

TRIP steels: the features of chemical composition and structure, prospects of application (overview)

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This article provides a brief overview of steels prone to transformation induced plasticity (TRIP), which belong to the class of advanced high-strength steels (AHSS). The necessary set of properties in these steels is formed due to the partial preservation of supercooled austenite in the structure. The article considers the mechanism of TRIP transformation, which depends on the value of the temperature of the beginning of the martensitic transformation. It is shown that the amount and stability of supercooled austenite can be influenced by varying the temperature and time parameters of heat treatment. In addition to heat treatment, the qualitative and quantitative parameters of metastable austenite are significantly influenced by the alloying of TRIP steels, and the alloying elements themselves can be divided into several main groups (ferrite-stabilizing, increasing the stability of supercooled austenite and micro-alloying). In the final part of the article, the prospect of using TRIP steels in the aerospace industry is considered, where reducing the metal consumption of parts is a priority. It is also worth considering that the production of parts using additive technologies is widespread in the aerospace industry. Therefore, the use of TRIP steels as a material in additive manufacturing leads to the formation of a new concept for creating parts with a unique set of properties, primarily with high structural strength, light weight and the possibility of self-adaptation to extreme external exposures.

Key words: TRIP steels, chemical composition, alloying, microstructure, mechanical properties, phase composition, heat treatment

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Introduction

Steels with TRIP effect (Transformation Induced Plasticity) were discovered at the end of the XIX century (Nippon Steel). However, mass production and consumption of this type of steels began only at the start of the XX century when automakers focused their attention on their products being economically efficient and environmentally friendly. It was TRIP steel that was able to adapt to such requirements as reducing the metal capacity of structures while increasing their strength characteristics. However, the possibility of using such steels is limited by the fact that they contain a significant amount of carbon, which affects the weldability of steel [1, 2].

TRIP steels belong to the class of modern high-strength steels (Advanced High Strength Steels - AHSS) with simultaneously high parameters of time resistance and elongation. TRIP steels were a logical continuation of the development of steels for auto manufacturing, which at an early stage were carbon steels alloyed with manganese. The structure of such steels consisted of ferrite and perlite, with yield strength of about 180 MPa, and tensile strength of about 330 MPa. The structure itself was formed due to continuous cooling from the austenitic state. The further improving of

the mechanical properties of AHSS was the development of the concept of nonequilibrium multiphase steel, which led to the development of two-phase steels (Dual Phase - DP). The microstructure of such steels consists of ferrite and a significant proportion of martensite and its production does not require major changes in the chemical composition of steel. Ferrite and martensite are obtained in the structure by influencing phase transformations through the redistribution of chemical elements between phases by changing the cooling rate. The basic concept of obtaining DP steels consists in slow cooling in the temperature range of ferrite release in pre-eutectoid steels, which leads to the release of ferrite and the redistribution of carbon with the increase of its concentration in austenite. It makes it possible to achieve a sufficient concentration of carbon in austenite for hardening and to increase resistance to pearlite transformation. After the ferrite is separated, the steel cools at a speed above the critical. The shear transformation of the supercooled austenite begins at a temperature of the martensitic transformation. By changing the temperature-time parameters in these steels, the quantitative correlation of ferrite and martensite is regulated which makes it possible to vary the value of the time resistance from 500 to 1200 MPa [3–5].

A. G. Korchunov, Dr. Eng., Prof., Head of the Dept. of Designing and Operation of Metallurgical Equipment participated in this work.

