DESIGN OF THE MOTOR VEHICLES FROM THE ASPECT OF HIGH STRENGTH STEELS APPLICATIONS

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INTRODUCTION

The present motor vehicle industry is focused on developing vehicles with higher safety, reduced fuel consumption, improved reliability by production processes that are more cost efficient. Those demands are opposite by nature with very complex interactions. The partial solution of problems can be accomplished through optimization of design and the continuous usage of newer, lighter and stronger materials. The controls of raw and prefabricated materials, so as their processing technology, come to the focus of testing methodologies. The listed tendencies at the area of motor vehicle industry cause the improvement of existing technologies, so as the development and differentiation of new, advanced methods of elements' joints realizations. In addition, the analyses of demands which are founded in vehicle design, at automotive industry especially, show that modern vehicles have, beside the primary function, numerous and very different additional functions. From the other side, they have to fulfill very strict requirements, which are fundamentally different. The estimated requirements and criterions often have complex system of interactions. All the presented facts must be adequately considered in the process of the vehicles design.

The present materials that are used for modern vehicles are very diverse by nature. From the aspect of design, material selection is one of the most important procedure at the process of the product development.

The bodies of first cars were built mostly of wood while engines were made of iron. Later, with evolution of vehicles, the steel body panels were used on wood frames with steel body panels. At the early years of 20th century the principle of body on frame was used at the current design of the vehicles. Those vehicles had chassis that supported all the parts and the body that was made of steel. Current design uses monocoque body solution especially for passenger cars and small sport utility vehicles. Heavy vehicles like trucks and busses uses the bodies on frames design solutions.

The steel is dominant material for making present vehicles due to specific characteristics and properties. With evolution of steel grades to high strength low alloyed steels and application for vehicles this steel grade become most important material. High-strength steels are the materials that fulfill the requirements for mass reduction, improve energy efficiency, reduced fuel consumption in present vehicle industry without compromising in safety and affordability. The lightweight capability of high-strength steels resulted from theirs microstructure, obtained through highly controlled production processes and combinations of micro alloying elements. Very beneficial combination of strength and ductility of high-strength steels implicate that this steel grade must be considered differently from the other steel grades during design process. This fact is the basis hypothesis for this

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paper. The research shown in the paper is done by relevant literature overview related to this area. The results presented in the relevant literature were analyzed and put into relationship with modern demands in vehicle design. The aim of this paper is to identify the design aspects at vehicles with high-strength steels application. Also, the perspectives of this application are highlight in this paper. The conclusion of investigation presented in the paper is that high-strength steels provide lightweight and environment friendly capability in vehicle design with sustainable prices, remained reliability and even improved safety [16, 2, 3 and 4].

THE BASIC CHARACTERISTICS OF HIGH STRENGTH STEEL GRADES

The high strength steels are developed in order to provide the favorable mechanical properties and higher corrosion resistance in relation to conventional carbon steel grades. Those steel grades are not classified as alloyed steel grades in common manner because its main requirements are defined mechanical properties. The chemical compositions of those steel grades are of less importance. The chemical compositions of those steel grades can even vary in order to ensure the homogeneity of mechanical characteristics by those variations. The high strength steels are usually produced as sheets and plates with low carbon content (0.05% to 2%), while manganese content is not higher than 2.0%. The sheets and plates are characterized by an extremely uniform surface and homogeneous microstructure across the entire cross-section. Those steels also contain small amounts of nickel, molybdenum, copper, nitrogen, vanadium, niobium, titan, zirconium and boron. By this combination of allying elements and their quantities, the proper weldability and deformability are obtained. Also, high strength steels are suited to different cutting techniques. This is achieved through highly controlled production processes special alloy design and a high degree of purity with respect to non-metallic inclusions. The production technologies are designed to minimize residual stresses and to avoid deformations [17 and 14].

The technological production process conditioned its microstructure and by that also conditioned its properties. The nature of microstructure of high strength steels, so as theirs characteristics must be considered adequately in design process. The microstructure of low alloyed high strength steel is typically fine grained after the production processes and consisted of fine ferrite (α) grains with uniformity of shapes. In addition, the small amounts of cementite is present in microstructures of those steels, so as fine dispersed particles of carbon nitride (Fig.1.) [17].

