corresponding to the TRIP 4 sample concludes the series of structures to which the annealing was applied after development - casting, in order to regenerate the structure.

The massive finishing of the granulation is obvious in this case as well, without noticing important changes of the constituents compared to those identified after casting. However, their higher degree of fineness facilitates clearer ordering.

Thus, the majority structure is bainitic (upper bainite and traces of lower bainite), similar to that of the TRIP 3 sample, which allows the generalization of the observation that Mn in significant quantities increases the calcification. Its gamagen character could be highlighted at maximum magnification powers (M = 1000x) when, particularly for this sample, small regions with retained austenite could be observed.

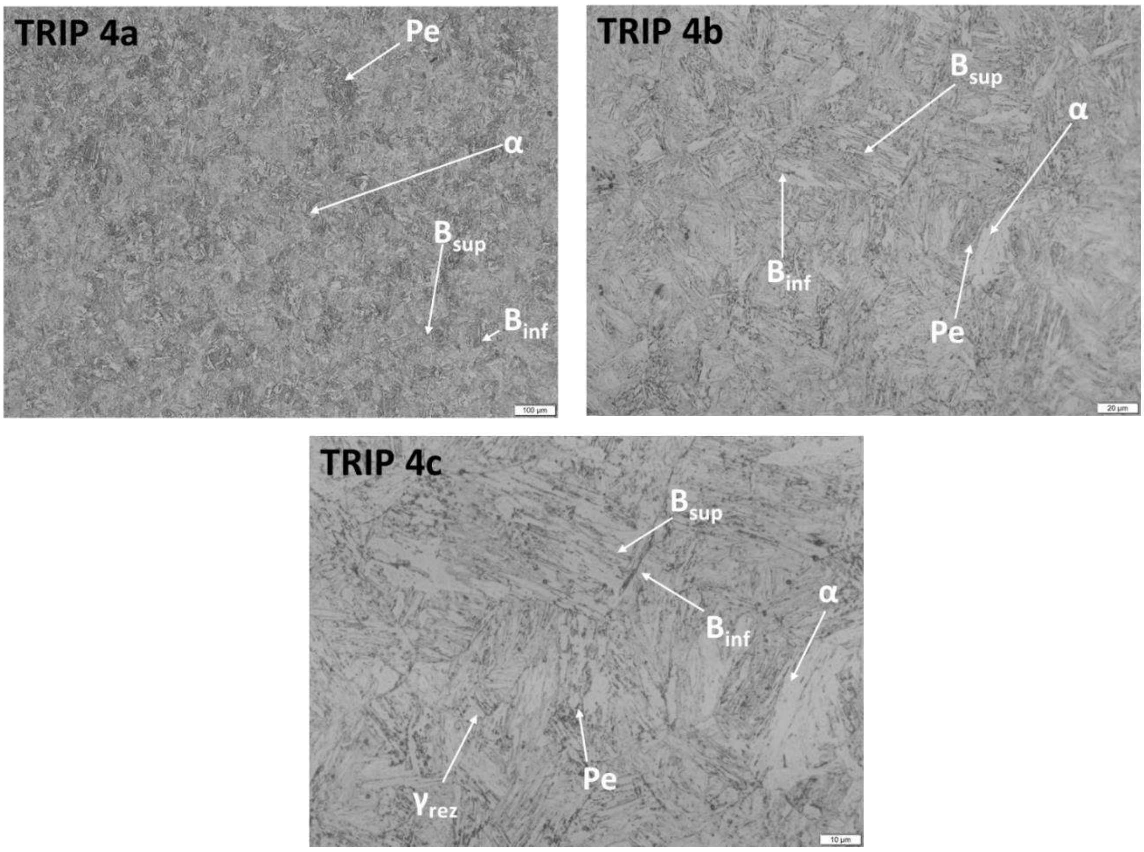

**Fig. 4. 15** Optical microscopy images of the TRIP 4 sample – heat treated for normalization. *Attack with Nital 2% (M = 100x (a); 500X (b); 1000x (c)*

The analysis of the micrographs corresponding to the TRIP 4 sample concludes the series of structures to which the annealing was applied after development - casting, in order to regenerate the structure.

The massive finishing of the granulation is obvious in this case as well, without noticing important changes of the constituents compared to those identified after casting. However, their higher degree of fineness facilitates clearer ordering.

Thus, the majority structure is bainitic (upper bainite and traces of lower bainite), similar to that of the TRIP 3 sample, which allows the generalization of the observation that Mn in significant quantities increases the calcification. Its gamagen character could be highlighted at maximum magnification powers (M = 1000x) when, particularly for this sample, small regions with retained austenite could be observed.

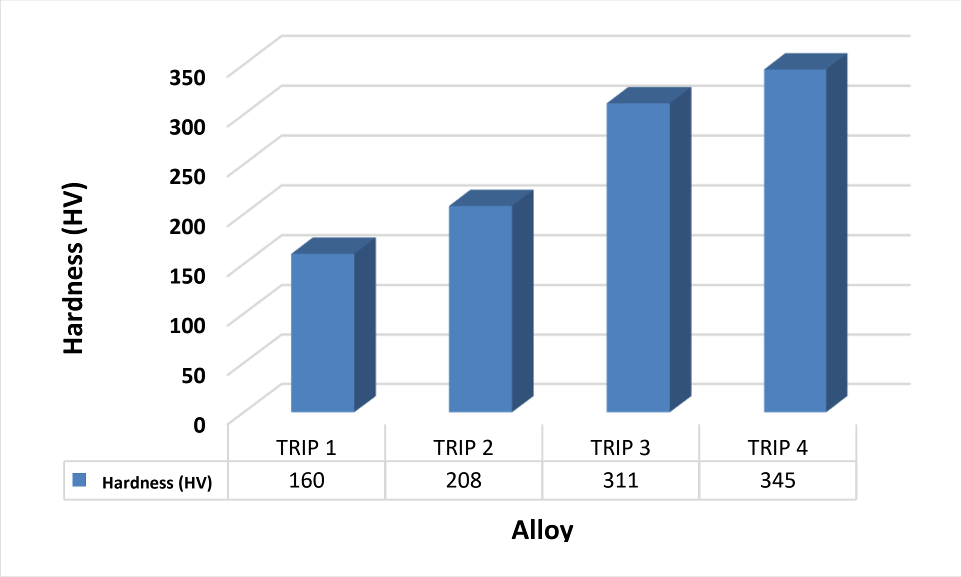

**Fig. 4. 6** *Graphical representation of the average hardness recorded in the analysis of TRIP steels after normalization heat treatment*

# Chapter. 5. RESEARCH ON THE HEAT TREATMENT OF TRIP STEEL CARRIED OUT FOR THE FORMATION OF THE RETAINED AUSTENITE REQUIRED TO CARRY OUT THE TRIP EFFECT

## 5.1. Heat treatment of TRIP steels

The heat treatments used involve rapid heating to a temperature in the bidirectional range $\alpha + \gamma$, leading to a microstructure of approximately 50% austenite and 50% ferrite, maintained at this temperature, followed by rapid cooling in the field of bainite formation, which leads to a diffusion of carbon in austenitic islands to form retained austenite, completed by cooling in air.