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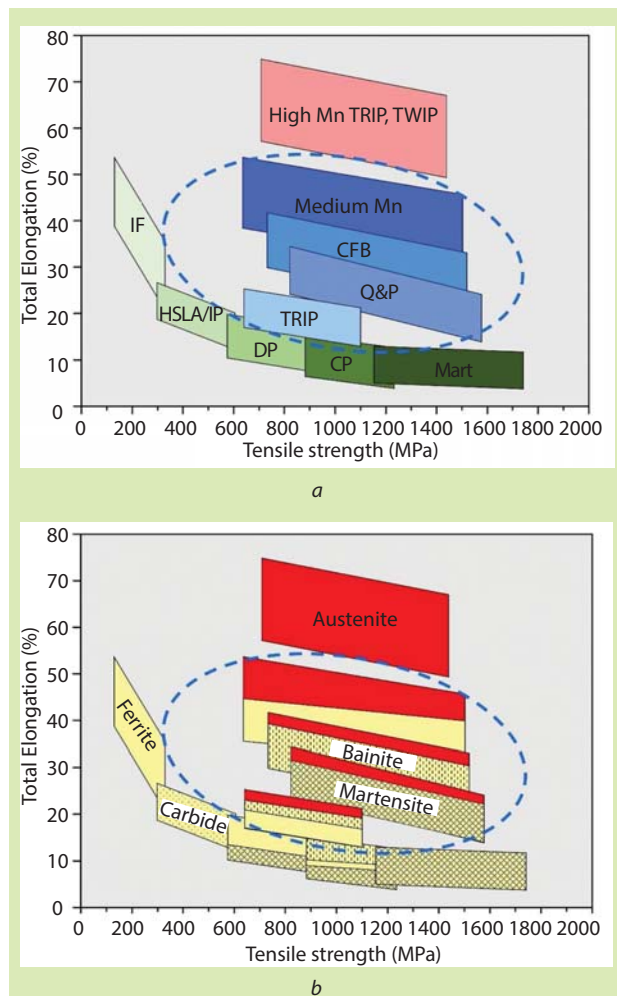


Fig. 1. Classification of various classes of steels according to their mechanical properties (a); and microstructure (b) [21, 22]

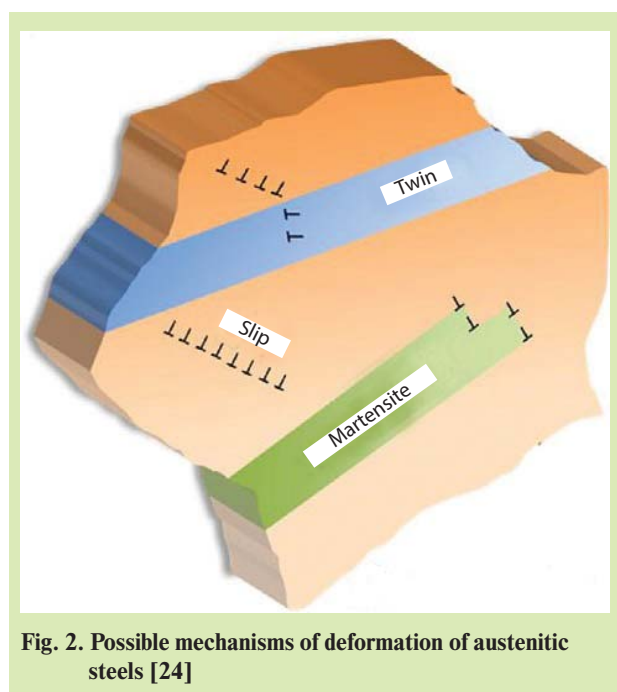


Fig. 2. Possible mechanisms of deformation of austenitic steels [24]

The next stage in the development of AHSS was to preserve the supercooled austenite in the microstructure, which can turn into martensite in the process of plastic deformation, thereby providing a more even elongation which leads to the formation of the neck, i.e. the effect of increased plasticity caused by the transformation [6]. To obtain such a microstructure it is necessary to pay more attention to both the chemical composition and the heat treatment modes compared to DP and simple pre-eutectoid steels. The growing interest in TRIP steels led to numerous studies aimed at correcting the chemical composition and production technology, which contributed to an increase in the strength characteristics of steel from 590 to 980 MPa [7-9].

However, TRIP steels are not the final stage of the development of AHSS. To improve the properties, there were developed steels in who's structure of ferrite was replaced by bainite (Carbide-Free Bainitic - CFB) and martensite (Quenching and Partitioning process - Q&P) while maintaining a certain amount of supercooled austenite [10-13].

