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DEVELOPMENT OF ADVANCED HIGH-STRENGTH STEELS USED FOR AUTO-BODY PARTS

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РОЗВИТОК СУЧАСНИХ ВИСОКОМІЦНИХ СТАЛЕЙ, ЩО ВИКОРИСТОВУЮТЬСЯ В КОНСТРУКЦІЇ АВТОМОБІЛЬНИХ КУЗОВІВ

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INTRODUCTION

Currently, different grades both of deep drawing quality steel and high strength low alloy steel are commonly used materials to manufacture the car bodies [1, 2]. The replacement of soft steels with higher strength steels allows to use thinner sheets. In fact, recently the weight of the vehicle is kept at a constant level because the weight reduction resulting from the use of thinner high strength steel sheets is balanced by additional equipment of cars, mounted in order to improve safety, comfort and so on. The world steel industry reacted to the lightweigthing challenge by launching the Ultra-Light Steel Auto Body - Advanced Vehicle Concepts (ULSAB-AVC) project with the aim the mass savings of 25 % over the benchmark without almost any cost penalty by using of approximately 10 % of advanced high strength steels (AHSS) in the body-in-white [3]. This project has triggered an extensive development of novel steel grades with predominantly higher strength at an appropriate formability, which successfully continues up to now.

The several properties should be primarily be taken into account in terms of the automotive industry [4]:

– mechanical properties, primarily the so-called high specific strength (the ratio of the ultimate strength of the material to the their density), that can reduce the weight of the vehicle,

– high absorbing energy capacity in the event of a collision,

– properties that minimize technological problems in manufacturing and ensure high productivity, in particular: the deformability (stamping of panels, bending, hydroforming, etc.) and ease of application of the coatings (Zn and Al coatings, varnishes), and furthermore, good weldability,

– operating features (high fatigue strength of the material and welds, low susceptibility to corrosion, easy replacement of components),

– economic considerations,

As a result, the steel industry is seeing unprecedented growth in AHSS automotive applications. Independent marketing research suggests that they are the fastest growing materials for future automotive applications [5].

The characteristics of Advanced High-Strength Steels and Transformation/Twinning Induced Plasticity steels with the examples of their applications in auto-body parts is presented in the paper.

The groups of steel for the automotive industry

According to the classification of steel for the automotive industry can be classified into three basic groups (fig. 1) [4]:

– soft and plastic low-carbon steels such as Drawing Quality Special Killed (DQSK) and Interstitial Free (IF) steels characterized by the tensile ultimate strength R_m of less than 300 MPa and a total elongation in a range of 30 to 60%,

– conventional high-strength steels such as Bake Hardenable (BH), Carbon Manganese (CMn), and High Strength Low Alloy (HSLA) characterized by 300 < R_m <700 MPa and the reduced value of total elongation compared to the previous group,

– advanced steels with very high strength (R_m above 700 MPa, even up to 2000 MPa) and elongation contained in a fairly wide range of 5÷30%, the increase in strength of these steels goes hand in hand with a reduction in plasticity.

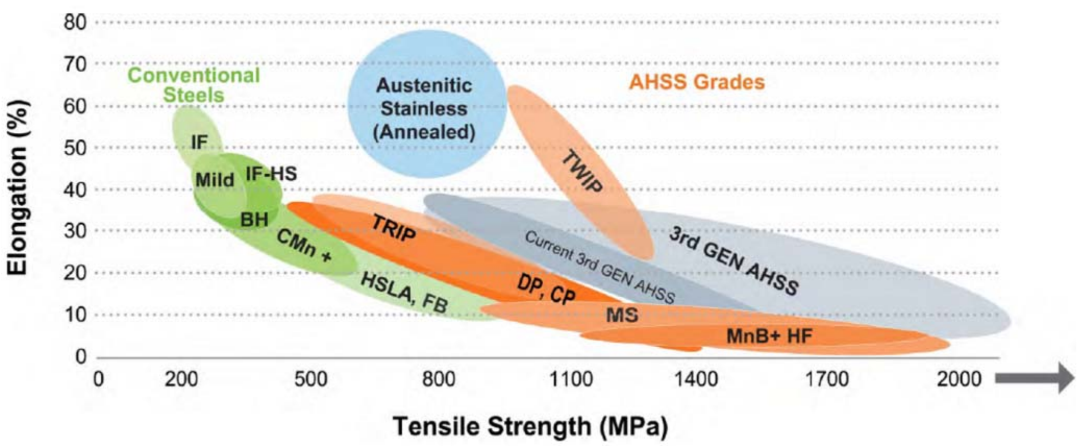

Fig. 1. Classification of steel used in automotive industry [5]

The 2010 Mercedes E-Class claims industry leadership in the utilization of 72 percent High-Strength Steel in its body structure, compared to just 38 percent in the previous model [5]. Seventy-five percent of these steels have yield strengths greater than 180 MPa, helping to achieve a structure that is lighter weight and 30 percent more rigid. Figure 2 presents the material usage for the E-Class.