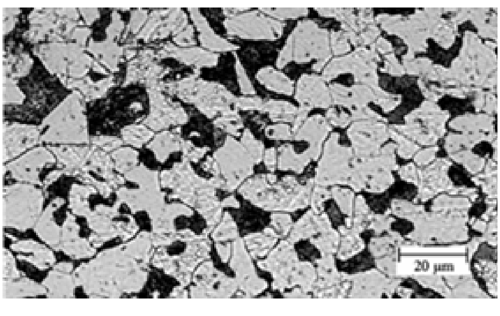

Fig.1: *Typical microstructure of high strength steels [17]*

During the final rolling process, the favorable conditions for creation of the large numbers of referent locations within the distinct formation of α metal grains. The locations, where energy level for formation of α metal grains, are dislocations, the grain binderies and sub-grains, duplicated grains, the deformation lines. The density of those locations in micro structure of those steels is the consequence of production process and level of its deformation during the production. As consequence of production process at high temperatures, the effects of microstructure regeneration are present, such as recuperation and recrystallization.

During production process of steels, the different phenomena, with opposite consecutive processes, are induced. Those phenomena cause increase, so as decrease of dislocation density. The recrystallization process is suppressed by decrease of speed of grains' nucleuses formation and by the reduction of movement of metal grains and sub grains boundaries. The recrystallization process is consequence of the presence of alloying elements' atoms in solid soluble of steels and it is induced by continual rolling with short break periods, when the effects of niobium are dominant. In addition, recrystallization process is induced as the consequence of precipitation during reversible rolling with longer break periods, when the dominant process is separation of carbon nitride. The development of high strength steels are linked to the technology of thermo-mechanical controlled process that provides highly controlled microstructure. The chemical composition of those steels conditioned its characteristics during production processes and final microstructure. Real microstructure and correspond mechanical properties are the result of very complex interaction of different and heterogeneous factors. The characteristics of high strength steels in exploitation are, on the other hand, the result of its microstructure and additional factors. The number and complexity of factors that influent to characteristic of material in exploitation conditioned that those characteristic can be determined only by experimental testing in real exploitative conditions [13 and 14]. The aim of stress-state analysis is formation of mathematical model to be verified by experimental testing. The numerical simulation of construction made of high strength steel answer to the exploitation conditions are one of the tool for identification of favorable design solution. Verification of design solution for construction made of high strength steels is done by experimental testing.

APPLICATION CHARACTERISTIC OF HIGH-STRENGTH STEELS IN VEHICLE DESIGN

The application of high strength steels in mechanical constructions can be considered from number of different aspects. In this paper, only the most significant aspect of this application is presented. The high-strength low-alloy steels with bainite or ferrite–pearlite microstructure are used for production of car bodies, shafts, elements of engines and so on. The high-strength steels with yield limit of 600 MPa are used for specific zones of car bodies [6]. For the analysis of application characteristics of high-strength steels in automotive industry, the example of car body presented at Fig. 2. is considered. Specific elements of car body are made of high-strength and high-strength low-alloyed steels in order to archive required strength and rigidity of car body with simultaneous reduction in its mass. By the aims of material selection and forming of those specific zones (Fig.2.), the beneficial mechanical properties are provided. Those zones represent the zones of energy absorption in case of collision and they improve passive safety of vehicles. Mechanical properties of selected materials provide decrease of dimensions of those specific zones and by that, increase of flexibility in car body design. The application of high strength steels for doors, cover of engine and trunk compartment provide 25% - 30% mass reduction to conventional steel applications with no additional cost [6, 11 and 12].