In the first case, austenite does not completely turn into bainite during isothermal treatment, while it is necessary to slow down the kinetics of bainite transformation due to greater alloying with manganese. In the process of partial extraction of bainite, carbon is redistributed and the remaining supercooled austenite is saturated with it. When a certain amount of bainite is released, the carbon concentration in austenite becomes sufficient to block the martensitic transformation during subsequent cooling. The structure of such steels at room temperature consists of bainite and metastable austenite, prone to transformation into martensite in the process of deformation.

In the second case, to form the structure of high-strength steels they are quenched from the fully or partially austenitic state to a temperature higher than the temperature of the end of the martensitic transformation, and then isothermally exposure at a temperature above the beginning of the martensitic transformation. At the same time, excess carbon diffuses from martensite into residual austenite, stabilizes it and prevents decay during subsequent cooling [10, 14-16].

Further development of AHSS is the development of steels with a manganese content of up to 10%, which is necessary to improve the qualitative and quantitative characteristics of supercooled austenite, including the possibility of preserving metastable austenite in the structure in an amount of up to 50 % [17-20].

Depending on the tensile strength and total elongation of AHSS steels of various grades can be presented in chart depending on their mechanical properties (Fig. 1, a), with classification by microstructure (Fig. 1, b) [21, 22].

Influence of the stacking-fault energy

The main types of deformation mechanisms of austenitic steels are transformation-induced plasticity (TRIP), twinning (TWIP) and dislocation slip (SLIP) [23]. The particular deformation mechanism is determined by stacking-fault energy (SFE) of the solid solution (Fig. 2).

The transformation of $\gamma \rightarrow \epsilon$ -martensite is possible if the deformation of austenite with SFE values is less than 16–20 MJ/m². Deformation twinning occurs if the value of the SFE lies in the range of 19–48 MJ/m². The change of the deformation mechanism to dislocation occurs at values of the SFE above 48 MJ/m². The stacking-fault energy depends on several factors, the most significant of which is the chemical composition of the alloy. It is also worth noting that the elements that make up austenitic steels, according to the degree of influence on SFE are divided into two types: elements increasing and decreasing its value. It is also known that the stacking-fault energy of austenitic steels is in direct ratio to the deformation temperature, and the grain size of austenite is in invers ratio [25, 26].

The mechanism of TRIP transformation

When supercooled (metastable) austenite is deformed, it can turn into martensite if critical stress or deformation is reached. However, the deformation must be carried out in a certain temperature range, i.e. below the critical temperature MD (the maximum temperature at which the deformation transformation of austenite–martensite is possible) and higher than the temperature MS (the temperature of the beginning of the martensitic transformation). The TRIP phenomenon implies that the local transformation of metastable austenite into martensite hardens exactly the part of the material where this transformation occurs, thereby preventing further localization of deformation in this area (Fig. 3). With further deformation, transformation and hardening occurs in another local area, which provides a very high rate of deformation hardening simultaneously with a high even elongation of the material [27–30].

Based on the temperature range, several conditions must be met during the production and operation of TRIP steels. Firstly, the MS temperature should be below room temperature. Secondly, the amount of carbon in supercooled austenite should be about 1% or more despite the fact that the total amount of carbon in steel is significantly less [4].

The temperature of the beginning of the martensitic transformation depends on the chemical composition and for TRIP steels can be estimated by the following mathematical expression:

$$MS = 539 - 423 \cdot C - 30.4 \cdot Mn - 7.5 \cdot Si + 30 \cdot Al \quad [31]$$

The enrichment of supercooled austenite with carbon in low-alloy steels is possible during certain phase transformations.