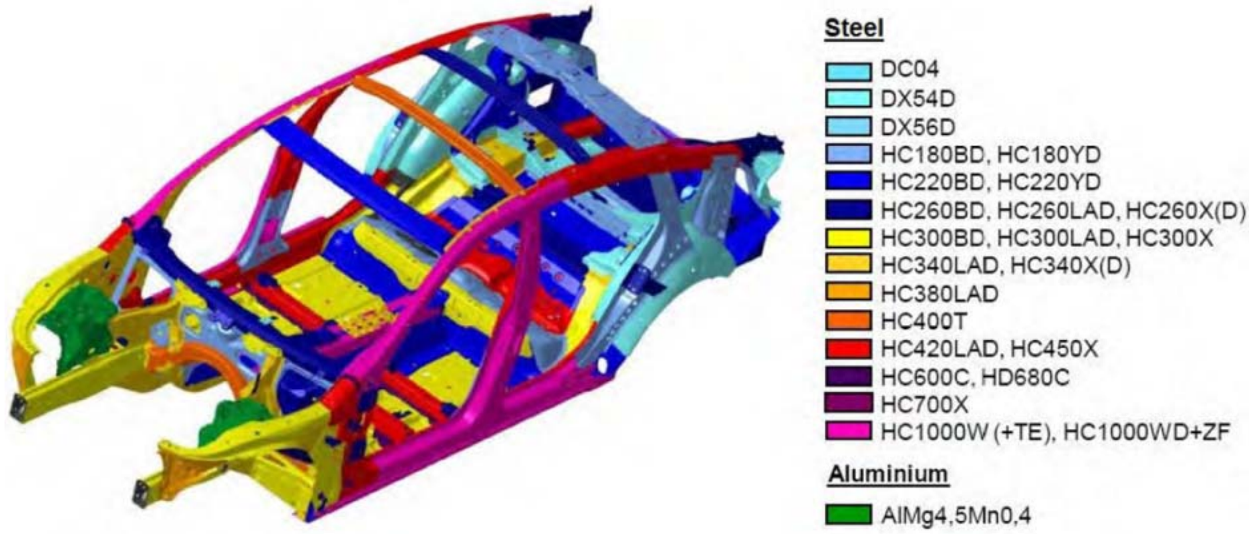

Fig. 2. Mercedes E-Class material usage [5]

HIGH-STRENGTH STEELS

The group of high-strength steels includes high strength interstitial free steels (IF), bake hardenable (BH) and isotropic (IS), steels C-Mn type steels, and high strength low alloy (HSLA) steels. The IF steel is further solution hardened by the increase in concentration of P (to 0.03%), B (to 0.003%) and Mn (1.2%). Its tensile strength can reach 390 MPa [6]. BH steel is silicone free steels containing less than 0.03% C, 0.1-0.5% Mn and up to 0.02% Nb. The concentration of phosphorus is often increased up to 0.03%, that cause an increase in strength and the coefficient of normal anisotropy of sheet [7]. Besides the strain hardening phenomenon during plastic deformation the car components made of BH sheets (e.g., a door, a boot lid) reinforce during „bake hardening” effect. This effect usually proceeds at the temperature of 170°C for 20 min, thereby the yield stress and ultimate tensile stress increased by about 20 to 40 MPa [1]. BH steel sheets are characterized by $R_{p0,2}$ yield strength 180 to 240 MPa, ultimate tensile stress R_m of 310 to 360 MPa, elongation A in a range between 42 to 36% and a normal anisotropy coefficient of about 1.6 [8].

Normally the tendency to strain hardening during bake hardening is determined as follows: typical sample is extended by strain of 2%, then the sample is withstand at 170°C for 20 minutes and then the tensile test is continued [9]. The increase in yield stress upon bake hardening process equal to the difference between the lower yield stress after baking at 170°C and a flow stress at deformation of 2% (prior to annealing) is called hardening during bake hardening or aging indicator during the bake hardening. Strain hardening during the bake hardening is useful, if an increase of yield stress is greater than 30 MPa (Fig. 3).

