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Preliminary note

DESIGN ASPECTS AT MECHANICAL CONSTRUCTIONS MADE OF HIGH STRENGTH STEEL GRADES

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Abstract: *In this paper, the design aspects at mechanical constructions made of high strength steel grades are shown. The advantages of high strength steels applications are put in correlation with particular mechanical design procedures which are required by those applications. The concrete tasks in design procedure which are related to applications of this steels are recognized. Analyses of demands, which are introduced to actual mechanical constructions, showed that those constructions obtained many and very diverse functions. On the other hand, those constructions have to fulfil strict limitations, which are opponent by its nature. Higher demands in energy efficiency and rising prices of materials impose reduction of constructions' weight. The design constraints and presented facts, altogether, implicate that the material selection is one of the most important procedure of design process. Also, only application of high strength steels can fulfil the most of the constructional demands. It is concluded in the paper that application of high strength steels obtain the reduction in emission of pollutants without compromises in safety, reliability and affordability. Furthermore, the major guidelines for improvement of design process of the mechanical constructions made of those steels are highlighted in this paper.*

Key words: *high strength steel grades, design of mechanical constructions, joint methodologies, safety, reliability*

1. INTRODUCTION

The characteristic and properties of the high strength steel grades provide its very numerous and diverse applications, from specific zones of vehicles bodies to highly loaded pillars and offshore platforms. Typical mechanical constructions that are heterogeneous systems from the material aspect with significant use of high strength steels are: mobile cranes, utility vehicles, railcars, concrete pumps, containers, agricultural and forestry machinery. The modern demands that are set on mechanical constructions induce significant decrease of usage of those steel grades. Replacing conventional structural steels by high strength steels results in unchanged load capacities with simultaneous reduction in material thickness of up to 70% [1, 2 and 3]. Significant reductions of thickness can be archived even under complex load conditions. By those facts, the application of high strength steels in mechanical constructions is the key to successful light weight design. The light weight design solutions are not the same in shape and dimension as the design solutions that they functionally replaced. The stress states in those design solutions are very complex. The analysis of those stress strain states are the basis of the design integrity analysis.
The decreases of dimensions at the cross sections of construction elements by applications of high strength steels conditioned the decreases of dimensions at zones of joints of elements. Due to those facts, the times used for forming of mechanical constructions are reduced. Applications of high strength steel grades at mechanical constructions provide the higher flexibility of its design. The mechanical properties and higher resistance to atmospheric corrosion of high strength steel grades provide improvement of safety and reliability, so it reduced maintains costs. The recycle ability of those steel grades at the end of exploitation period of the constructions provides reductions of ecological impacts. But, the applications of those steel grades put some new, significant and specific problems [4, 5, 6 and 7].
In this paper, some specific problems related to applications of high strength steels in mechanical constructions are presented. Those problems are put in correlations to characteristics and properties of high strength steel grades. The meta analysis of typical applications of high strength steels, found in present literature surrey, are given in this paper to highlight the specific problems that must be solved in design procedures. The nature, characteristics and properties of high strength steels are briefly discussed in the paper to establish the set of influential factors of high strength steels applications in mechanical constructions.

2. THE BASIC CHARACTERISTICS OF HIGH STRENGTH STEEL GRADES

The high strength steel grades are developed in order to improve mechanical properties and corrosion resistance in relation to conventional carbon steel grades. Those steel grades are not classified as alloyed steel grades in common manner. The main requirement that this steel grades have to fulfill is defined mechanical properties, while the chemical compositions are of the less importance. The chemical compositions of those steel grades can even vary in order to ensure the homogeneity of mechanical characteristics by those alterations. The

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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 distortions [4 and 5].

The technological production process conditioned its microstructure and, by that, its properties. The microstructure of low alloyed high strength is typically fine grained after the production processes and consisted of fine ferrite (α) grains with uniformity of shapes. The small amounts of cementite are present in microstructures of those steels, so as fine dispersed particles of carbon nitride. *Typical microstructure and grain refinement of different high strength steels grades are presented at Fig. 1.* [2].

