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Effect of laser strengthening on the mechanical properties of car body steels presently used in automotive industry

Abstract: The article describes advanced very high-strength steels having the DP-type ferritic-martensitic structure, steels having the TRIP-type ferritic-bainitic structure with retained austenite and hot stamping steels. The research was focused on the selective DY044 laser strengthening of DP600, TRIP700 and 22MnB5 steels. The tests involved the determination of strengthening curves for the parent metal and for the weld as well as the determination of mechanical properties for DP600, TRIP700 and 22MnB5 steels strengthened by laser beam penetration, depending on the penetration depth. The research also involved the preparation and verification of parent metal and weld numerical models.

Keywords: laser strengthening, car body steels, DP600, TRIP700 and 22MnB5

Introduction

New worldwide vehicle-related standards concerning safety, fuel consumption and CO_2 emission are gradually coming into force. Presently, the ongoing negotiation includes CO_2 emission standards for 2020-2025 (Fig. 1). Car manufacturers are searching for new structural and material solutions enabling the satisfaction of new requirements and, at the same time, ensuring a high-volume production [1].

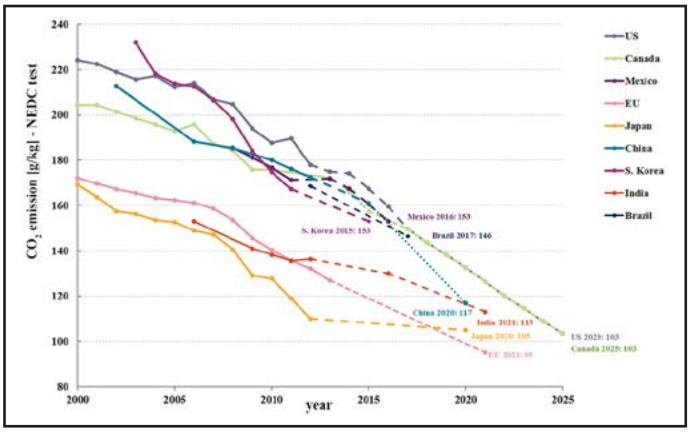

Fig. 1. CO_2 emission standards for 2020-2025 [14]

In spite of information concerning the development and production implementations related to cars made of aluminium alloys, magnesium alloys, composites and plastics, steels continue to be the dominant car body material in the automotive industry [2]. Numerous developmental programmes such as *Worldautosteel* have contributed to the development of advanced steels for the automotive industry. Custom-made materials should have an appropriate structure characterised by specific physico-mechanical properties. Research shows that the production of materials meeting manufacturer requirements at a required time and place (*Material on demand*) constitutes the priority of new material technologies and manufacturing processes [3].

High demands set for car parts and elements including the increase in safety, the minimisation of weight, environmental friendliness and manufacturing cost reduction have triggered the development of the thermo-mechanical

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production technology. The functional properties of many products depend not only on the possibility of transmitting the load through the whole active element cross-section, but also on the structure and properties of the surface layer. Appropriate manufacturing enables the obtainment of the most advantageous combination of the properties of the core and those of the surface layer. Presently, surface gradient materials are very popular, with gradient material properties obtained by changing chemical composition, phase composition, structure and arrangement of atoms. Designers constantly endeavour to develop and manufacture the ideal material, e.g. for tools which would be maximally resistant to wear and highly ductile. The work [4] contains a comparison of the mechanical properties of sheets having ferritic-martensitic structure, made of C-Mn structural steel containing Nb and Ti microadditions and manufactured using the thermo-mechanical treatment technology or after conventional hardening from a temperature slightly higher than that of AC1. It has been demonstrated that the microalloyed steel developed can be successfully used in the production of sheets having ferritic-martensitic structure (dual phase) both by means of the thermo-mechanical treatment and by classical hardening.

One of the presently developed methods aimed to meet the challenges mentioned above is the technique of selective laser strengthening. This process is industrially applied for hardening of stamping tool work surfaces. It is also the subject of tests conducted by research institutions continually discovering the possibilities of selective laser strengthening.

The work [5] presents the possibility of using laser technology for strengthening supporting structures in the automotive industry. The research involved tensile tests of test pieces with laser beam penetration and determining the numerical model of a replacement material taking into consideration three zones (weld, HAZ and parent metal).