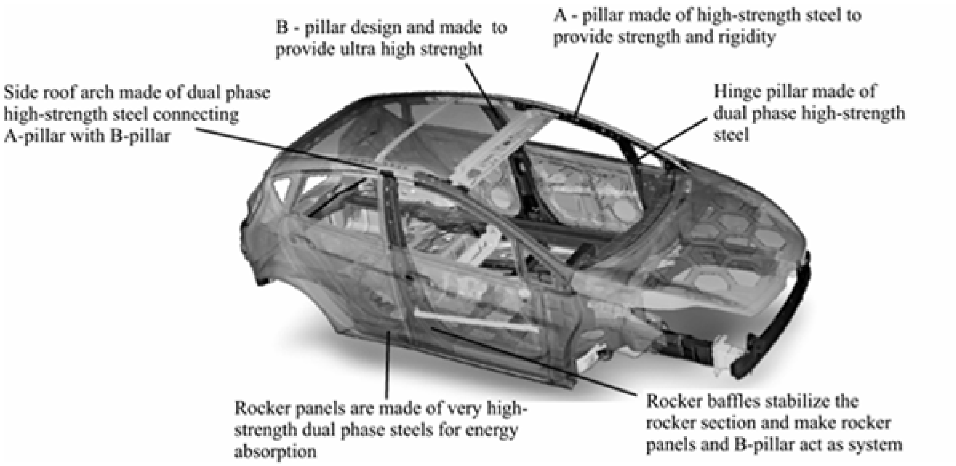

***Fig. 2**: Materials of specific zones of car body*

The adequate material selection, especially use of high strength steel provides very significant benefits. The passenger zones of the car body, according to passive safety requirements and regulations have to resist to deformations to prevent imposition in case of collision. The materials for this zone of the car body have to obtain sufficient strengths, so martensite, and boron steels are preferred (Fig. 3.). From the other side, intensive use of high strength steels provide additional positive effects such as mass reduction, flexibility of design, wide range and cost effective joining methods, and so on. Also, production processes of high strength steel grades provide very narrow tolerances of dimension and shape that is important for present press - lines and robotic joining methods in present automotive industry. The processing of high strength steel grade is comparable to processing of conventional steels, so additional costs for processing are minor. This fact is opposite to other materials that provide mass reduction without compromises in safety.

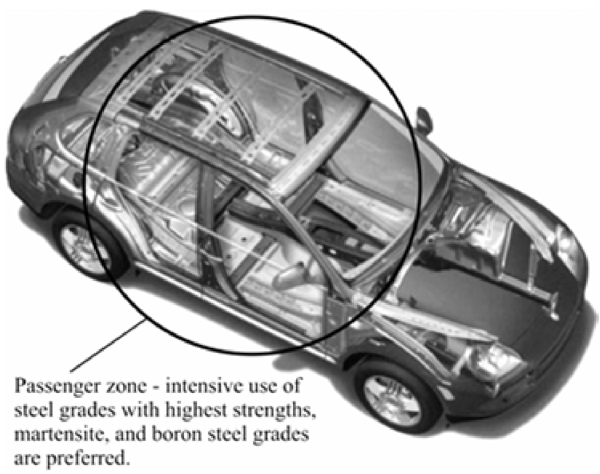

***Fig. 3:** Steel grades at passenger zone of car body made to resists deformation and provide passive safety*

The engine zone and trunk are zones that are intended to manage and absorb energy in case of collision. The design solution and material selection have to provide high energy absorbing, strength and ductility (Fig. 4.). The favorable materials for made of those zones are dual phase and transformation induced plasticity high strength steel (TRIP).

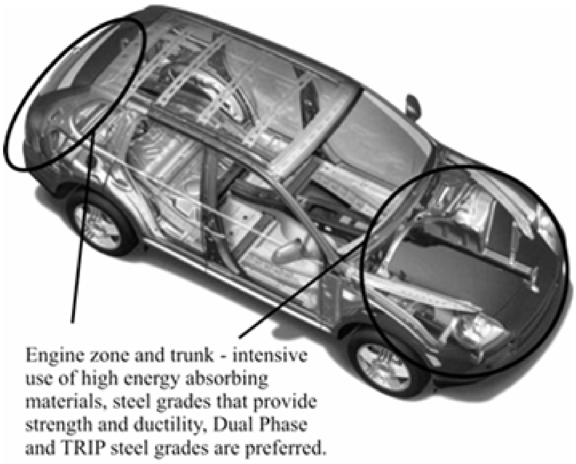

Fig. 4: *Steel grades for energy management zones of car body made to deform for absorb energy in collision*