In order to obtain this thermal path, a bath of Barium Chloride ($BaCl_2$) salt was used. The principle of heat treatment involves heating the alloy to a temperature close to the critical upper $A_3$, followed by cooling close to the bainite formation temperature. These temperatures vary depending on the composition of the alloy and involve a mathematical calculation to determine the critical temperatures $A_1$ and $A_3$ using the formulas:

$$A_1 = 727 - 14[\%Mn + \%Ni] + 22[\%Si + \%Cr + \%Al] \qquad (5.1)$$

$$A_3 = 855 - 180[\%C] - 14[\%Mn] - 18[\%Ni] + 45[\%Si] + 1.7[\%Cr + \%Al] \qquad (5.2)$$

After determining the values $TA_1$ and $TA_3$, the temperature of the heat treatment to be applied to each steel can be calculated using the formula:

$$T_T = \frac{A_1 + A_3}{2} \qquad (5.3)$$

Prior to the start of the heat treatment process, the steels were sectioned longitudinally for use in the heat treatment process.

Using these formulas, depending on the composition of each TRIP alloy, it was possible to determine the temperature required to obtain the optimal amount of retained austenite for each steel made.

The compositional calculations led to the determination of a unique heat treatment regime for each alloy. These heating regimes can be seen in Figure 5.1.

**Tabel 5. 1** *$TA_1$, $TA_3$ and heat treatment (TT) values for processed steels*

| *Probă* | *$TA_1$ (°C)* | *$TA_3$(°C)* | *$T_T$(°C)* |
|---|---|---|---|
| ***TRIP 1*** | 750 | 813 | 781.5 |
| ***TRIP 2*** | 737 | 800 | 768.5 |
| ***TRIP 3*** | 659 | 773 | 716 |
| ***TRIP 4*** | 661 | 766 | 713.5 |

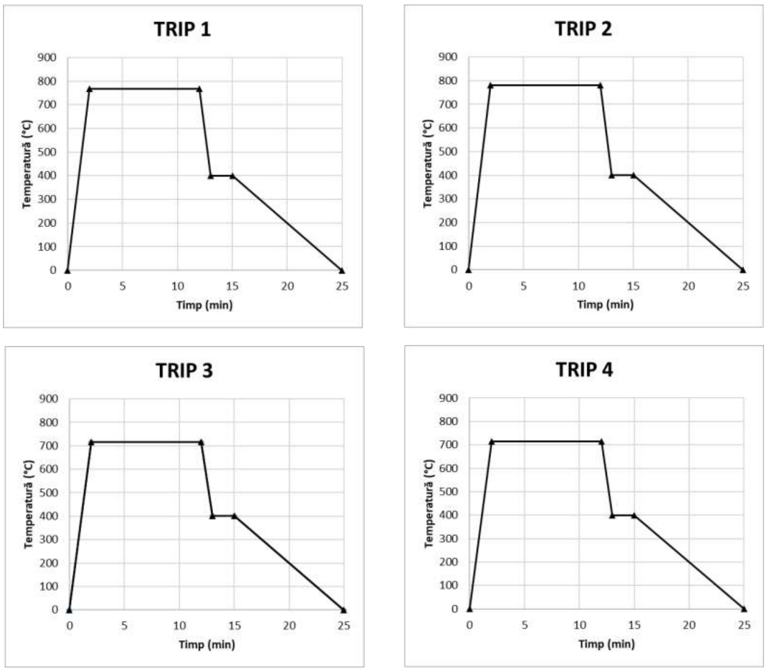

**Fig. 5. 1.** *Heat treatment regimes applied to TRIP steels*

### 5.2. Investigation of the structure by optical microscopy after unconventional heat treatment

According to research conducted by H. Bhadeshia [22], the promoter of TRIP steels, a controlled structure capable of meeting the special requirements assigned to these steels can only be achieved by applying an unconventional heat treatment.

The standard steel patented by the author mentioned above has the chemical composition 0.15% C, 1.5% Si, 1.5% Mn, rest. Fe, and the proposed structure is as follows:

- ferrite, to ensure proper machinability;
- bainite (superior) which through its tenacity, but also advantageous machinability ensures special mechanical characteristics;

- retained austenite in small quantities, resulting from the specificity of the bainitic transformation and which, in shock conditions, turns into martensite, ensuring an increased mechanical resistance to impact.