The first transformation is the separation of ferrite during isothermal exposure in the two-phase region; the second is

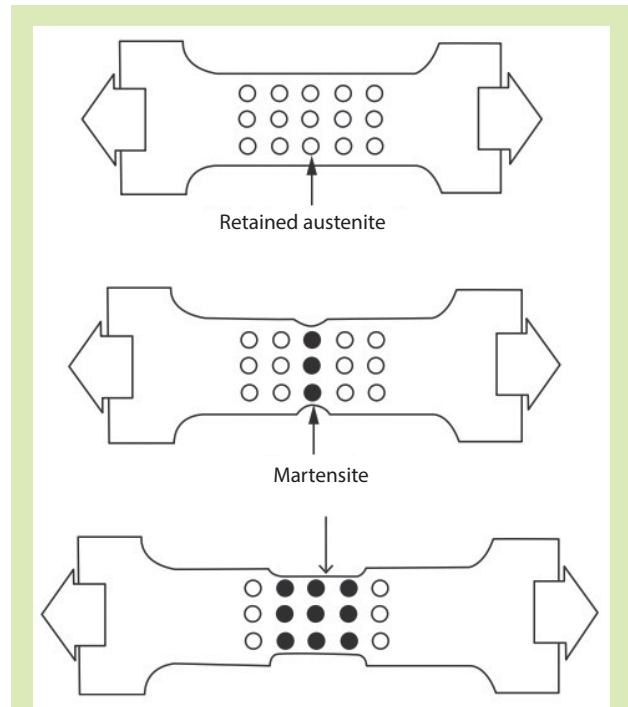


Fig. 3. The mechanism of TRIP transformation of supercooled austenite [27]

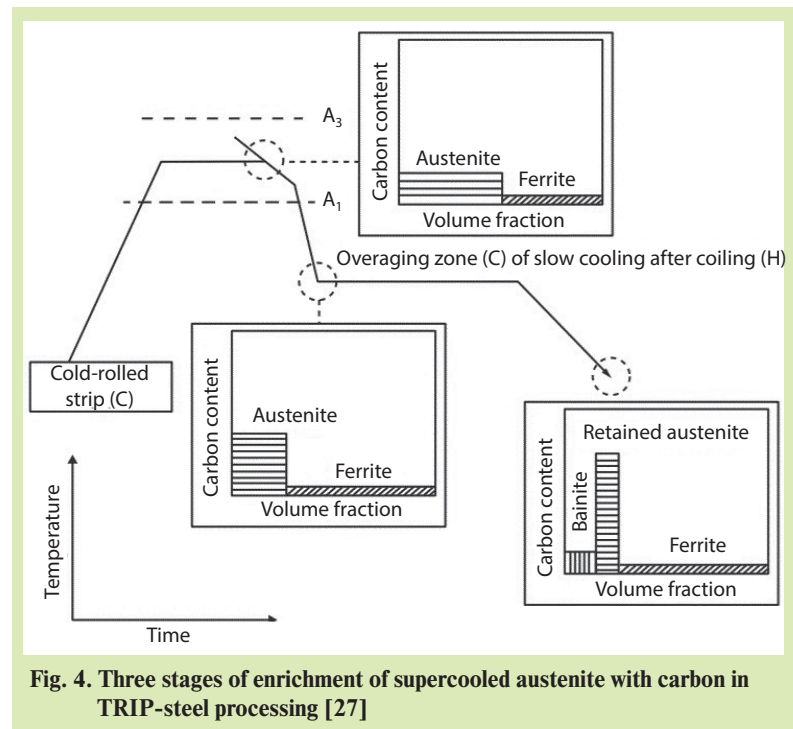


Fig. 4. Three stages of enrichment of supercooled austenite with carbon in TRIP-steel processing [27]

the partial transformation of supercooled austenite into ferrite during monotonic cooling below A₁ temperature [32]; the third is the partial transformation of supercooled austenite into bainite (Fig. 4) [27, 33].