The presented facts implicate that by the applications of high strength steels the higher level of flexibility in design is obtained [11 and 12]. Furthermore, the mass reduction makes ability for reduction of fuel consumption and further reduction of pollutant gases emissions. All this, reduced the complete ecological impact of production and exploitation of vehicles. Aggressive reduction of vehicles' mass by the application of high-strength steels and its design optimizations highlights the new tendencies in car design. In modern automotive industry, high concerns are put on passive safety. Behaviors of vehicle structure at collisions are analyzed, firstly, by numerical simulations and then experimentally tested. The major influential factors for behavior of vehicle structure in collision are the characteristic and mechanical properties of specific zones made of high-strength low-alloy steels.

JOINING METHODOLOGIES

In the area of present design of motor vehicles, one of the most critical factors in safety and reliability analysis are the joint zones of elements. Design of element joints zones represents the most complex procedure in the process of the motor vehicles development. The zones of elements joints are the zones with high level of stress concentrations and with high heterogeneity level of characteristics at the whole vehicle' structure. In present motor vehicles industry, different joining methodologies are used. Welding joints provide material continuity at the joint zones. Stress concentrations at vehicles' structures, as complex phenomena, can be analysed from large number of very different aspects. For example, it can be considered locally and structurally, in relation to dimension level of analysis. Different from other joining methods that required holes in the joining zone, the flow of stress lines at welded joints are beneficial. It is obvious that, from the aspect of stress concentration, this joining method is preferable in relation to other joining methods, which induced higher variations of stress lines. Also, from the aspect of high strength steels use in motor vehicles, the problems of welding of this steel grade are very important. Availability of welding technology, altogether with other aspects of this technology application, conditioned that this technology become dominant joining method in production of motor vehicles in cause were rejoin is not necessary. As consequence of applied technology of welding in the zones of the welds and in the heat affected zones the residual stresses are induced. Adequate welding technology represents the condition for providing required mechanical characteristics of welded joints zones and by that, the condition for proper joining. The literature related to the welding of high-strength low-alloyed steels showed that existing references are not satisfactory clear and precise. Using of those steels, for forming the elements in motor vehicles, is valid only if adequate joining methodology is provided. Intensive development of new steel grades must be followed with progress in welding procedures. Relatively high level of embrittlement that is the result of improved mechanical characteristics make this steel grade very sensitive to heat effects of welding in relation to conventional carbon and carbon-manganese steels. In relation to heat cycle of welding, the different transformations in microstructures are induced and those transformations lead to decrease in hardness and embrittlement in heat affected zone [5, 15 and 18].

Characteristic of formed zones at joints of the elements, made of high-strength steels, in motor vehicles can be degraded, generally, in three manners. Firstly, it is in case of using high energy of welding or when temperature of preheating is higher then allowed. Secondly, it is in case when energy level of welding or temperature of preheating is low and under the allowed limits. Thirdly, it is when the heat cycle of welding is related to heat cycle that induces segregation of some elements at the binderies of metal grains and forced degradation of toughness [1, 15 and 18]. With the improvement in mechanical characteristics, the diapason of allowed welding parameters is reduced and, by that, the risks of using welding parameters that are out of limits are higher. This fact must be considered properly, especially in case of high-strength low-alloy steel application in motor vehicles especially from the aspect of automated welding processes. The design solution of the elements of the motor vehicles must considered automated joining methodologies adequately.