N. Peixinho [6] conducted tests of car crossbars made of, among others, DP600 steel. The research involved testing the dissipation of energy for static and dynamic loads of, among others, laser welded joints. The work [7] presents the method of influencing weld properties by controlling laser beam power and monitoring the temperature of a surface subject to treatment. The system enables eliminating the partial melting of treated steel obtaining the uniform hardness of the hardened layer. L. Jaewon et al. in the work [8] provided the extensive presentation of the strength analysis of a laser welded overlap joint. The numerical simulations of the laser-made weld were carried out at three stages. First, only the parent metal was taken into consideration. Following that, a model with three zones, i.e. weld, HAZ and parent metal was tested. The next stage involved a model containing 6 zones, i.e. two for the weld, three for the HAZ and one for the parent metal. It is also necessary to mention tests focused on hot stamping [9], where strengthened material was divided into 10 zones and each of the zones were provided with an appropriate strengthening curve. However, the authors do not specify how individual strengthening curves were determined.

The objective of this work was to verify the treatability of modern car body dual phase DP600 steels, TRIP700 steels and the 22MnB5 grade manganese-boron steels as regards the surface layer laser processing. The authors wish to determine the strengthening parameters and transfer them to the virtual material model enabling the simulation of laser beam strengthened complex structures.

Car Body Steels for Automotive Industry

Presently, car bodies are mainly made of hot or cold rolled low carbon conventional steels. Post-work annealing and cooling is conducted in a manner enabling the obtainment of ferritic structures. In turn, the new generation of steels requires special processing leading to more complex structures [2].

Car body steels for the automotive industry are classified in several different ways, one of which, consisting in dividing such steels into three basic groups, is provided by Professor J. Senkara [2]:

I. soft, plastic low-carbon steels (DQSK, IF steels) of temporary tensile strength R_m below 300 MPa and total elongation A in the 30÷60% range;

II. conventional high strength steels (HHS) (BH, CMn, IF with microadditions, HSLA): $300 < R_m < 700$ MPa and lower A in comparison with the previous group;

III. advanced very high strength steels (R_m above 700 MPa, reaching even 2000 MPa) and elongation restricted in quite a wide range of 5÷30%, where the increase in strength is accompanied by the decrease in plasticity.

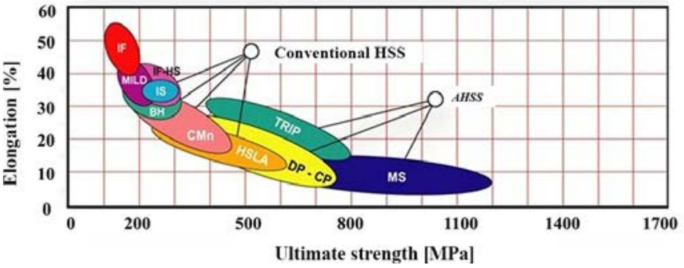

Fig. 2. Comparison of mechanical properties of steels used in the automotive industry [1]

This work describes steels representing the third group, i.e. advanced (very) high strength steels (AHSS) (Fig. 2). These steels are characterised not only by high strength, but also by high plasticity. This group includes the DP (*Dual Phase*) type ferritic-martensitic steels, TRIP type (*Trans-formation Induced Plasticity*) ferritic-bainitic steels with retained austenite, steels undergoing strengthening (during technological processing) resulting from the transformation of the martensitic phase γ, steels composed of various phases referred to as CP (*Complex Phase*), and steels having MART type martensitic structure (*Martensitic Steel*) [10].

The AHSS category includes steels strengthened by the phase transformation, where for the CP, DP and MS steels this strengthening takes place at the material preparation stage, whereas the TRIP effect takes place during a vehicle collision. The technological operation common for the CP, DP and TRIP steels is the processing at the intercrystalline temperature (the area of phases α and γ coexistence) after cold rolling, with the low temperature austenite transformation. The proper selection of annealing temperature affects the austenite-ferrite ratio. The final structure depends on temperature control during cooling and can be the combination of ferrite, bainite, martensite and retained austenite. In turn, the MS steels are obtained by quick cooling from the phase γ existence range to the obtainment of fully martensitic structure. The temporary strength of such steels can reach 2000 MPa. In order to improve the ductility of these steels it may be necessary to use controlled tempering [2].