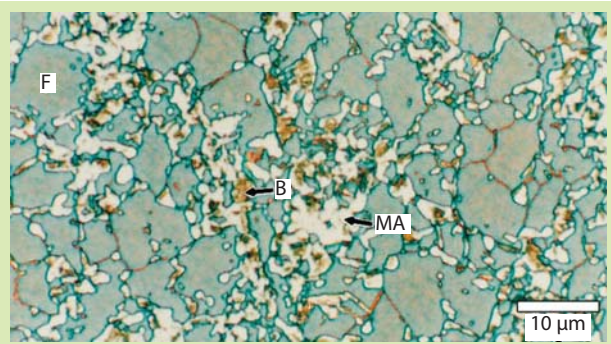


Fig. 5. The microstructure of TRIP-steel [5]

Before the separation of both ferrite and bainite, austenite contains a greater amount of carbon than the ultimate solubility of the released phases, therefore diffusive redistribution and carbon saturation of austenite occurs. It is also worth noting that strong ferrite stabilizers must be introduced into the chemical composition of TRIP steels, which is necessary for the formation of "low-carbon" bainite preventing potential carbon losses in austenite [16].

Heat treatment

The properties of TRIP steels depend on the structural state of ferrite and the volume fraction of the remaining metastable austenite, its morphology and its carbon content. The main goal of heat treatment is the complete dissolution of cementite and carbon enrichment of austenite; recrystallization or restoration of the original ferrite.

Isothermal annealing in the two-phase region should be carried out at temperatures close to A1 to form the maximum possible amount of "low-carbon phase" - ferrite. If the annealing temperature is close to the A3 temperature, then the maximum amount of austenite remains in the structure. However, the amount of carbon in austenite will decrease. It should also be taken into account that the higher the temperature is, the faster and more complete the process of dissolution of the carbide phase is. A decrease in the annealing temperature will contribute to a greater saturation of austenite with carbon and its resistance to decay in the process supercooling, therefore, the bainite reaction during isothermal exposure may be delayed if the stability of the initial austenite is too high [34].

Since the main alloying elements of TRIP steels are silicon and aluminum, which shift points A1 and A3 to the region of higher temperatures, annealing at higher temperatures is required [35, 36].

In addition to temperature, the completeness of phase transformations during the annealing is also affected by the exposure time and the cooling rate. The longer the isothermal exposure in the two-phase region is, the more complete the phase transformation is. When the cooling rate decreases from the annealing temperature to temperature A1, more ferrite is released, which leads to additional saturation of austenite with carbon. The second isothermal expo-

sure occurs in the temperature range of bainite extraction. The temperature is chosen as close as possible to the temperature of the lowest stability of bainite and depends on the alloying of steel. The temperature of the second isothermal exposure is about 400 °C. Exposure at high temperatures of the bainite region stimulates the formation of cementite in TRIP steels. Another important factor in isothermal exposure in the temperature range of bainite transformation is the exposure time. The longer the exposure time is, the greater the degree of completion of the bainite transformation is, the smaller the amount of supercooled remaining austenite is. As the bainite transformation develops, the amount of high-carbon metastable austenite increases until it reaches a maximum [37-41]. In this case, the bainite transformation is accompanied by a decrease in the temperature of the MS of the supercooled austenite remaining in the structure, and the possibility of quenching martensite formation during further cooling gradually decreases. With sufficient enrichment of austenite with carbon, the temperature of MS decreases below room temperature. This contributes to the formation of a microstructure containing ferrite, bainite and supercooled austenite, stable at ambient temperature [12, 32, 42].

If the isothermal exposure is too long, the amount of metastable austenite in the structure of TRIP steels begins to decrease due to the release of the carbide phase in the bainite, which leads to the depletion of austenite with carbon and a decrease in its resistance to decay during further cooling [43-45].

Phase composition

Basically, the microstructure of TRIP steels consists of 50-55% ferrite, 30-35% bainite and 7-15 metastable austenite. In addition to these phases, the structure of TRIP steels may also contain a certain amount of martensite (2-3 %) (Fig. 5) [5, 46, 47].