DESIGN RULES FOR APPLICATION OF HIGH STRENGHT STEELS

The applications of high strength steels in mechanical constructions, so as in motor vehicles are regulated by Serbian national standard that is in agreement with Europe Union Norm -EUROCODE 3. This norm considered the application of high strength steels to steel grade S460. The Part 1-12 was added to EUROCODE 3 in order to enclose the application of high strength up to grade S700. The basic design rules and procedures regulated by EUROCODE 3 can be adopted to use at design of elements of motor vehicles made of high strength steels. But, there are not enough experimental data and information about characteristic and properties of joining zones of elements made of those steels at motor vehicles. The design rules for elements made of high strength low alloyed steels are still very limited and on the recommendation level. EN 1993-1-12 regulate the application of steels with characteristics and properties defined by EN 10025-6 and EN 10149-2. Those norms enclosed steels up to grade S960, but those steels with very high strenght do not have significant application in general purpose motor vehicles. EN 10149-2 defined the thermo-mechanically produced steels with favorable ability for additional processing and enclosed steel grades from S500 to S700, while theirs application is regulated by EN 1993-1-12. The obligation for impact toughness testing in norm EN 10149 is not proposed. Because of that, impact toughness testing of steels is regulated in EN 1993-1-12 by definition of minimal impact toughness as energy of 40 J at -20°C for fracture of sample [5].

The providing of adequate resistance to brittle fracture is regulated by norm EN 1993-1-1. The resistance to brittle fracture is obtained by selecting of materials with proper toughness and this norm does not provide any other recommendations for avoiding the brittle fracture [5]. The reason for this is economic because the other design rules based on the resistance to brittle fracture induced additional costs. The method for determining the minimal dimensions at cross section of element is given in norm EN 1993-1-10 and can be used also for elements made of high strength steels up to grade S690. Ductility of steel is its important mechanical properties that are not defined precisely. Norm EN 1993-1-1 proposes the general requrements for mechanical properties, but does not enclosed requirements for its ductility. From the aspect of ductility as design criterion, the special design procedure and rules must be used. The functional requirements for elements made of high strength low alloyed steels at motor vehicles are based on maintaining of strength in cases of high plastic deformations due to collision. The requirements for ductility of material are given at part 3.2.2(1) EN 1993-1-1 with recommended values. That recommended values are modified in part EN 1993-1-12 for application of high strength steels and they are presented as

$$\frac{f_u}{f_y} = 1,05, \tag{1}$$

where f_u - ultimate tensile strength and f_y - nominal values of yield strength and elongation at failure is less then 10%. Also, it is

$$\varepsilon_u \geq 15\frac{f_u}{E}, \tag{2}$$

where ε_u - the elongation at failure and E – elastic modulus. The analysis of stress-strain state in elements made of high strength steels is based on elastic analysis method and on nonlinear finite element method [5].

Buckling of elements made of high strength steels at structure of motor vehicles are rear, but significant and potentially dangerous problem. But, on the bases of reduced levels of material inhomogeneity, the elements made of high strength steels are more resistant to buckling than the same constructions made of different kind of steels. The criterions of design used for lower strength steels can be used even for high strength steels. Those criterions of design can be improved by the use of adopting additional factors to consider the higher resistance of material to buckling in relation to its homogeneity level.

Low alloyed high strength steels have good welding ability. But, welding of high strength steels reduced the diapason of available parameters for welding. In relation to that, the risk that welding parameters step out of defined limits is higher. Welding of high strength steels with filler materials of lower strength provide much ductile welds. Those welds are less sensitive to cracks. The using of those filler materials is not regulated by EN 1993-1-8, but it is regulated in part EN 1993-1-12. The design of those welded joins is based on strength of filler materials and not on the strength of parent material. For example, for T joints at materials with different strengths, the correlation factor have the value of $\beta_W = 0$. On the bases of experimental testing of welded joints with filler materials with different strength to strength of parent material, the modification of relation in EN 1993-1-8 for design rule is done to the following form

$$\sqrt{\sigma_{\perp}^2 + 2\tau_{\perp}^2 + 3\tau_{||}^2} \leq \frac{f_u + f_{eu}}{2\gamma_{M2}}, \tag{3}$$

where is: $\sigma_{\perp}$ - is the normal stress perpendicular to the throat, $\tau_{\perp}$ - is the shear stress (in the plane of the throat) perpendicular to the axis of the weld, $\tau_{||}$ - is the shear stress (in the plane of the throat) parallel to the axis of the weld [5]. In equitation (3) f_u is the nominal ultimate tensile strength of the weaker part joined, f_{eu} - the nominal tensile strength of material of filler material and γ_{M2} is partial safety factor for joint. The design criterion presented by equitation (3) can be used for welded joints with lower and higher filler materials strength to strength of parent material. On the bases of this design criterion the more uniform factor of safety are obtained in case of load that act at direction parallel to axis of the weld or in plain perpendicular to this axis.