### *Optical microscopy of the TRIP sample 4*

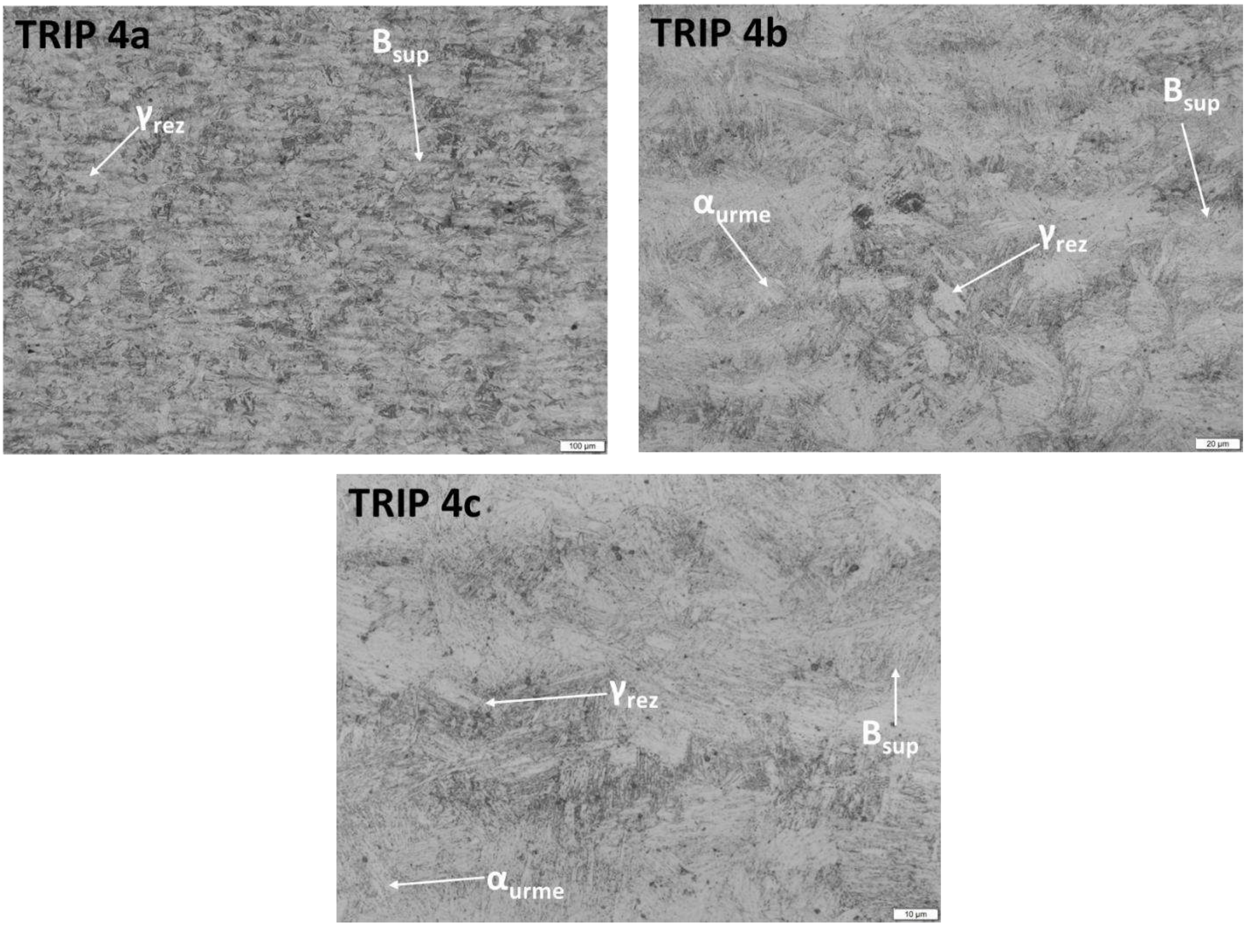

**Fig. 5. 2** *Optical microscopy images of the bainitic tempered TRIP 4 sample with austenite formation - Nital Attack 2% (a-M=100X, b-M=500x, c-M=1000x).*

The microstructure of the TRIP 4 sample has a combined structure compared to the previously investigated structures.

Basically, it resembles the structure obtained in the case of TRIP 3, but the presence in the chemical composition of a small amount of Al, alpha-gen element brings some varieties of structure.

Thus, the predominant structure of upper bainite is accompanied by larger areas of proeutectoid ferrite. Although the carbon content is the same as in the case of the TRIP 3 sample, the slight increase in Mn induces the maintenance in the structure of a larger amount of retained austenite, quite easily visible even from magnification powers of M = 500x.

The average hardness values (316HV) are in full accordance with the structure.

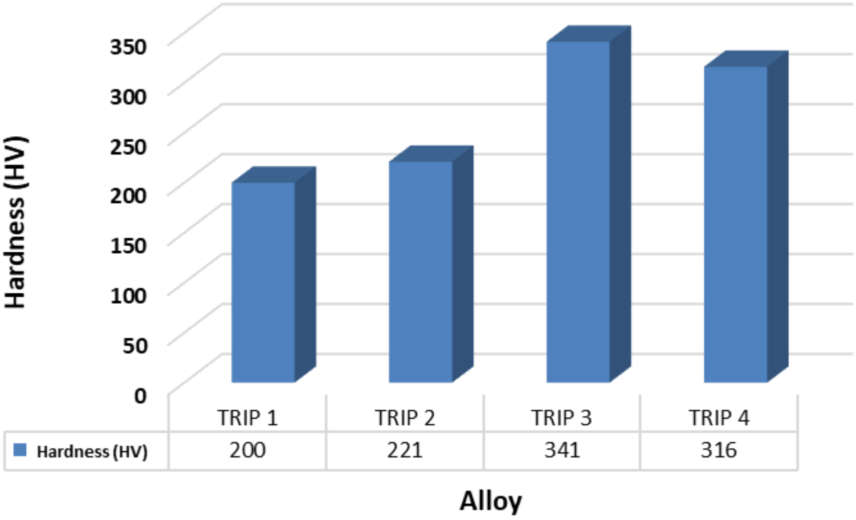

**Fig. 5. 3** *Graphical representation of the average hardness recorded in the analysis of TRIP alloys after heat treatment*

***Electron microscopy of the TRIP sample 4***

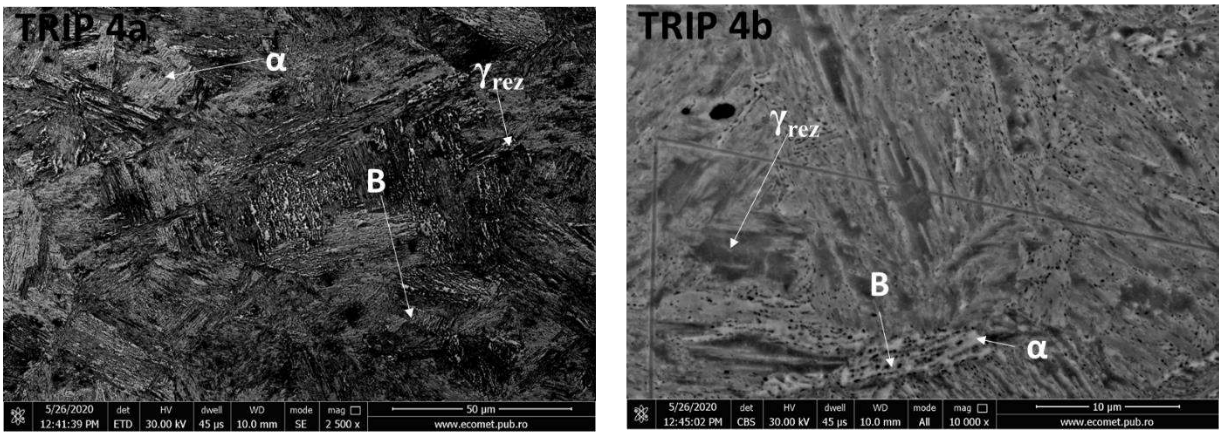

**Fig. 5. 4** *SEM micrographs of TRIP 4 steel at magnifications of 2500x and 10000x*

The compositional combination of the TRIP 4 sample brings to the fore the most varied structures. Thus, the proeutectoid ferrite joins with the bainitic ferrite forming a unitary whole, the majority structure being the superior bainite, with a very clear distribution in the rods.

In the third quadrant of the composition image, the moment of precipitation of the carbides inside the ferrite plate is captured, morphological aspect specific to the upper bainite.

A more visible structural detail in this sample is related to the areas where retained austenite is identified. Being wider, their insular distribution between the bainitic ferrite plates is clearly observed. This distribution clearly explains the mechanism of the existence of retained austenite in the bainitic transformation process.

### 5.5. Determination of the retained austenite content by the X-ray diffraction method

The determination of the retained austenite content on TRIP steel samples was performed using the X-ray diffraction technique according to ASTM E 975-03, *Standard Practice for X-Ray Determination of Retained Austenite in Steel with Near Random Crystallographic Orientation*.

The equipment used was a Rigaku AUTOMATE II diffractometer, used in the following configuration:

- radiation $Cr\ K\alpha$, $(\lambda = 2{,}29092\text{Å})$;
- X-ray beam parameters: 40kV, 40mA, $irradiated\ area = 1{,}15 \cdot 1{,}15\ mm^2$;
- detector: D/teX Ultra 2000 silicon strip;
- XYZ automatic movement test holder, CCD microscope and zoom function for precise irradiated area selection;
- calculation ratio of the volume of retained austenite according to ASTM E 975-03:

$$V_\gamma = \left[\frac{I_\gamma}{R_\gamma}/\left(\frac{I_\alpha}{R_\alpha}\right) + \left(\frac{I_\alpha}{R_\alpha}\right)\right] \ (1);$$

in which:

$I_\alpha$ = the integrated intensity corresponding to the diffraction line $\alpha_{(211)}$;

$R_\alpha$ = correction corresponding to the diffraction line $\alpha_{(220)}$;

$I_\gamma$ = integrated intensity corresponding to the diffraction line $\gamma$ $(_{220})$;

$R_\gamma$ = correction corresponding to the diffraction line $\gamma_{(200)}$.