Austenite. An important factor is the stability of supercooled austenite, which depends both on the carbon content in it and on the size of its inclusions, since the TRIP effect implies the transformation of metastable austenite into martensite, occurring in a sufficiently large range of tensile deformations, with a simultaneous delay in the formation of the neck. If the supercooled austenite is not stable enough, then its transformation into martensite during deformation occurs without any noticeable effect on plasticity. On the other hand, if the inclusions of supercooled austenite are too small and at the same time stable, then the transformation into martensite does not occur during deformation, therefore, the TRIP effect does not occur [45].

According to morphological features, austenite inclusions can be divided into two types: "film" inclusions - with a thickness and length of ~20 and ~200 nm, respectively, and equiaxed grains with a diameter of 1~2 μm. "Film" inclusions are usually located between bainite sites, while globular supercooled austenite is located near or inside ferrite grains [4, 23, 27]. At the same time, they have different

resistance to decay: "film" austenite begins to transform into martensite later than globular austenite [48].

Ferrite. For maximum plasticity of TRIP steels, it is necessary that their structure should contain recrystallized equiaxed ferrite grains (~10 μm), which contributes to minimal localization of deformation near the phase boundaries. The ferritic phase with a relatively large grain size and low hardness provides better elongation and formability compared to the bainite microstructure [4, 23, 27, 49].

Bainite. The presence of "low-carbon" or "ferritic" bainite in the structure of TRIP steels is the most rational. However, as a result of isothermal exposure at low temperatures of bainite transformation or insufficient exposure time, the formation of lower bainite with a high carbon content is possible [38, 39].

Martensite. The amount of martensite in the structure of TRIP steels depends on their yield strength. The presence of martensite in the structure after cooling from the temperature of isothermal exposure in the bainite transformation interval suggests that austenite has not been sufficiently enriched with carbon, therefore the MS temperature of such supercooled austenite is higher than room temperature. To improve the properties of TRIP steels containing martensite in their structure, it is possible to use low (~ 200 °C) tempering, at which additional enrichment of metastable austenite with carbon and relaxation of residual stresses occurs [50, 51].

Factors affecting the stability of austenite

The factors affecting the stability of austenite after isothermal exposure can be listed in the following order: chemical stability of supercooled austenite due to the amount of carbon; the alloying of austenite; grain size of metastable austenite [52].

In TRIP steels containing 1.5 % manganese and silicon, with an increase in the carbon content in supercooled austenite from 1.0 to 2.0 %, the temperature of the beginning of martensitic transformation decreases from 200 to 35 °C, and the dependence itself has an exponential character (in degrees K) [53]:

$$M_s = 273 + 545,8 \cdot e^{-1,362 \cdot C}$$

The amount of carbon in supercooled austenite can be influenced by alloying. When TRIP steels are alloyed with silicon alone, the maximum amount of carbon in the re-cooled austenite reaches a value of ~ 1 %. In steel with the addition of aluminum, this value approaches ~1.6 %, which causes a higher stability of supercooled austenite in the process of deformation. It should also be taken into account that excessive alloying of austenite in order to suppress ferritic and pearlite transformations is undesirable, since such alloying also slows down the intermediate transformation [27].

The MS temperature is strongly influenced by the grain size of metastable austenite. When the grain size decreases,

the temperature decreases significantly. On the other hand, too small austenite grains may have high stability to decay, which prevents the effect of transformation into martensite in the process of deformation [45].

Alloying

The most important role of alloying TRIP steels is to increase the hardenability of the γ-phase and to prevent the formation of perlite during initial cooling from the intercritical temperature to isothermal exposure in the bainite region in such a way as to preserve and ensure the necessary kinetics of bainite formation and proper enrichment of the remaining austenite with carbon to reduce MS below the room temperature. Thus, alloying elements can be divided into several main groups, such as ferrite-stabilizing elements, elements that increase the stability of supercooled austenite and micro-alloying elements [4].