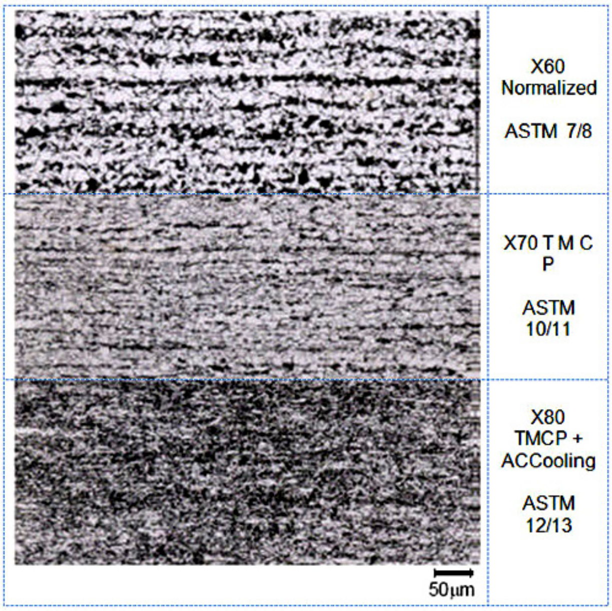

Fig.1. Typical microstructure and grain refinement in different high strength steels grades [2]

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.

Real microstructure and correspond mechanical properties are the result of very complex interaction of different and heterogeneous factors and it must be considered adequately in the process of design. 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 [8]. 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. The stress state at the elements of mechanical construction made of high strength steel in exploitation is complex and it resulted from number of heterogeneous factors that is presented illustratively in Fig.2. The characteristics of constructions made of high strength steels and its answer to load are influenced by factors related to stress-strain state besides of factors related to its microstructure. From the aspect that welding is dominant method of joining elements at the construction made of high strength steel, the heat input in material due to this joining method must be considered. The exploitation factors that influent to characteristic of constructions made of high strength steels are presented in Fig.2. at thermal stresses and deformation heat.

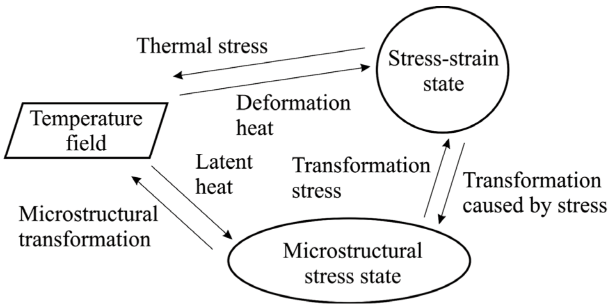

Fig.2. The stress – strain state in mechanical construction

The dominant factor is microstructure of this steel grade. The best mechanical properties are providing by steels with microstructure that is homogeneous mixture of two phases. In this case one of those two phases is precipitated phase with combination of coherent and semi coherent precipitate with uniform distribution of dislocations.

The directions of developing of high strength steels in last ten years are determined by two major directions. On one hand, the quenched and tempered constructional steels with high strength are developed (S690Q, S890Q, S960Q and S1100Q) and on the other hand, thermo-mechanically rolled steels with medium strength but improved toughness are produced (S355M, S460M and S500M). The chronology of development of specific steel grade and its level of yield strengths are presented in Fig.3.

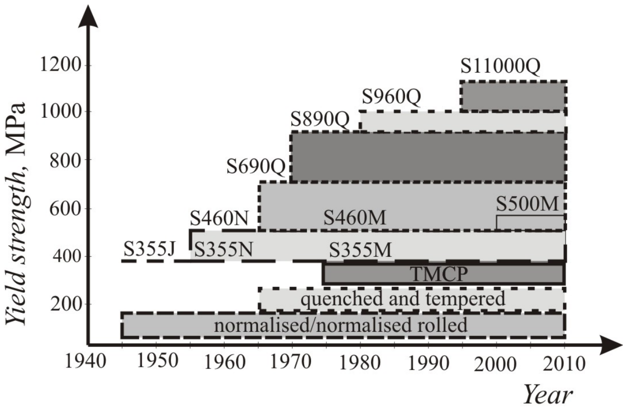

Fig.3. The evaluation of general purpose constructional steels and its yield strength

The different technological procedures are based on different phenomena of material reinforcement, but theoretically favorable microstructure of material is impossible to obtain. Real microstructure of material differs with certain level from theoretic microstructure and that condition the real characteristics and properties of material.