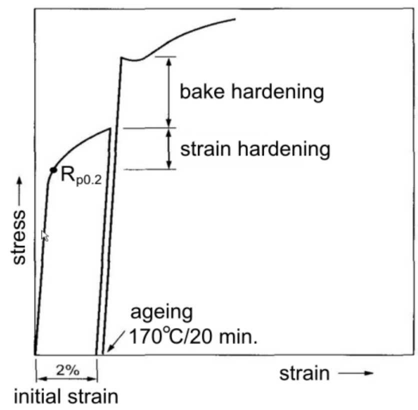

Fig. 3. Effect of bake hardening on the stress value [9]

IF steels have the chemical composition and mechanical properties similar to IF-HS steels (Fig. 1). They are characterized by a ferritic microstructure, and their characteristic feature is the value of planar anisotropy coefficient Δr = 0. This means that the steel sheets exhibit isotropic properties during the drawing process, allowing to obtain the drawpiece without "ears" [1]. The traditional C-Mn steels exhibit ferrite-pearlite microstructure, and typically contain less than 0.1% C and 1.5% Mn.

Complex Phase steels

CP steels contain the fine ferrite, bainite, martensite and retained austenite. They are usually hot-rolled and further hardened by the dispersed particles of carbonitrides of Nb and Ti. An increase in the hardenability is provided by the addition of Cr and Mo. CP steels exhibit particularly high susceptibility to absorbing energy under dynamic loads [10]. These steels are used to construct the bumpers as a specific reinforcement, on which both the expanded polystyrene pads and plastic plates are mounted [11].

DUAL PHASE STEELS

DP steels are characterized by high initial difference in yield stress and ultimate strength that during the cold working is quickly reduced. Properties of DP steel, that is a specific type of composite, are the resultant of the participation of hard and durable martensite and ductile ferrite. The dual phase steel does not exhibit the Lüders effect during deformation. Furthermore, the other positive properties are crack resistance to low temperature and low value of plastic anisotropy coefficient [4, 12]. These steels are used as pipes in prams or bikes frames. Furthermore, DP steels increase safety in cars, where is used as bumpers reinforcements, seats guides, child seats, and windscreen pillars [11]. Thanks to the high strength and high hardness that affects wear resistance, the clutch plates are also made of DP steel.

In DP steels, for a fixed volume fraction of M-A constituents, both applied stress and the work hardening rate at a given true strain can be related to the average size of M-A particles (f_{MA}) by the Hall-Petch type equation. Frequently cited expressions, for f_{MA} = 0.2, were developed by Lanzilotto and Pickering [13]:

$$\sigma_{f(\varepsilon=0.2)} = 350 + 18.1 \cdot \lambda^{-0.5} \quad (1)$$

$$\frac{d\sigma}{d\varepsilon_{(\varepsilon=0.2)}} = 40.1 \cdot \lambda^{-0.5} \quad (2)$$

where λ is the average size or diameter of M-A particles.

The variation of stress as a function of martensite content in DP steels has been frequently modelled on the basis of the rule of mixtures, applying the continuum mechanics models [13]:

$$\sigma = V_m\sigma_m + (1 - V_m) \cdot \sigma_f \quad (3)$$

where σ_m, σ_f, σ are the stresses of the martensite, ferrite and composite structure respectively.

Low-alloy Transformation/Twinning Induced Plasticity steels

Modern low-alloyed TRIP steels have different chemical compositions. The amount of alloying elements composition equals to some % wt. The carbon content is critical, and in these steels usually comprising in the range of 0.10 ÷ 0.25%. The steels with higher amount of carbon content, to 0.6% C, despite the beneficial effects on the structure (bainite and austenite is formed), these steels have not found wider application due to the significant worsening of weldability [14, 15].

In order to achieve a superior combination of strength and ductility, which allows engineers to design complex car parts where even parts integration has become possible, Twinning Induced Plasticity, and Duplex/Triplex steels were developed by the steel industry [16]. As the consequence of that, the plastic deformation is characterized by the pronounced dislocation glide and the dissociation of perfect dislocation to Shockley partial dislocations and formation of wide stacking faults.