The influence of ferrite stabilizing elements

The presence of silicon, aluminum and other ferrite stabilizers in TRIP steels is necessary to suppress the formation of carbides during bainite transformation, which allows the maximum possible amount of carbon to be preserved in supercooled austenite [13].

Silicon. It is the main element in TRIP steels, which makes it possible to store supercooled austenite in the structure at a relatively low carbon content. Silicon additives contribute to the enrichment of supercooled austenite with carbon and, thus, influence the stability of austenite, which leads to an increase in the amount of metastable austenite. If a content of silicon is 1%, the release of carbides is greatly delayed in the structure of bainite. The release of carbides in bainite is delayed due to a shift of this release to the range of higher temperatures. At the same time, there is an increase in the amount of supercooled austenite with the preservation of carbon content in it. It is also worth noting that silicon increases the time of the bainite transformation, which requires a longer exposure during isothermal exposure [54, 55].

Aluminum. Similarly to silicon, it suppresses the process of release of carbides during the intermediate transformation. According to some calculated data, it contributes to a more intensive release of ferrite during cooling after annealing in the two-phase region. Aluminum reduces the tendency to pearlitic transformation and slightly reduces the incubation period during bainitic transformation [56, 57].

The influence of elements that increase the stability of supercooled austenite

Carbon. It is the most powerful element that increases the hardenability of austenite. An increase in the carbon content also reduces the transition temperature from upper to lower bainite, and also controls the amount of initial austenite in the process of annealing in the two-phase region of TRIP steels. The negative effect is manifested in a strong slowdown in the kinetics of bainitic transformation, as well as a deterioration in weldability [4, 13, 27].

Manganese. Manganese prevents the formation of perlite, allowing it to cool down more slowly from the annealing temperature, reduces the MS temperature, but slows down the formation of bainite. Manganese increases the strength of steel due to solid hardening. Excessive manganese content hinders ferrite formation and reduces the enrichment of austenite with carbon in the process of initial cooling [58].

Molybdenum. Depending on the concentration, it has a different effect on the forming structure of TRIP steels. In small quantities it acts as a stabilizer of austenite; in large quantities it acts as a stabilizer of ferrite. At the concentrations used in the alloying of TRIP steels, molybdenum slows down ferritic and pearlite transformations and reduces the temperature interval of the intermediate transformation.

The influence of micro-alloying elements

Niobium. Niobium accelerates the process of austenite decomposition, contributing to the formation of ferrite during cooling after annealing, which should contribute to the initial stage of enrichment with the carbon of the γ -phase. Niobium additives delay the formation of bainite, which is explained by the blocking of the nucleation sites by fine carbonitrides and the enrichment of austenite with carbon due to the formation of more ferrite during cooling after annealing. Niobium also reduces the average grain size of austenite, which complicates its shear transformation into martensite and strengthens ferrite [4, 48, 59, 60].

Vanadium. It refers to elements that do not influence the amount and stability of supercooled austenite. At the same time, the strength of TRIP steels increases due to solid-solution hardening [4, 61, 62].

Destruction of TRIP-steels

These steels have a unique high energy absorption potential, which can be decisive when choosing these materials for the production of certain parts and structures. Despite the transformation of metastable austenite into high-carbon and, consequently, brittle martensite, the tendency of steel to cracking does not manifest itself under certain microstructure parameters. The determining factor in this case is the size of martensitic inclusions in the austenitic-martensitic structure: small inclusions separated by a layer of partially preserved supercooled austenite do not crack. A distinctive feature of TRIP steels is also that during dynamic loading, the yield strength increases with a one-time preservation of the hardening effect, as with static loading. All this allows steels to absorb more energy regardless of the speed and degree of deformation.

TRIP steels show greater resistance to fatigue failure under conditions of cyclic alternating loads compared to two-phase steels of the corresponding strength class. At the same time, changes in the structure are reduced to a gradual partial transformation of metastable austenite into martensite, and the high fatigue limit of steel can be explained by a slowdown in the propagation of microcracks due to the presence of compressive residual stresses caused by this transformation [4, 27, 63].