DP Steels

The first group includes dual phase steels. The properties of DP steels, being a form of specific composite (Fig. 3), are the resultant of hard and resistant martensite and of ductile ferrite [11, 2]. Such steels are characterised by very good formability combined with high strength. The steels are also characterised by the initially significant difference between the yield point and the ultimate strength, quickly decreasing after cold working. Such an approach ensures lower springback than for low-alloy steels (e.g. HSLA) of similar strength [2]. The steel is characterised by the lack of the so-called Lüders effect during straining, low temperature crack resistance and low anisotropy of plastic properties [2].

DP steels are annealed at the temperature corresponding to the coexistence of the α and γ phases. Afterwards, appropriately quick cooling transforms austenite into martensite and the “composite”, i.e. ferrite + martensite structure is obtained.

Another method for obtaining the structure as described above is the thermo-mechanical treatment combining the heat and plastic treatments (hot rolling) with subsequent cooling. The steel production based on this method enables manufacturing more fine-grained structure and more advantageous mechanical properties than after conventional cooling from the dual α+γ phase range [4, 12].

The temporary tensile strength reaches 1000 MPa at the elongation between 10% and 20%. If compared with low-alloy steels (e.g. HSLA) having the same yield point, the energy absorptivity in the tensile strength is significantly higher for DP steels [1]. After holding at a temperature exceeding 200°C DP steels reveal hardening by approximately 30 MPa; this is a typical process used for soaking varnished surfaces in the automotive industry [13].

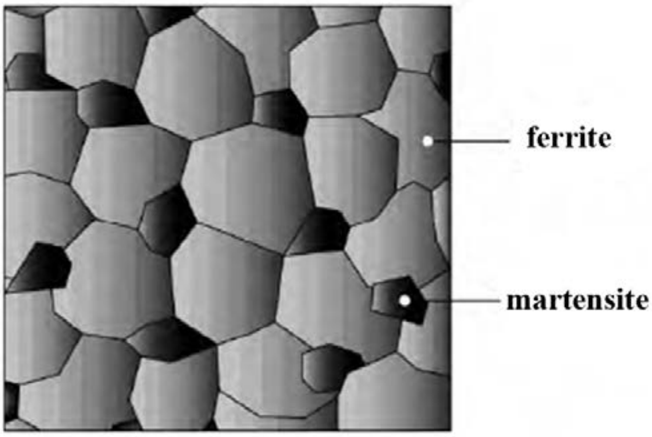

Fig. 3. Scheme of the metallographic structure of DP steels [1]

TRIP Steels

A major disadvantage of DP steels is their relatively low ductility. Steels which can rival dual phase steel in this respect are the low-alloy TRIP steels containing ferrite, retained austenite and bainite (Fig. 4).

Trip steels usually require isothermal hold at 350-400°C, during which the bainitic transformation takes place [1,10]. The high contents of silicon and carbon trigger the formation of retained austenite in the final structure. Subjected to plastic strain during forming, the austenite transforms into martensite. In conventional steels martensite is usually associated with an increase in brittleness. However, in multi-phase steels the gradual martensitic transformation causes significant work hardening of steel resulting in the delayed initiation of the neck in the test piece during tension [14]. In this way a material characterised both by significant strength and ductility is obtained. TRIP steels undergo faster plasticisation than DP steels, yet hardening maintains significantly higher strain values.

The vast majority of multi-phase steels are obtained by the hot working of sheets after cold rolling. The hot working includes the following [14]:

- holding of cold rolled sheets in the Ac1 – Ac3 temperature range,
- controlled cooling of sheets from a temperature slightly above Ac1 to 350÷500°C at a rate preventing the initiation of pearlitic transformation,
- holding on the continuous sheet annealing line in order to enrich the final austenite content in carbon, with the limited possibility of cementite precipitation,
- slow cooling to the room temperature.