The chemical composition of materials, characterized by carbon equivalents is dominant influential factor to the determination of preheating levels for the prevention of hydrogen cracking. Carbon equivalent (CE) formulae according to International Institute of Welding, and implemented in EN 1011-2:2001

$$CE = C + \frac{Mn}{6} + \frac{(Mo + Cr + V)}{5} + \frac{(Ni + Cu)}{15} [\%], \tag{4}$$

where the chemical symbols of elements present its concentration in percentage. The influence of the chemical composition on the cold cracking behavior of steels are expressed also as theoretic carbon equivalent (CET) and provides information on the effect on the individual alloying elements on these properties in relation to that of the carbon by following relation

$$CET = C + \frac{(Mn + Mo)}{10} + \frac{(Cr + Cu)}{20} + \frac{Ni}{40} [\%], \tag{5}$$

where, also, the chemical symbols of elements present its concentration in percentage.

As consequence of welding procedure a different types of defects are always present in zones of welds. The potentially most dangerous defects in welding of high strength steels are hydrogen cracks that are transversally oriented. Because of the difficulties in identification and determination of defect dimensions, the method of allowable level of defect is adopted. By this method, certain level of density of defects with defined properties is always present in the zone of welds. The value of allowable dimensions of defects depend to the impact toughness of material and in case of weld metal, also, depend on level of deformation in exploitation of motor vehicle structure.

CONCLUSIONS

High-strength low-alloy steels are the materials with currently fastest growing share of application in motor vehicles. Those steels have significantly different characteristics from the characteristics of conventional steels that they replaced. Their lightweight capability is linked to specific ratio of strength and toughness to weight, as result of complex, multi- phase microstructure. Mechanical properties, resistance to atmospheric corrosion, the availability of joining methods, beneficial economic and ecologic effects conditioned that this steel grade become very important from the aspect of application in motor vehicles. Also, from the aspect of evaluation of new type of steel from this steel grade, the further enlargement of application can be expected. The considerations of this paper are linked to application of first generation of high strength steels. The microstructure of the second generation of high strength low-alloy steels is, basically, austenitic at room temperatures due to high content of manganese. The step forward is done in forming technology of those steels by development of specific technology that induced the twinning of metal grains (TWIP - twinning induced plasticity). The deformation process of those steels induced the twinning of metal grains and by that, refinement of microstructure is obtained and resulted in high deformation reinforcement. The tension strength of those steels is higher than 1000 MPa with simultaneous deformation of 60%. The prices of those steels are very high due to high prices of alloying elements. The complex microstructure of those steels causes decrease of weldability. The mechanical properties of second generation of high strength low-alloy steels overcome the requirements of general purpose mechanical constructions. The evolution of high strength low-alloy steels is continued by development of the third generation of high strength low-alloy steels. The intended microstructure of the third generation of high strength low-alloy steels have to be less complex then the microstructure of the second generation, which will improve the weldability with minimal compromises in mechanical characteristics. Those intended properties of the third generation of high strength low-alloy steels will even induced expansion of their application in mechanical constructions [7, 8, 9 and 10].

By the application of high strength steels in motor vehicles a number of significant advantages in design can be done. The optimization of design of elements made of this steel grade in motor vehicles can be done only by adequate consideration of its specific nature and characteristic. Higher safety and load capacity, low weight, improved environmental compatibility, decreased fuel consumption are just some of the advantages of high strength steel applications in motor vehicles. From the aspect of producer of elements of motor vehicles advantages are satisfied workability, good weldability and formability, fewer filler materials required, good cutability, reduced costs and so on. High strength of steels means a higher degree of elements' hardness, so application of high strength steels also improved its wear resistance. Application of high strength steels in mechanical constructions put new significant perspectives in design of motor vehicles, but, also brings some problems that must be solved in process of design.

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