The samples were processed metallographically for analysis in section, with the surface brought to metallic luster. For the quantitative analysis, the diffraction lines $\alpha_{(211)}$ (2θ = 156.40 °, t = 100s) and $\gamma_{(200)}$ (2θ = 128.40 °, t = 300s) were purchased at three points on analysis surface, located at about 2mm distance from each other. For the tests subjected to the impact tests, the analysis was performed in section, in the middle of the plastically deformed area and at + 2 mm left / right of the central point. Integral intensities were determined for each diffraction line, with corrections according to ASTM E 975-03. The volume of retained austenite was determined using relation (1), using the mean value of the integral intensity.

**Fig. 5. 5** *Rigaku AUTOMATE II diffractometer with Cr tube for the determination of retained austenite*

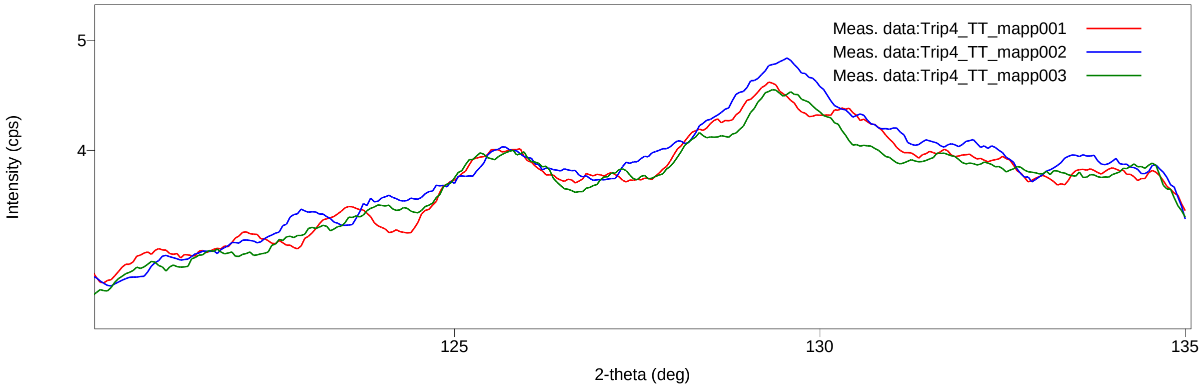

**Fig. 5. 6** *Diffraction peak measured at three points on the TRIP 4 sample, corresponding to phase* $\boldsymbol{Fe_{\alpha}}$

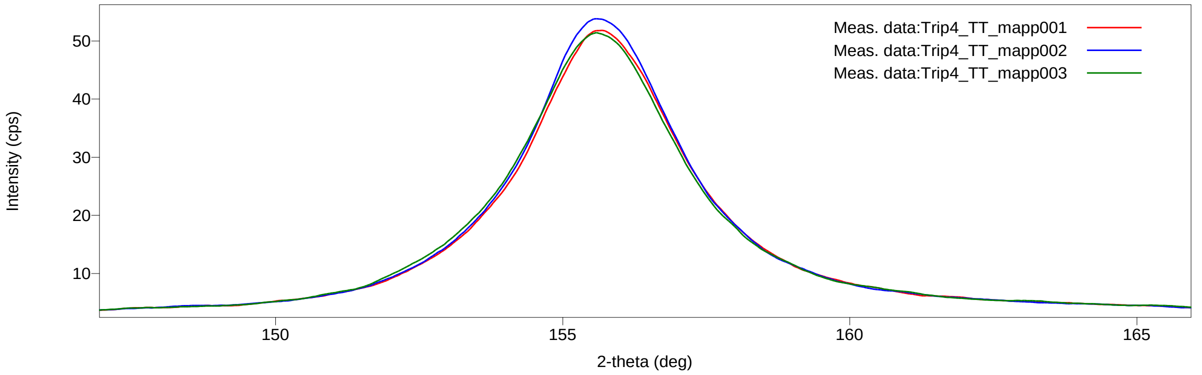

**Fig. 5. 7** *Diffraction peak measured at three points on the TRIP 4 sample, corresponding to phase* $\boldsymbol{Fe_{\gamma}}$

The calculated values of the retained austenite content from the processing of the experimental data are presented in Table 5.3.

**Table 5. 2** *Calculated values of the level of retained austenite following the heat treatment*

| **Nr.crt.** | **Sample*** | $V_\gamma$ |
|---|---|---|
| 1 | TRIP 1 | 9,29 |
| 2 | TRIP 2 | 7,40 |
| 3 | TRIP 3 | 4,63 |
| 4 | TRIP 4 | 10,63 |

# Chapter. 6. RESEARCH ON THE IMPACT BEHAVIOR OF EXPERIMENTED TRIP STEELS

## 6.2 Purpose and experimental research

The experimental research carried out on the impact behavior of the studied TRIP steels aimed to characterize the hardening process of these materials subjected to the action of the impact force. For this, the objectives of the tests were pursued:

- - highlighting the existence of the response force ($F_r$) of the material and how it varies during the impact ($t_r$);
- - analysis of structural transformations produced in the material under the action of the impact force ($F_i$);
- - evaluation of the TRIP effect specific to the investigated steels.

## 6.3.1 Impact tests

Experimental impact tests were performed on an INSTRON Ceast 9340 equipment, fig. 6.1, provided with the module for data acquisition and specialized software VisualIMPACT V.6 and CeastVIEW.

**Fig. 6. 1** *Experimental assembly for dynamic impact tests: 1 - INSTRON Ceast 9340 equipment (USA); 2 - PC unit equipped with data acquisition system;*

The plastic deformation had a dynamic character, the impact through mechanical shocks being achieved with a speed of approx. 60 km / h and the application of a impact mass of 3,219 kg which will generate an impact energy of 18J. The flat samples subjected to the tests were made of the investigated steels, which are in a heat-treated state and with the outer surfaces cleaned of the salt film formed during the bainitic hardening in salt baths. The positioning of the specimens in relation to the direction of application of the impact force (F) corresponds to the method of the three points of contact, fig. 6.2.

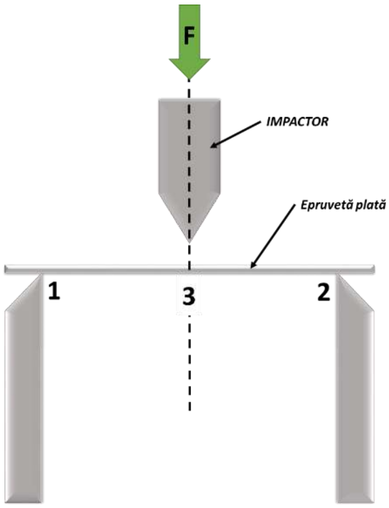

**Fig. 6. 2** *Procedure for dynamic impact tests*

Investigations into the structural changes produced under the action of the impact assessment referred to:

- - assessment of the amount of retained austenite present in the initial structure of TRIP steels,
- - highlighting the structural transformations produced.