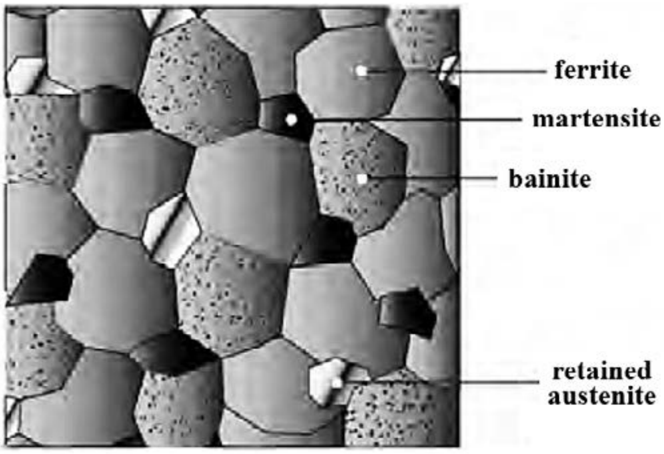

Fig. 4. Scheme of the metallographic structure of the TRIP steel [1]

Steels for Hot Stamping

The most popular steel which can be used for hot stamping is the 22MnB5 steel. The material in the as delivered state has the ferritic-pearlitic structure with the ultimate strength of 600 MPa. After hot stamping the steel structure becomes martensitic with a strength of 1500 MPa (Fig. 5). In order to obtain such a structure and hardness transformation, a preform made of the 22MnB5 steel must undergo austenitisation in a furnace at 950°C for a minimum 5 minutes. Afterwards, the preform is formed and at the same time cooled by the tool for approximately 5-10 s. If cooling intensity exceeds the minimum cooling index (approximately 27°C/s), the martensitic transformation will be initiated at approximately 400°C. This will result in the formation of the resistant final structure [14].

The mechanical properties of the steel after cooling change depending on carbon content, which means that the post-cooling strength can be controlled by an appropriate carbon content. Alloying agents such as manganese and chromium have only a little influence on the strength after cooling. However, chemical elements, particularly boron, affect steel hardenability. Boron slows down the transformation into the soft microstructure and leads to the formation of the martensitic structure. In order to prevent surface oxidation during hot stamping, most materials are provided with protective coatings such as the commonly used Al-Si layer.

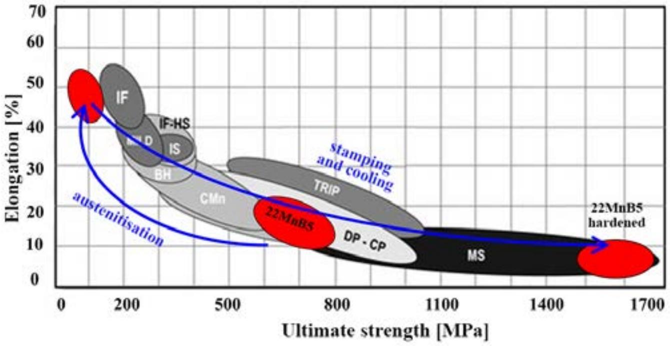

Fig. 5. Mechanical properties of the 22MnB5 steel [1]

Selective Laser Strengthening

Hardening is the basic operation in many thermal processes and has two phases. The first phase consists in heating the material to a temperature above that of the austenitic transformation (for carbon steel 727°C; usually 30°C to 50°C above the austenitic transformation temperature) and soaking sufficiently long for the whole object to obtain this temperature. The second phase is fast cooling. The cooling rate must be selected in a manner which prevents the precipitation of cementite from austenite and enables maintaining austenite structure until the martensitic transformation takes place during which austenite transforms into martensite. Steels having the martensitic structure are referred to as martensitic or hardened [16].

During selective laser strengthening, surface heating lasts a split second and is followed by fast cooling of the heated zone by the cold steel matrix. This favours very fast crystallisation followed by martensitic transformation. Almost immediately after hardening, the elements are available for further production stages. The tremendous advantage of the process is the short production time. Selective laser strengthening does not require any additional auxiliary processes or the use of cooling media. The process can usually involve elements made of machinery steel, tool steel and cast steel with a minimum carbon content of 0.2% [7].

Laser strengthening is one of the most difficult laser processes. Some authors recommend that the process should be conducted in a manner preventing the partial melting of the material, as hardness in the melted zone is 20-30% lower than that in the hardened zone [17]. Nonetheless, in the case of DP steels it is possible to assume that the structure will undergo hardening in spite of the melting, as is the case with spot welding [18].

Test Materials and Methodology

The tests involved 1.5 mm DP600, TRIP700 and 22MnB5 steels of the chemical compositions and mechanical properties presented in Tables 1 and 2.