3. HIGH STRENGHT STEEL GRADES - DESIGN RULES

The applications of high strength steels in mechanical constructions 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 constructions made of high strength steels. But, there are not enough experimental data and information about characteristic and properties of joining zones at constructions made of those steels. EN 1993-1-12 regulates 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 strength do not have significant application in general purpose mechanical constructions. EN 10149-2 defined the thermo-mechanically produced steels with favourable 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 of the mechanical construction 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 [8]. 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 of mechanical constructions 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 constructions is its important mechanical properties that are not defined precisely. Norm EN 1993-1-1 proposes the general requirements for mechanical properties of construction, but does not enclosed requirements for its ductility. This mechanical property is very important for construction made of high strength steels, for example, in case of earthquake resistant structures. In this case the special design procedure and rules must be used. The functional requirements for those structures are based on maintaining of strength in cases of high plastic deformations. The requirements for ductility of material are given at 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

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

ε_u - the elongation at failure and E – elastic modulus. The analysis of stress-strain state in mechanical construction made of high strength steels is based on elastic analysis method and on nonlinear finite element method [5]. Presented considerations in this paper are related to cases of tension loads.

Buckling of elements is significant and potentially dangerous problem at mechanical constructions so as for construction made of high strength steels. But, on the bases of reduced levels of material inhomogeneity, the constructions 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.

Very important aspect of high strength steel application in mechanical constructions is the methodology of joining the elements. The zones of joints are the zones with high levels of stress concentrations. Also, those zones are characterized by high levels of material heterogeneity. The presented facts implicate that those zones present the critical zones from the aspects of safety and reliability. Those zones are critical from the aspects of mechanical properties and characteristic and, also, from the aspects of material usage. The different methods of joining are used at present mechanical constructions. Welded joints provide material continuity at the joints zones, but they are sources of stress concentration and the zones with high level of residual stresses by its nature. Stress concentration at constructions made of high strength steels as complex phenomenon and can be considered from the number of different aspects. The stress concentration 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 by hydro-dynamical analogy are beneficial. The high strength steels, especially 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 diapason 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 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

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

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, $\tau_{\parallel}$ - 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 [9, 10 and 11]

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

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 welded construction.

4. CHARACTERISTICS OF HIGH STRENGTH STEEL GRADES APPLICATIONS

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.

On the basis of very favorable relation of strength and toughness to the mass, the high strength steels provide significant reductions of masses of mechanical constructions. On the other hand, the applications of high strength steels provide decrease of load capacity at the same dimensions, regarding the same masses of constructions. Mechanical properties of those steel grades provide reduction of dimensions at cross sections of elements of constructions.

The adequate material selection, especially use of high strength steel provides very significant benefits [6, 7, 14 and 15]. 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. 4.). On, the other hand 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 [12]. 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.

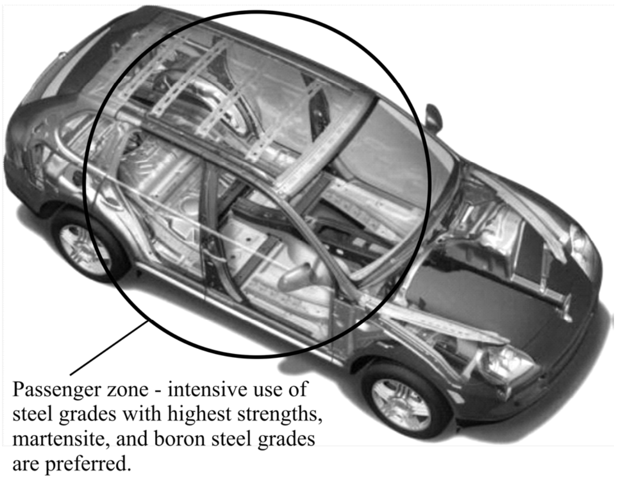

Fig.4. Steel grades at passenger zone of car body made to resists deformation and provide passive safety

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. 5.). The favorable materials for made of those zones are dual phase and transformation induced plasticity high strength steel (TRIP).