The chemical composition of the TWIP steel is characterized by a high content of manganese (15 to 35%). The constitution of other alloying elements comprising from 2 to 4 % Al and/or Si. TWIP steels have a face-centered cubic (fcc) crystal structure of the austenite constituent [3]. These steel grades have a medium to high total alloying additions, and they have a manganese concentration comprising from 12 wt.-% to 35 wt.-%. The high content of Mn stabilizes austenite at room temperature. A fully austenitic structure without martensite and other phases exhibits high toughness and drawability. Twinning occurs at high strain speeds.

During forming the steel sheet is deformed and strain hardened locally, and passes the rest energy to the next region of material. The effect of strain hardening causes that yield stress value increases with the rate of deformation. In this way, the deformation by twinning moves in the form of a specific wavelength, scattering, and absorbing efficiently the impact energy [17]. Deformation by twinning occurs in the case of alloys with low stacking fault energy, and TWIP steels satisfy this criterion [17, 18].

MARTENSITIC STEELS

Martensitic (MART) steels exhibit the martensitic microstructure and these steels sometimes contain a small proportion of the bainite and/or retained austenite. They have the highest mechanical properties, that depend mainly on the content of carbon steel. Martensitic steels are based on fully martensitic microstructures, leading to high levels of strength, but these materials perform poorly on elongation [19]. Due to the elongation of less than 10% their plastic deformation is only possible in the rolling process [6]. The MART steels are almost entirely martensite, and can have tensile strengths up to 1700 MPa [20] These steel sheets are used for reinforcing members as the ultra high-tensile steel exceeding the 980 MPa class, for responding to the trend of higher strength [21].

MECHANICAL PROPERTIES OF AHSS STEELS

Automotive forming methods usually consist of a sequence of individual forming operations [22]. Figure 4 defines the basic forming operations such as deep drawing, stretching, stretch flanging, and bending. Each forming mode has additional demands with regard to specific mechanical parameters like the Lankford parameter (r-value), work hardening coefficient (n-value) and hole expansion ratio (γ-value). These parameters are strongly related to microstructural features of the material and, hence, they can be influenced by niobium microalloying in combination with a suitable processing strategy [22].

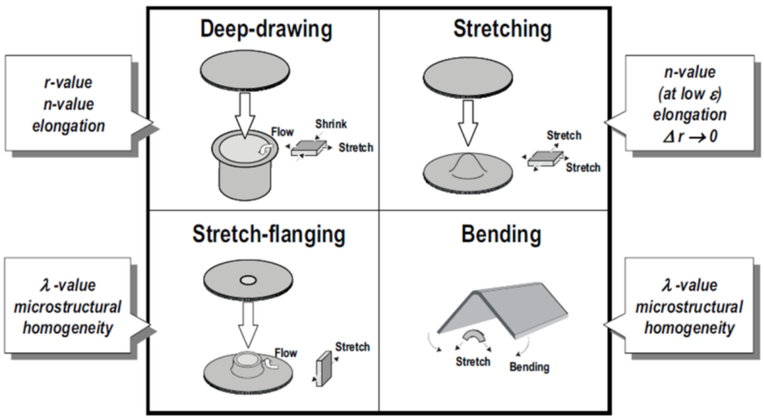

Fig. 4. Different modes of sheet metal forming and characteristic material properties influencing the forming behaviour [22]

Depending on the load characteristics and the design criteria materials with optimal ratios E/ρ, G/ρ and $R_{p0.2}$/ρ (E - elastic modulus, G - shear modulus, $R_{p0.2}$ - yield stress, ρ - material density) should be used to manufacture car body elements [23]. The value of the exponent n depends on the load characteristics of the element and the constructional criteria and is varied between 0.33 and 1.00. Thus, the coefficient of elasticity, density and yield stress are the main parameters that decide on applications of various grades of steel.

Figure 5 presents the microstructure of selected novel multiphase AHSS steels in comparison with a single phase ferritic ultra-low carbon steel, showing how the complexity of microstructure has led to diversification of mechanical properties [3]. Single ferritic microstructures used in case of mild steels allowed to achieve tensile strengths lower than 350 MPa and elongations from 30–50 % [24]. The mechanical properties of selected advanced high-strength steels are presented in table 1.