The mechanical properties-related tests of the steels were carried out at Fraunhofer Institute, Dresden, Germany and included static tensile tests and hardness measurements. The static tensile tests involved three types of test pieces (Fig. 6):

Table 1. Chemical composition of DP600, TRIP700 and 22MnB5 steels (acc. to analysis)

Material	C [%]	Si [%]	Mn [%]	P [%]	S [%]	Al [%]	Nb [%]	Ce [%]	St [%]
DP600	0.0680	0.217	0.818	0.0103	0.0042	0.0523	0.0139	0.21	0.02
TRIP700	0.178	0.0853	1.64	0.0271	0.0041	1.3	-	0.46	0.01
22MnB5	0.167	0.329	1.21	0.0206	0.0035	-	-	0.40	0.03

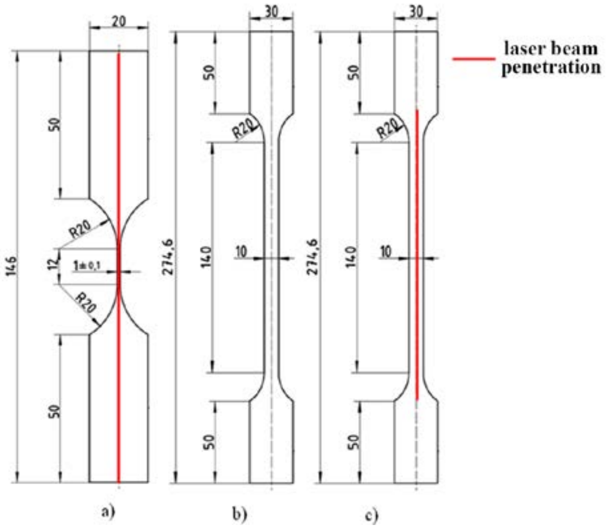

Fig. 6. Test pieces for tensile tests a) micro test piece, b) standard test piece, c) standard test piece with laser beam penetration

- tension of the micro test piece having the cross-sectional area of $1\ mm^2$ in the contraction (Fig. 6a),
- tension of the standard test piece (Fig. 6b),
- tension of the standard test piece with laser beam penetration along the test piece length (Fig. 6c).

The laser strengthening process involved the use of a DY044 laser, i.e. a Nd:YAG solid-state laser the basic element of which is a rod made of crystalline material, i.e. yttrium-aluminium granite of the chemical composition $Y_3Al_5O_{12}$ with a 3% neodymium ion admixture - Nd^{3+} in the weight ratio [15]. The penetration process required the use of the beam having the following parameters:

- power – 4 kW,
- focal length – 200 mm,
- laser beam diameter - 600 µm.

For instance, the penetration obtained for the DP600 steel was 1.4 mm wide, and its depth was controlled by modifying a longitudinal velocity. For the laser travel rate of 5 m/min 100% of penetration, for the travel rate of 9 m/min -

Table 2. Mechanical properties of DP600, TRIP700 and 22MnB5 steel (average of three measurements)

Material	Re MPa	Rm MPa	A_{80} [%]
DP600	463	660	15
TRIP700	477	705	33
22MnB5	384	589	12

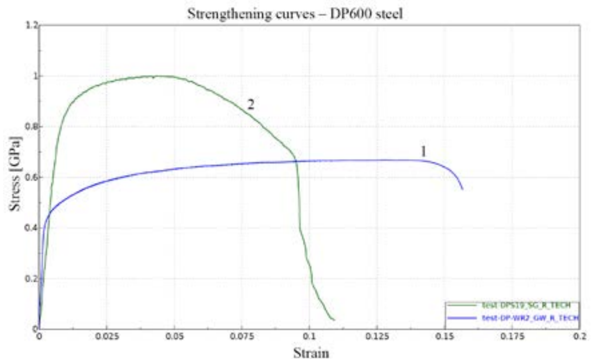

Fig. 7. Strengthening curves for the DP600 steel – for the parent metal – standard test piece (1) and the weld – micro test piece with laser beam penetration (2)