Prospects for the use of TRIP steels

One of the promising areas of application of TRIP steels are additive technologies due to the huge range of products created in this area of production. In comparison with the classical production of rolled steel sheets containing metastable austenite in the structure, additive manufacturing is characterized by the possibility of more flexible control of the production technology and the operational characteristics of the product itself. Another advantage of additive technologies over "classical" ones is that it is not necessary to carry out pressure treatment of sheet steel to give the final shapes of the product, which is carried out at certain temperatures, which affects the technology as a whole, limiting it in a certain way.

The prospect of using TRIP steels in additive manufacturing allows the manufacturer to control a large number of technological parameters with simultaneous localization of mechanical properties and the possibility of subsequent self-adaptation of products to external influences. At the same time, additive technologies make it possible to fully realize the potential of steels prone to deformation phase transformation due to controlled structure formation at the production stage, thereby making it possible to manufacture parts with a gradient structure and a high complex of operational properties.

The most relevant is the use of TRIP steels parts in difficult operating conditions characterized by uncontrolled shock and pulse loads, as well as intense wear, which includes aerospace industry. Also, the high potential for the use of metastable steels can be realized at the stage of product design by controlling the localized strengthening of individual elements. For example, it becomes possible to locally and significantly strengthen potentially more loaded elements such as threads, chamfers, bends, etc. Moreover, almost all industrial processes of manufacturing products using additive technologies have a large number of controlled technological parameters (temperature, speed, strain rate, combination of various loading schemes and methods of different physical nature), which allows manufacturer to flexibly control the localization of mechanical properties. The previously described experience of using TRIP steels in the fields of passive transport safety allows us to assert the high efficiency of such solutions for the development of the industry.

The use of TRIP effect steels beyond the passive safety of cars opens up broad prospects for the creation of self-adapting steel billets for the aerospace industry. At the same time, these billets will have technological flexibility, allowing them to be used for a wide range of products with high variability of operational characteristics. The features of metastable steels billets will make it possible to create elements of critical structures with complex shapes of the entire product and its individual elements. The increased plasticity of metastable steels will make heat treatment unnecessary for individual technological operations, which will also reduce the cost of production. The ability to adapt to the effects of the operational environment will signifi-

cantly reduce the wear and repair of equipment and structures. At the same time, due to the preservation of strength properties, it will be possible to reduce the weight and metal consumption of structures. Also, the increased plasticity of the billet will also reduce the wear of the technological tool in the production process, and its strength properties will allow the manufacturer to abandon medium- and high-carbon steels for individual structural elements [64–72].

It is also worth noting that the increased plasticity of metastable steels contributes to a partial or complete reduction of intermediate thermal processing operations and, as a result, a reduction in the cost of production. The increased strength of TRIP steels reduces the metal consumption of products.

The concept of using TRIP steels in additive manufacturing has been formed relatively recently, and the research of several scientific teams has been devoted to its development [73–75]. Summarizing the data obtained, the following conclusions can be drawn:

- in order to introduce TRIP steels into the 3D printing industry it is necessary to modify of their chemical composition;
- due to changes in the technological parameters of additive manufacturing, a local influence on the processes of structure formation becomes possible (a change in the amount of supercooled austenite, the formation of the necessary texture).

Conclusion

Currently, TRIP steels are thoroughly studied from the point of view of a material widely used in the auto manufacturing due to a unique set of properties, which gives an advantage over other materials used in the auto manufacturing. However, such a combination of operational properties is also in demand in other industries, due to a possible reduction in the metal consumption of products while maintaining the necessary strength properties. Reducing the weight of parts is most relevant for the aerospace industry, in which additive technologies are also widely used to produce durable and lightweight structural elements.

Thus, it can be concluded that the use of TRIP steels as a material in additive manufacturing is relevant for both aerospace and auto industries. The use of TRIP steels allows the manufacturer to create parts with a unique set of properties, primarily with high structural strength, low weight and the possibility of self-adaptation to extreme external influences.

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