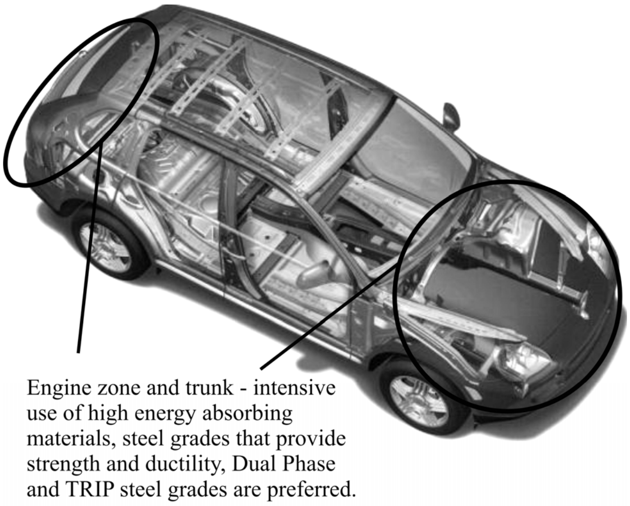

Fig.5. Steel grades for energy management zones of car body made to deform for absorb energy in collision

The presented facts implicate that by the applications of high strength steels the higher level of flexibility in design is obtained [13]. Special high strength low allowed steel grades with improved formability were developed for the automotive industry to replace low carbon steels without compromises in strength and simultaneous mass reduction and improved safety. The improved formability put new dimension to design of cars. The complexity of design solutions does not result in additional cost of productions.

Trucks, construction equipment, agricultural and mining equipment, and other heavy duty vehicles are mechanical constructions with intensive use of high strength steels as sheets or plates for chassis components, buckets, and structural members. The high strength steel with yield limit of 450 MPa to 550 MPa are are specified in applications such as offshore oil and gas platforms, electrical power transmission towers, railroad vehicles, and ships. For machine constructions such as cranes, cement mixers, excavators the high strength steels with yield limit of 500 MPa to 700 MPa are used [4, 5 and 13]. Forming, drilling, cutting, and other machining operations on high strength steels usually require 25 to 30% more power than related operation on structural carbon steels at same conditions. But, due to obtained reduction of dimensions at cross section of the machine construction elements made of this steel grade the used energy for processing decreases.

The reduction of constructions' masses resulted in increase of energy efficiencies of those constructions. The total ecological effects of constructions are reduced by application of high strength steels during the whole life of constructions, not only during exploitation. Economic effects of applications of high strength steels are multiple and significant. The prices of structural steels rise as its strength rise that is presented by trend line in Fig.6. The relative prices of high strength steel plates of three leading European producers are presented in Fig.6. The average price of steel grade S235 is selected as referent. The trend line of price increase due to increase of strength of corresponding steel is presented also in Fig.6. The trend line followed the shape of square root function from value of stress at yield limit. The variations from presented trend are result of market disturbances and present market strategy of producers.

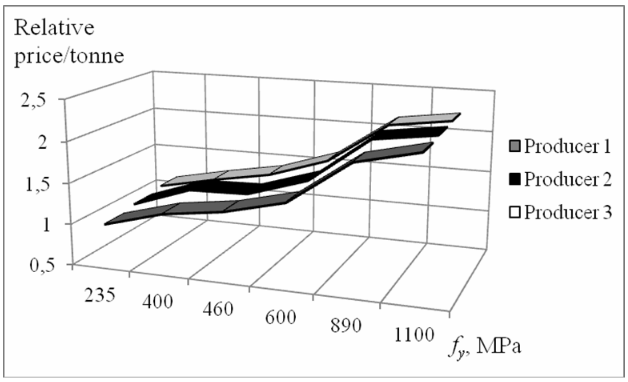

Fig.6. The average referent prices of high strength steels in function of yield limit

In case that required load capacity have to be obtained the relative material costs will decrease by application of high strength steels, as it is illustrated in Fig.7. But, the price of mechanical construction is highly dependent on production costs then costs of used materials. For the aim to simplify the analysis only costs related to materials is taken into account in this consideration. When the integrity and load capacity of the construction is determined by the resistance to buckling, the economic effect of application of high strength steel is slightly reduced.