**Table 6. 1** *Conditions for impact requirements and resilience values for TRIP steels*

| Sample | Impact speed, [m/s] | Impact energy, [J] | Resilience, [kJ/m$^2$] |
|---|---|---|---|
| TRIP 1 | 3,344 | 18 | 491,84 |
| TRIP 2 | | | 478,21 |
| TRIP 3 | | | 480,07 |
| TRIP 4 | | | 499,36 |

The impact behavior of the four types of TRIP steels studied followed the variation of the response force (Fr) of each material, during the considered duration of the mechanical stress produced. Based on the values recorded by the data acquisition module, the variation curves Fr = f (tr) were drawn, for each investigated alloy, fig. 6.3.

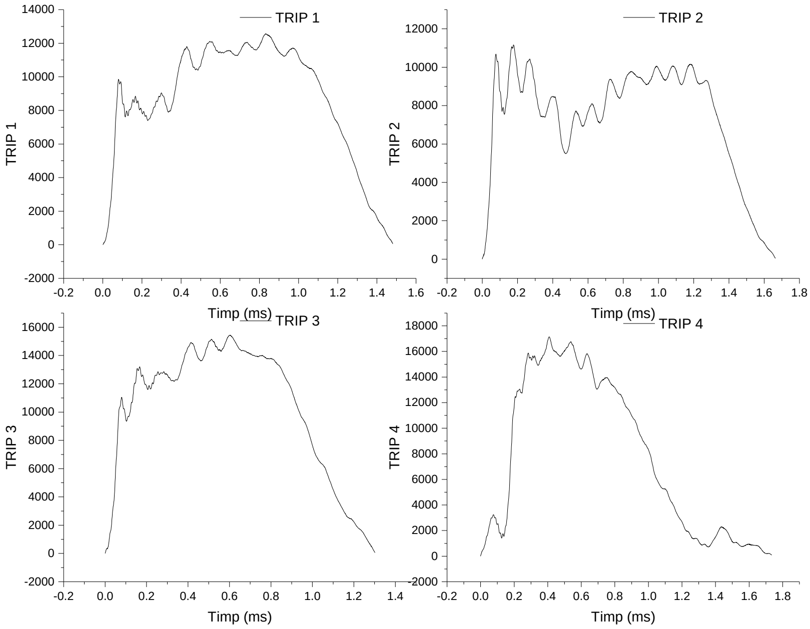

**Fig. 6. 3** *Variation curves* $Fr = f_{(tr)}$ *specific to the TRIP steels investigated: a - TRIP steel 1; b - TRIP steel 2; c - TRIP steel 3; d - TRIP steel 4.*

Performing the comparative analysis highlights the following:

- - weakly alloyed TRIP steels (TRIP 1 and TRIP 2) have the lowest response force values and the longest durations for the response time. Probably, the small amount of alloying elements led to a low degree of hardening, which allowed the metallic material to oppose a limited resistance to the action of the deformation force;
- - the small amount of alloying elements considerably reduced the possibility of forming structural phases such as precipitate particles, which would have been barriers to the movement of linear defects (dislocations), thus limiting the process of plastic deformation under the action of impact force. The superficial hardening of the materials (hardening), achieved by blocking the dislocations would have been a way to increase the response capacity of the material;
- - medium alloyed TRIP steels (TRIP 3 and TRIP 4) showed the highest response capacities. The increase in the amount of chemical compounds formed in the presence of alloying elements contributed to the structural hardening of the two steels.

### 6.4.2 The mechanism of the TRIP effect

For TRIP steels, the production of a structural transformation induced by plasticity is characteristic. The $A_{rez} \rightarrow M$ transformation is specific to the investigated steels as a way to evaluate the TRIP effect.

In the case of the elements from the construction of the resistance structure of the vehicles, two particularities are specific:

- - the plastic deformation that ensures the energy necessary for the structural transformation is the result of the effect of the mechanical shock produced by the impact;
- - the structural change that characterizes the TRIP effect of these steels refers to the possibility of transforming the retained austenite into martensite based on the energy absorbed following the mechanical impact.
- The intensity of the TRIP effect was highlighted in two ways:
- - by X-ray diffraction;
- - by microstructural analyzes.

*6.4.2.1 Highlighting the effect of TRIP by X-ray diffraction*

By X-ray diffraction performed on the Rigaku AUTOMATE II diffractometer, the volumes / quantities of retained austenite existing in the structure of the investigated TRIP steels were determined, before the plastic deformation and after the production of the mechanical shock.

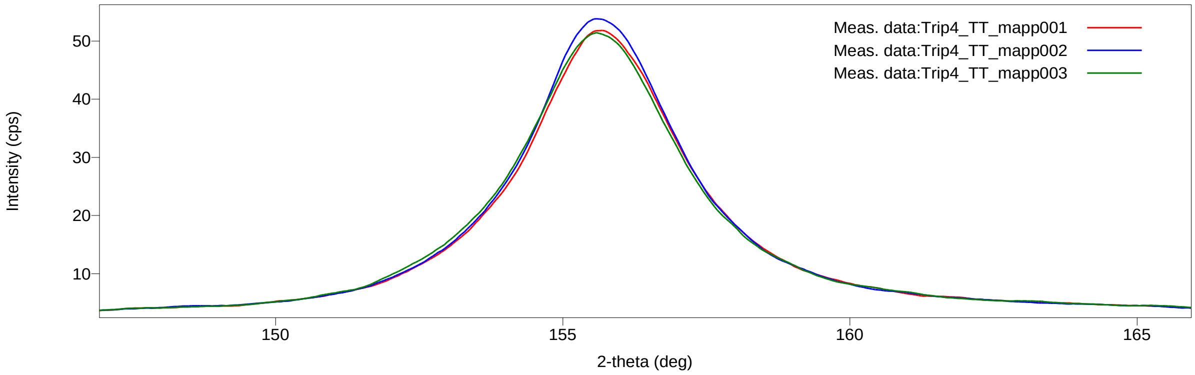

**Fig. 6. 4** *$A_{rez}$ diffraction peaks measured at three points on the surface of sample TRIP 4, before mechanical shock*

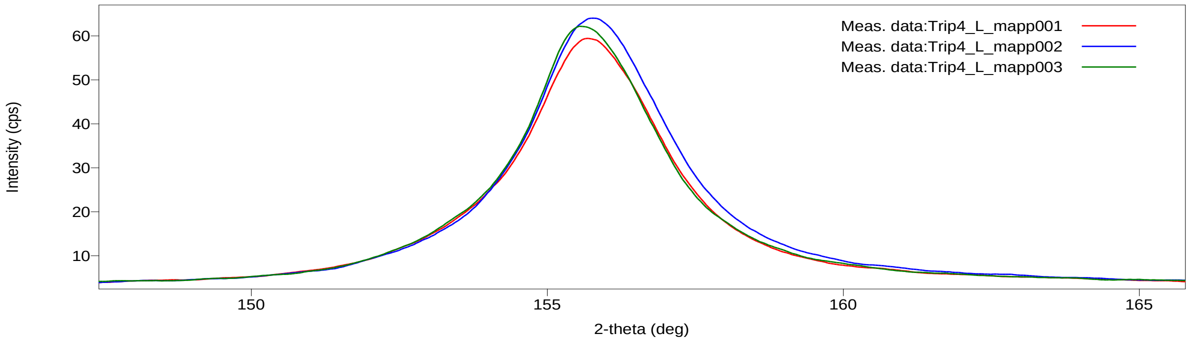

**Fig. 6. 5** *$A_{rez}$ diffraction peaks measured at three points on the surface of the TRIP 4 probe after mechanical impact*