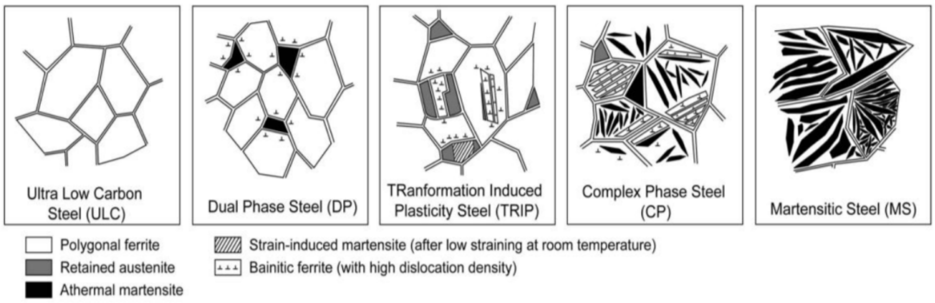

Fig. 5. Microstructure of selected modern steels for automotive industry [3]

Table 1. Mechanical properties of selected advanced high-strength steels [11]

Steel type	Steel grade	$R_{e\,min}$ MPa	$R_{e\,max}$ MPa	$R_{m\,min}$ MPa	$R_{m\,max}$ MPa	A_{80}, %
MART	DOCOL 1100M	860	1100	1100	-	5
	OPTIM 900 QC	900	1000	1050	1150	11
	RAEX 500	1250	-	1450	-	8
	RAMOR 500	1450	-	1700	-	7
	SZMS 1200	900	1050	1200	1450	5
DP	DOCOL 1180DP	830	1220	1180	-	6
	DOGAL 100 DPX	800	1000	1000	1200	6
	DP-K 34/60 HF	340	410	600	700	23
	DP-W 700	450	580	680	800	16
	LITEC 1000DP	600	750	980	-	8
CP	CP-K 60/78	600	700	780	940	10
	CP-W 1000	720	920	950	1130	10
	DOGAL 800CP	500	700	780	950	10
	LITEC 100CP	700	900	980	-	5
TRIP	LITEC 700 TRIP	430	550	690	-	21
	RA-K 40/70	410	510	690	790	23

Particularly the refinement of cementite particles is beneficial to improve the forming behavior [22]. The desired strength level is adjusted by the Nb content (0.02 - 0.05%) and the content of solid solution strengtheners like Mn and Si. To achieve a yield stress of more than 400 MPa additional microalloying of Ti is applied (fig. 6) [22].

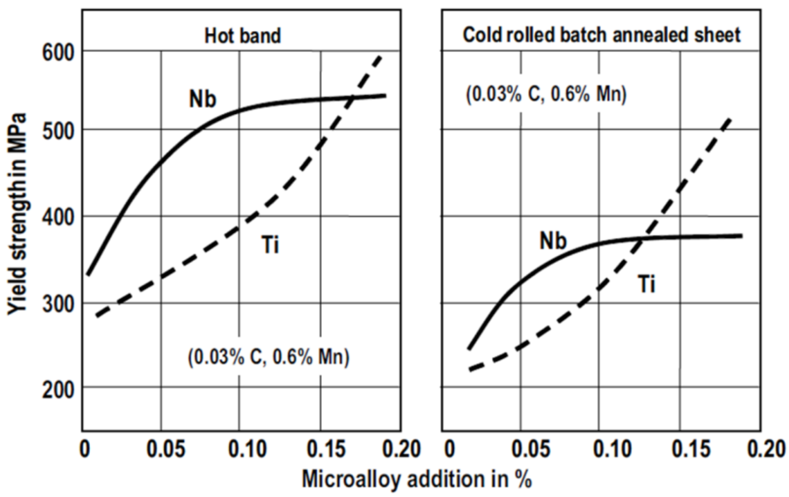

Fig. 6. Strength increase of low carbon-manganese steel by Nb or Ti microalloying [22]

FUTURE DEVELOPMENT

Currently, most energy absorbing elements are manufactured by bending or drawing. During these processes the material is deformed only in the vicinity of the bending line or the drawpiece edge. The analysis of the calculated distribution of strains in the profile after deformation shows that the majority volume of the material has been subjected to deformation in the range of 0.0-0.2 [25]. The utilization capacity of DP, TRIP and TWIP steels for the production of energy absorbing elements occurs when such components are manufactured by the processes of deep drawing or hydroforming. In these processes the initial deformation of the material proceeds so, that during the dynamic deformation the elements that are pre-hardened have a greater ability to absorb energy .