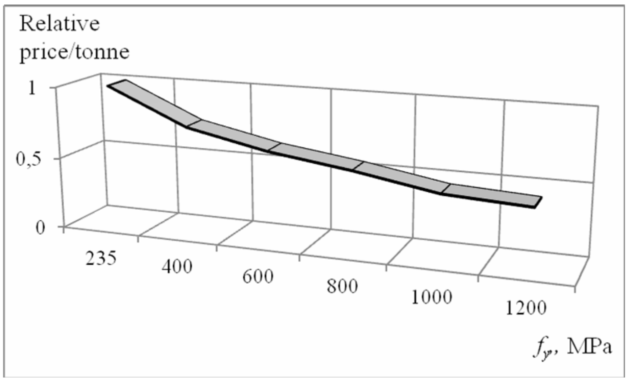

Fig.7. Approximate referent price of high strength steels on the basis of load capacity

The very interesting application of high strength steels are for forming of hybrid girders for different constructions. A hybrid steel girder is a welded girder with different steel grades. The example of bridge design with hybrid girders is presented in Fig.8. in order to illustrate the flexibility of design provided by applications of high strength steels. For hybrid girders, as used at presented bridge design, the high strength steels are used for flanges where stresses are maximal. For the web, the low strength steels are used because the stresses are low at this zone. By this combination of different steel grades at the cross section the beneficial economical effect is obtained with simultaneous increase of safety and reliability and improvement of mechanical characteristic of bridge structure.

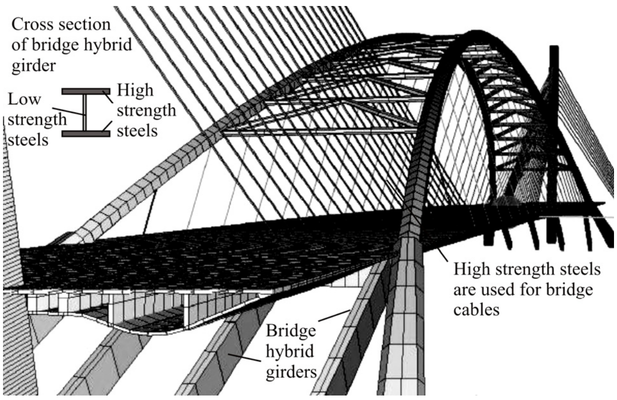

Fig.8. Bridge design with hybrid girders

The economical benefit is multiple and it is present in almost every stage of construction forming (Fig.9.). Due to application of high strength steels for some elements of mechanical construction the reduction of structure elements thickness is obtained. This reduction of elements thickness implicate shorter cutting time, shorter joining time, for example welding time and less filler material is used [12]. Further, less dimensions and mass of construction elements implicate reduction of transportation and manipulation costs. Also, reduction in dimension and mass of the construction elements make possible to use small transportation and lifting devices that are fast, flexible and more efficient in correlation to big ones. The time needed for forming of construction is also reduced. The costs are reduces at every stage of construction forming.

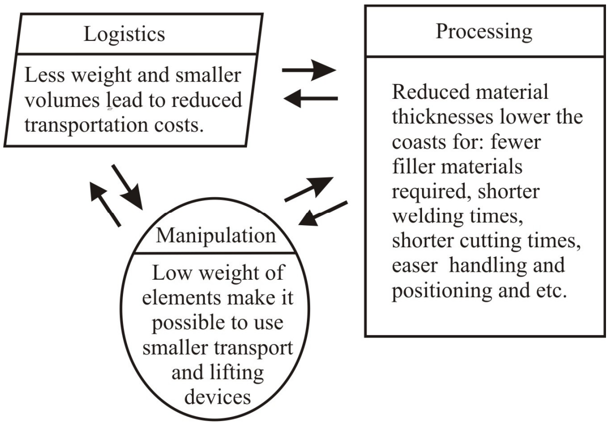

Fig.9. Savings at different production stages provided by application of high strength steels

The actually achieved savings and the real benefits of application of high strength steels have to be implemented step by step in design process.