**Table 6. 2** *Values of the amount of retained austenite transformed by the TRIP effect*

| Nr. crt. | TRIP steel | | $V1\gamma$ | $V2\gamma$ | $\Delta V1\gamma$ | $\Delta V2\gamma$ |
|---|---|---|---|---|---|---|
| 1 | TRIP 1 | Before impact | 9,29 | - | 1,96 | 0,21 |
| 2 | | After impact | - | 7,33 | | |
| 3 | TRIP 2 | Before impact | 7,40 | - | 2,17 | |
| 4 | | After impact | - | 5,23 | | |
| 5 | TRIP 3 | Before impact | 4,63 | - | 0,94 | 1,14 |
| 6 | | After impact | - | 3,69 | | |
| 7 | TRIP 4 | Before impact | 10,63 | - | 2,08 | |
| 8 | | After impact | - | 8,55 | | |

The analysis of the values presented in the table shows the following:

-- of the two low-alloy steels, TRIP 1 steel has the highest values of retained austenite, both before and after the mechanical shock;

-- of the two medium alloy steels, TRIP 4 steel has the highest values of retained austenite both before and after mechanical shock;

-- the highest amounts of austenite converted to martensite by the TRIP effect are TRIP 2 and TRIP 4 steels;

-- weakly alloyed TRIP steels show closer values for the quantities of retained austenite transformed into martensite by plastic deformation;

- medium alloy steels TRIP 3 and TRIP 4 have strongly differentiated values for the variation of the quantity of $A_{rez}$. It may be necessary to increase the impact force in order to obtain the intensification of the Arez → M transformation, especially in the case of these steels with a high manganese content.

### *6.4.2.2 Highlighting the effect of TRIP by electron microscopy*

Microstructural aspects specific to TRIP 1 steel are presented in fig. 6.14.

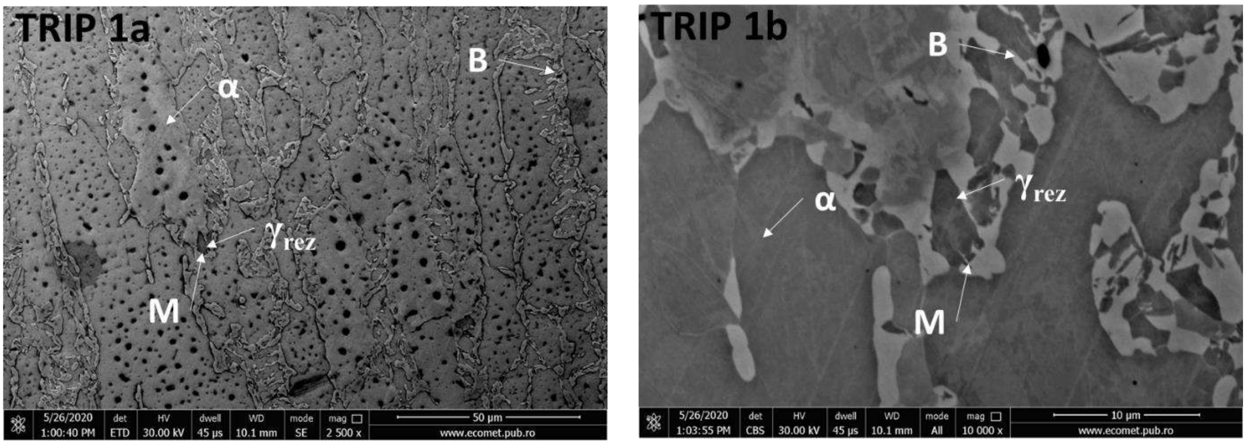

**Fig. 6. 6** *SEM images of TRIP 1 steel a– magnification power 2500: 1; b - magnification power 10 000: 1*

After heat treatment and plastic deformation by mechanical shock, the microstructure of this steel consists of:

- - solid solutions represented by initial α ferrite (Fα) and retained austenite (Arez);
- - mechanical mixture of pearlite type represented by bainite (B);
- - supersaturated solid solution, out of equilibrium, represented by martensite (M) resulting from impact stress.

The ferritic phases with low hardness present an arrangement oriented on the direction of plastic deformation, thus favoring the production of the structural hardening of the steel. Acicular martensite formed by the transformation of Fα → M is arranged inside the austenite islands.

SEM analysis of TRIP 2 steel

Microstructural aspects specific to TRIP 2 steel are presented in fig. 6.15.

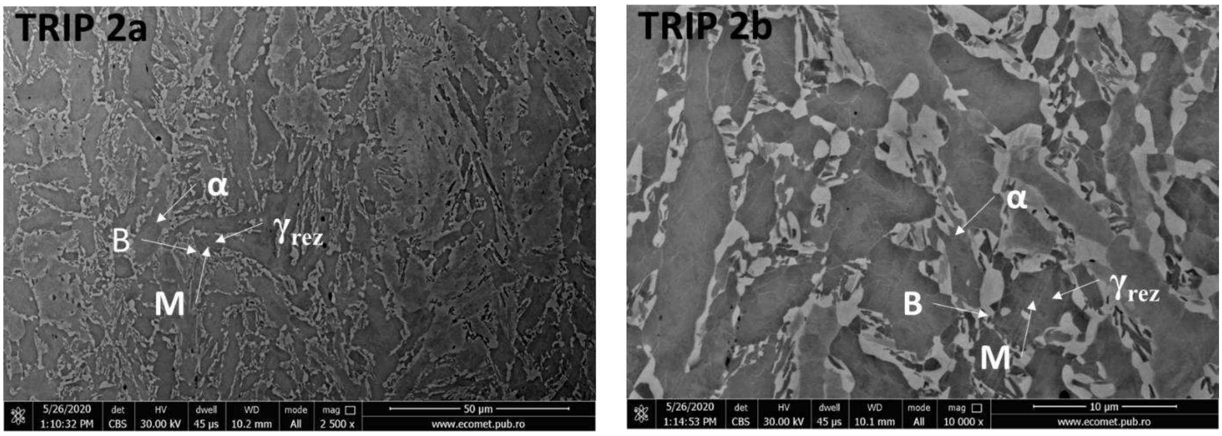

**Fig. 6. 7** *SEM images of TRIP 2 steel a - magnification power 2500: 1; b - magnification power 10 000: 1*

The chemical composition similar to TRIP 1 steel and the maintenance of the same structural transformations during thermal and mechanical processing led to the identification of similar microstructures for TRIP 2 steel.

SEM analysis of TRIP 3 steel

In the chemical composition of TRIP 3 and TRIP 4 steels the amount of manganese was considerably increased, which made them medium alloys. Through the stabilizing effect of austenite, manganese influences both the initial microstructure of steels and the structural transformations produced by heat treatment, respectively by subsequent plastic deformation (mechanical impact).

Microstructural aspects specific to TRIP 3 steel are presented in fig. 6.16.