A comparison of the weight reduction potential using different material concepts is shown in figure 7. It is apparent that relative to a conventional steel body the all aluminum body has the highest weight reduction potential, however at a high cost surplus (fig. 7) [22]. On the contrary, an advanced steel body allows reducing the body weight by about 10-20% and simultaneously lowers the body cost by the same order of magnitude.

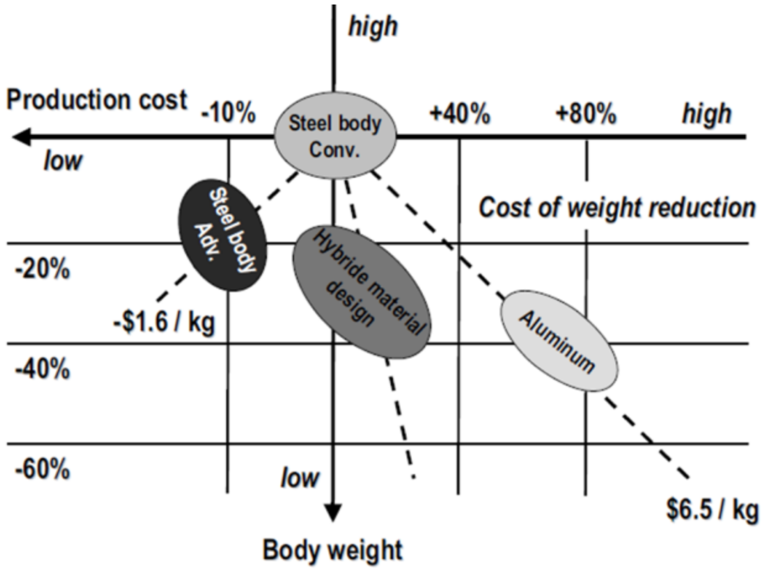

Fig. 7. Impact of material concepts on the weight and cost balance of a car body [22]

SUMMARY

The utilization of energy absorbing structures is one of the most important issues in the development of safer car constructions. They are arranged in the work-hardening zones of cars. Their function during the collision is progressive absorption of energy and maintenance of secure values of loads acting on the passengers. The design of energy absorbing zones is a very complex task, because despite of the knowledge of the overloads during the impact requires the consideration of the geometric conditions resulting from the vehicle structure and properties of materials used. The progress in development of advanced high-strength steels is connected with the introduction into the market high-strength steels, which include DP, TRIP, TWIP, CP and martensitic steels. Furthermore, the conventional high-strength low-alloy steels are successfully used in the construction of cars.

Hybrid body concepts, where for instance the front car is made from aluminium and the remaining structure consists of an advanced steel concept is 3 offering a compromise in the weight reduction to cost balance. Often carmakers are willing to pay a higher cost for weight reduction in the front and upper area of the car to optimize driving performance and handling. In other areas cost increases are less or not tolerated unless the total weight can be significantly reduced.

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ABSTRACT

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Steel sheet is still dominated structural material in the automotive industry despite the implementation in car production such materials as aluminium alloys, magnesium alloys, composite materials and plastics. This paper presents the characteristics of Advanced High-Strength steels and Transformation/Twinning Induced Plasticity steels with the examples of their applications in auto-body parts. The future development of energy-absorbing materials is also presented.

KEYWORDS: AUTOMOTIVE INDUSTRY, HIGH-STRENGTH STEEL, MARTENSITIC STEEL, TRIP, TWIP.

РЕФЕРАТ

ТЖЕПІЦІНСКІ Томаш. Розвиток сучасних високоміцних сталей, що використовуються в конструкції автомобільних кузовів / ТЖЕПІЦІНСКІ Томаш // Вісник Національного транспортного університету. Серія “Технічні науки”. Науково-технічний збірник. – К.: НТУ, 2016. - Вип. 2 (35).

Сталевий лист – домінуючий структурний матеріал в автомобільній промисловості, незважаючи на освоєння у виробництві автомобілів таких матеріалів, як алюмінієві сплави, магнієві сплави, композиційні матеріали та пластмаси. У даній статті представлені характеристики сучасних високоміцних сталей і індукованих пластичних сталей трансформації/роз’єднування з прикладами їх застосування в конструкції автомобільних кузовів. Представлено подальший розвиток енергопоглинаючих матеріалів.

КЛЮЧОВІ СЛОВА: АВТОМОБІЛЬНА ПРОМИСЛОВІСТЬ, ВИСОКОМІЦНІ СТАЛІ, МАРТЕНСИТНА СТАЛЬ, TRIP, TWIP.

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