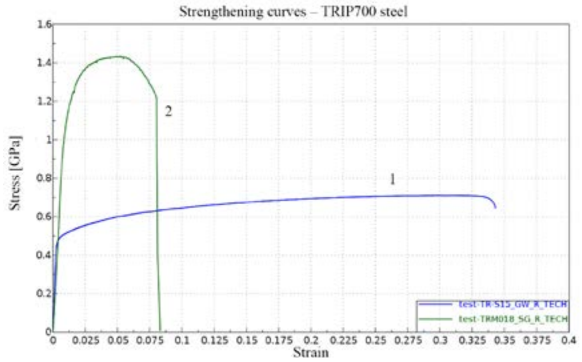

Fig. 8. Strengthening curves for the TRIP700 steel – for the parent metal – standard test piece (1) and the weld – micro test piece with laser beam penetration (2)

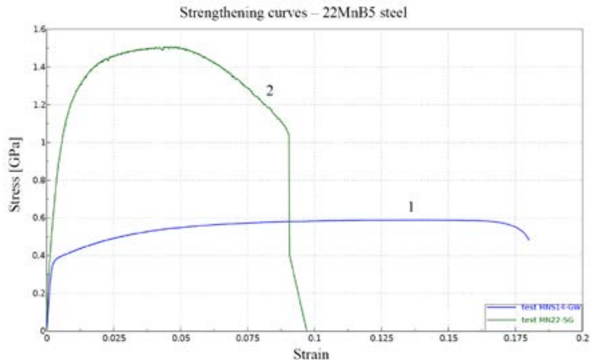

Fig. 9. Strengthening curves for the 22MnB5 steel – for the parent metal – standard test piece (1) and the weld – micro test piece with laser beam penetration (2)

40% of penetration and for the travel rate of 14 m/min - 30% of penetration was obtained. The tensile tests enabled obtaining the strengthening curves for the parent metal and for the weld (Fig. 7, 8, 9). The tests also involved the analysis of the microhardness distribution across the weld – 0.2 mm below the face (Fig. 10a, 11a, 12a) and deep inside the weld (Fig. 10b, 11b, 12b). Figure 13 presents microhardness measurement results for laser strengthening and for the parent metals of the materials tested.

The tests revealed hardness increase in the welds of all the materials tested (DP600, TRIP700, and 22MnB5). The most significant hardness increase in the weld compared with that in the parent metal was observed for the 22MnB5 steel. It was also noticed that an increase in the laser travel rate and the obtainment of penetration less than the full material depth increased microhardness in relation to full penetration.

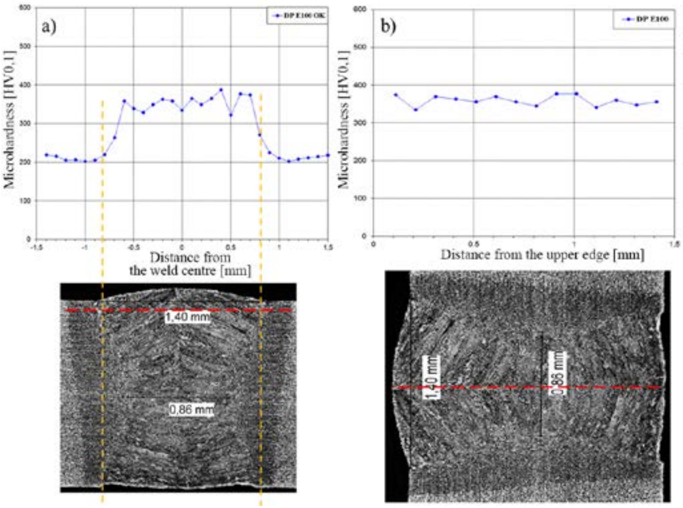

Fig. 10. Microhardness distribution (DP600 steel)
a) across the weld, b) deep inside the weld