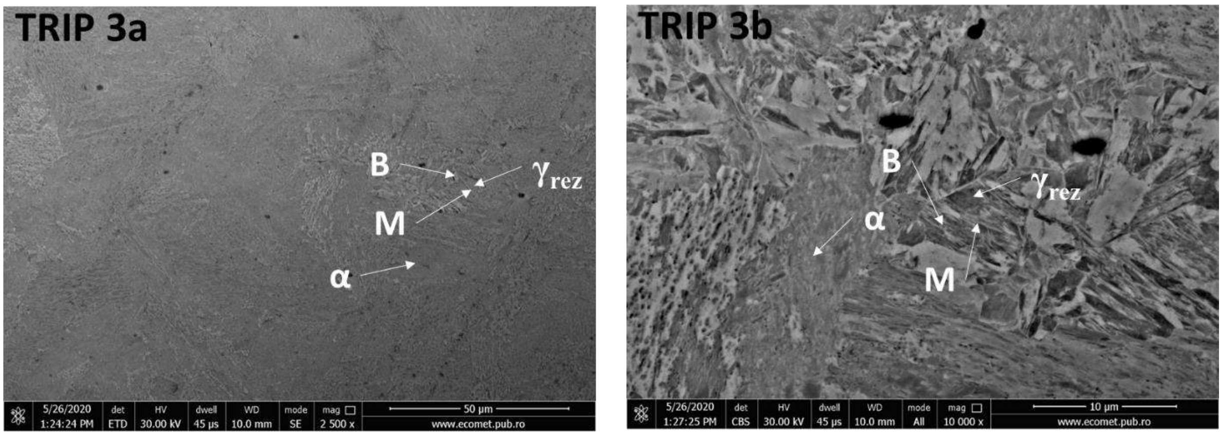

**Fig. 6. 8** *SEM images of TRIP 3 steel a - magnification power 2500: 1; b - magnification power 10 000: 1*

The microstructure consists of the same constituents, the differentiations referring to:

- emphasizing the oriented disposition of the Fα phase, especially that of the bainite constitution;
- the trend of orderly arrangement of martensite needles inside the austenitic islands.

SEM analysis of TRIP 4 steel

Microstructural aspects specific to TRIP 4 steel are presented in fig. 6.17.

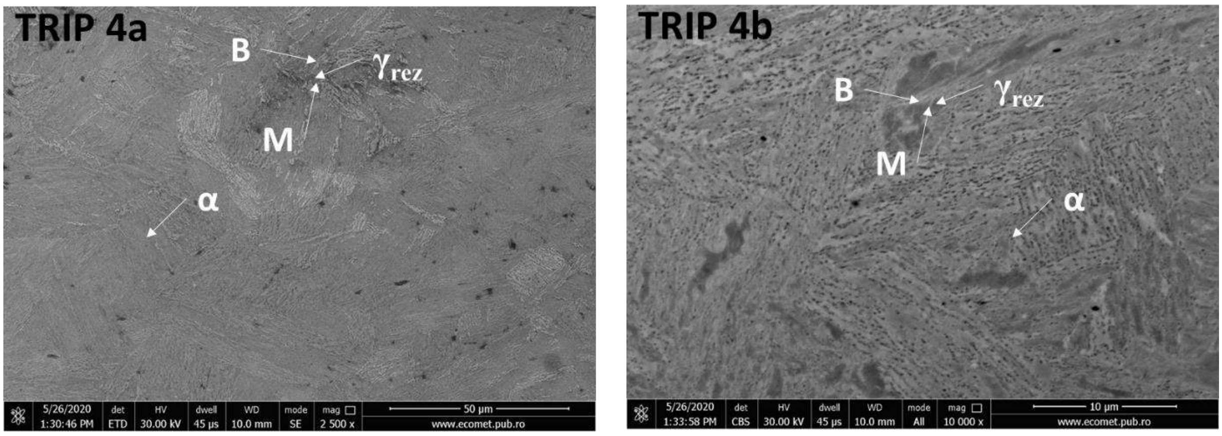

**Fig. 6. 9** *SEM micrographs of TRIP 4 steel a - magnification power 2500: 1; b - magnification power 10 000: 1*

Because the chemical composition contains the highest manganese content, it results that this steel will be characterized by the highest amount of retained austenite present at the end of the induced plastic transformation.

The oriented disposition of the ferritic phase (Fα) can determine a tendency of structural hardening. The most important role belongs to the existence of the martensitic phase. At the level of martensite formations is observed the presence of needles of different sizes: long and thick needles (8 - 9 μm) formed at the beginning of the transformation by impact and short and thin needles (1 - 2 μm) formed at the end of the structural transformation. The orientation of these needles allows the appreciation of the direction of plastic deformation produced by mechanical shock.

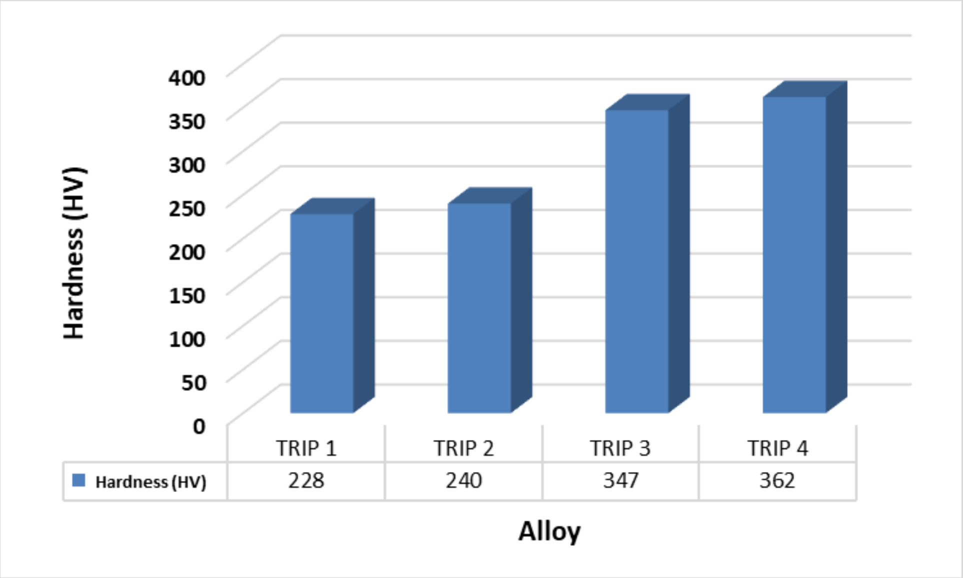

**Fig. 6. 10** *Graphical representation of average Vickers hardness values for TRIP steels, after impact stress*

**Table 6. 3** *Plasticity-induced transformation and increased Vickers hardness*

| TRIP Steel | The volume of $A_{rez}$ transformed into M | Increase of Vickers hardness |
|---|---|---|
| TRIP 1 | 1,96 | 8 |
| TRIP 2 | 2,17 | 19 |
| TRIP 3 | 0,94 | 6 |
| TRIP 4 | 2,08 | 46 |

# Chapter 7. GENERAL CONCLUSIONS, ORIGINAL CONTRIBUTIONS AND FUTURE RESEARCH DIRECTIONS

## 7.1 General Conclusions

➢ TRIP steels have the best combination of mechanical strength - plasticity - hardening (hardening under stress).