5. CONCLUSION

Mechanical properties, resistance to atmospheric corrosion, the availability of joining methods, beneficial economical and ecological effects conditioned that high strength low alloyed steel grade become very important from the aspect of application in mechanical constructions. Also, from the aspect of evaluation of new type of steel from this steel grade, the further enlargement of application can be expected. The generations of high strength steel grades and its basic mechanical properties are presented at Fig. 10. 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.

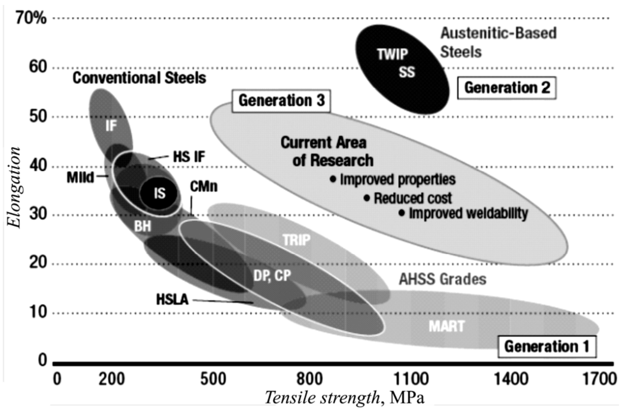

Fig.10. The generations of high strength steel grades and its basic mechanical properties

Present data about the use of high strength steel grades in mechanical constructions still show that this steel grade is not sufficiently used (Fig. 11.) [4].

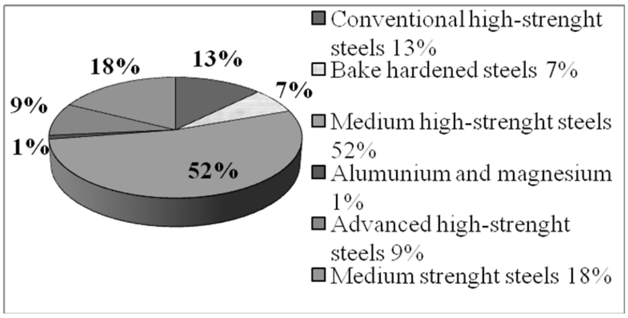

Fig.11. The materials shares for application at present mechanical constructions

But, according to projections of shares of application of those steels in mechanical constructions by Ducker WorldWide, in year 2015 this steel grade will have further enlargement of applications (Fig.12.) [4]. The further enlargement of application of high strength steels can be expected with third generation of this still grade.

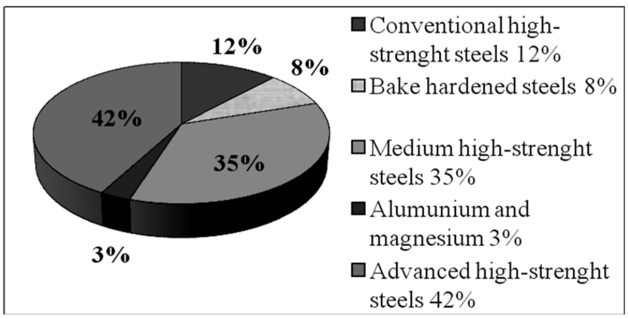

Fig.12. The projections for materials shares in 2015 year at mechanical constructions

By the application of high strength steels in mechanical construction a number of significant advantages in design of mechanical constructions can be done. The optimization of design of mechanical construction made of this steel grade can be done only by adequate consideration of its specific nature and characteristic. Higher lifting and load capacity, low weight, improved environmental compatibility, decreased power consumption are just some of the advantages of high strength steel applications in mechanical construction. From the aspect of producer of mechanical construction 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 hardness, so application of high strength steels also improved wear resistance. Application of high strength steels in mechanical constructions put new significant perspectives in design of those constructions, but, also, brings some problems that must be solved in process of design.

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