➢ The TRIP effect specific to these steels consists in producing a martensitic transformation induced by plasticity (under the action of impact energy).

➢ Retained austenite is the initial phase that will turn into mechanical martensite due to the storage of impact energy.

➢ From the point of view of the chemical composition for the formation of a larger amount of retained austenite it is necessary that the steel has:

- a higher carbon content and be weakly alloyed with γ-gene elements (Mn);
- low carbon content and be medium alloyed with γ-gene elements (Mn);

➢ For the studied steels, the structural transformation is of the type $A_{rez} \rightarrow M$, under the action of the energy supplied to the alloys through an impact / shock stress.

➢ The research conducted aimed at the impact behavior of four steels, to characterize the intensity of the TRIP effect induced by plasticity.

➢ The methodology of personal research development required:

- - knowledge of the current state of research carried out, at national and international level;
- - establishing the Personal Research Development Plan specific to the proposed research direction.

➢ The research topic aimed at implementing modern concepts on TRIP steels for the construction of elements in the strength structure of vehicles.

➢ The objective of the topic was represented by the complex and comparative study on the TRIP effect for a medium alloy steel with an original chemical composition.

➢ The complexity of the studies was determined by the multitude of experimental research performed:

- development and casting of four TRIP steels, of which one steel with original chemical composition.
- microstructural and property characterization of each cast steel;
- hot plastic deformation, followed by the normalization heat treatment applicable to the investigated steels;

- formation of retained austenite by practicing bainitic hardening in the salt bath of steels;
- microstructural characterization and compositional characterization of steels, after bainitic hardening;
- evaluation of the intensity of production of the TRIP effect by analyzing the structural transformation Arez → M, induced by mechanical impact (plasticity);
- microstructural, compositional and property characterization of steels, after mechanical shock test;
- analysis of the variation of the response force of the considered materials, during the investigation of the mechanical impact.

➢ SEM electron microscopy highlighted:

a. for weakly alloyed TRIP steels: allotriomophic character of α proeutectoid ferrite, similar morphologies for proeutectoid Fα and bainitic Fα, elongated shape (rod) of bainite grains;

b. for medium alloy TRIP steels, extreme values were obtained for $A_{rez}$ (4.63% for TRIP 3 and 10.63% for TRIP 4), a situation that can be explained by the large amount of manganese (chemical element γ - gender) and by the addition of Al (α-gen chemical element) in the case of TRIP 4 steel,

➢ Plastic deformation by impact was performed in similar conditions for the four steels studied: impact mass 3.219 kg, impact velocity of approx. 60 km / h (maximum speed limit allowed when traveling through localities), impact energy W = 18J. The flat samples subjected to the tests were in the condition resulting from the heat treatment;

➢ At the action of the impact force (Fi) TRIP steels used in the construction of body elements react with a response force (Fr), whose variation was studied during a response time tr = 1.8 ms;

➢ Through SEM electron microscopy, the microstructural constitution of TRIP steels was investigated, after the impact stress. The presence of martensite under the action of impact energy was identified. Structural constituents with low hardness of the ferrite type (free ferrite and bainite ferrite) begin to acquire a character oriented in the direction of the plastic deformation force,

➢ Hardening of steels resulting as a consequence of the TRIP effect was a way to assess the intensity of its manifestation;

## 7.2 Original contributions

During the development of personal experimental research, original contributions were made in the scientific field approached:

- A medium alloy TRIP steel (TRIP4) with an original chemical composition was developed and cast, in which the presence of a quantity of 6.10% Mn ensures the possibility of increasing the amount of austenite necessary for the martensitic transformation specific to the TRIP effect.
- Development and casting of three types of TRIP steels (two brands of low-alloy steels TRIP 1 and TRIP 2 and one medium-alloy steel brand TRIP 3) with chemical compositions taken from the literature. These steels were required for comparative studies with the new brand of steel (TRIP 4).
- The design of a personal technology for processing the studied TRIP steels which includes the application of the normalization heat treatment after hot plastic deformation and the assimilation of the impact test with the cold plastic deformation operation.
- Video recording of the manner of the shock load in order to observe the stages that follow one another in the process of plastic deformation by impact of the elements from the construction of the vehicle body structure.
- Comparative and differentiated analysis of transformations: bainitic and martensitic. Through SEM electron microscopy, microstructural investigations were performed, at different resolution powers, on the transformation of $F\gamma$ (A) → B + $A_{rez}$ (bainitic hardening) and $A_{rez}$ → M + $A_{rez}$ (martensitic hardening).
- By X-ray diffraction were determined:

  - the amount of austenite that turns into bainite, when hardened in a salt bath;

  - the amount of retained austenite that turns into martensite when cooled at high speed in the air.
- Carrying out experimental research on impact behavior by adopting conditions similar to real ones, for example the impact speed corresponds to a vehicle speed of 60 km / h.
- Highlighting the response capacity of each type of steel mechanically required on impact by determining the mode of variation of the specific response force (Fr).
- Assessing the intensity of the TRIP effect for each type of steel studied by studying the quantitative evolution of structural transformations induced by impact, but also the hardening process of steels.

➢ Evaluation of the variation of the hardness of steels measured after each technological processing operation.

## 7.3 Future directions of scientific research

Future directions of experimental research will refer to the possibilities of improving the two requirements imposed on TRIP steels.:

- increasing the capacity to absorb and dissipate impact energy;
- structural hardening of the alloys to ensure its strength in response to stress on mechanical shock.

In order to meet these conditions, some study topics are formulated for the continuation of personal research:

➢ Development and casting of at least four new steels, of which:

- two steels with a higher carbon content, maintaining their quality as low-alloy manganese steels;
- two steels with a diversified content of γ-gene alloying elements, having the quality of an alloyed environment and with a low carbon content.

In this way it will be possible to carry out comparative studies on the possibility of increasing the amount of retained austenite necessary for the martensitic transformation at the end of the technological processing.

➢ Carrying out the analysis of the structural transformation $A_{rez} \rightarrow M$ induced by plasticity, in the specific conditions of weakly alloyed TRIP steels (TRIP1 and TRIP2) respectively of medium alloyed TRIP steels (TRIP3 and TRIP4);

➢ Establishing the dependence between the values of the impact force (Fi) and the response force (Fr), for each TRIP steel studied. In this way it will be possible to determine the value of the force (Fr) for which the TRIP effect has the highest intensity;

➢ Qualitative and quantitative microscopic analysis on the types of structural constituents formed in the presence of different alloying elements present in the chemical composition, or applied heat treatments;

➢ The study on the structural components that can favor the increase of the hardness of steels, after the stress request, by: mechanical hardening and structural hardening;

➢ Optimizing the conditions of mechanical impact stress in order to obtain the most favorable values of the TRIP effect;

- Evaluation of the plastic deformation process at impact of the steels made, through analyzes based on the theory of dislocations: determining the evolution of the dislocation density and establishing the processes of movement, respectively blocking, of these linear defects;
- Replacement of some heat treatments present in current technologies with other variants of heat processing (eg application of a hardening solution instead of normalization after plastic deformation);
- Development, by cold plastic deformation of the semi-finished products obtained by hot plastic deformation, of some elements from the resistance structure of the vehicle body. In this way we will move to the component of the functional implementation of personal research results.

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