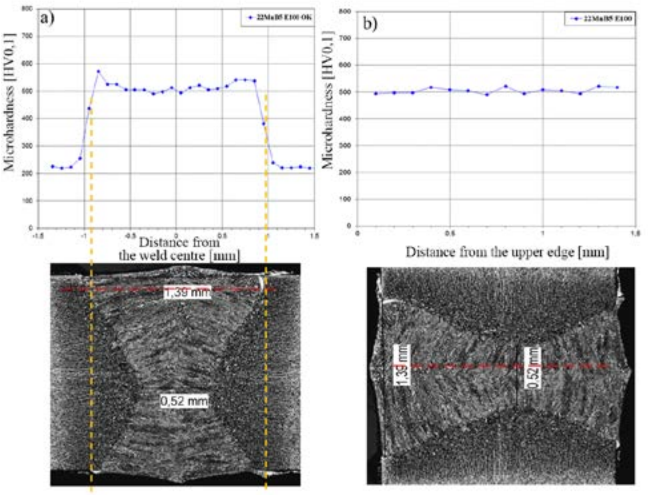

Fig. 12. Microhardness distribution (22MnB5 steel)
a) across the weld , b) deep inside the weld

Numerical Model

The research-related calculations were prepared in the Pam Crash 2008 software for non-linear dynamic analysis. The calculations involved the Finite Element Method and explicit integration algorithms. The analysis involved tensile tests for which discrete test piece models were prepared (Fig. 14).

The discrete model was made of 73456 Hexa and Pentra type volumetric elements. Material properties were reflected using the numerical elasto-plastic material model (Pam-Crash designation: MAT16). The boundary conditions of the simulation (test piece shape, test piece fixing manner, loads imposed) reflect the tests conducted.

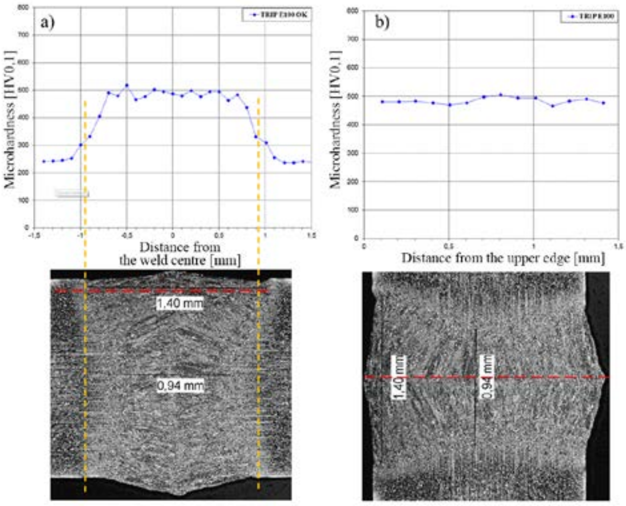

Fig. 11. Microhardness distribution (TRIP700 steel)
a) across the weld , b) deep inside the weld

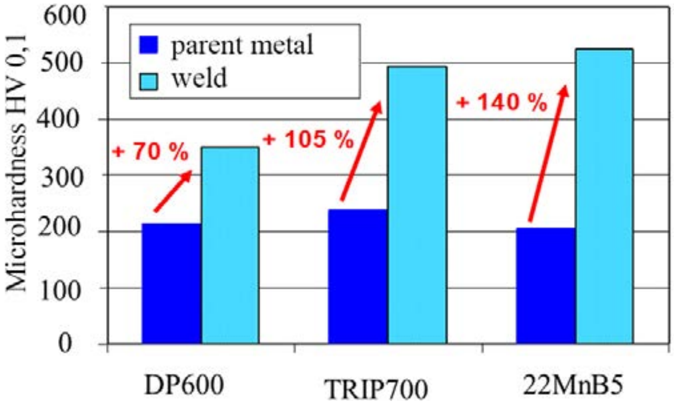

Fig. 13. Hardness after laser strengthening compared with the parent metal

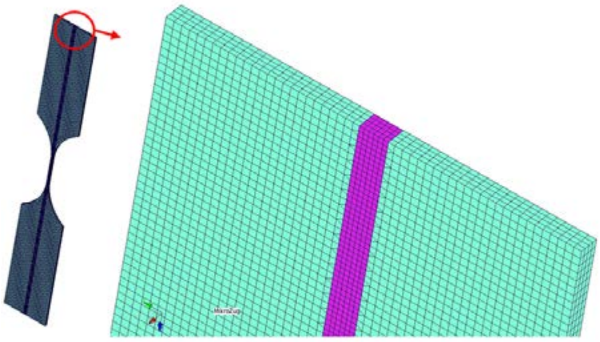

Fig. 14. Discrete model of the micro test piece for the tensile tests

The numerical simulation results coincided well with those obtained in the real tensile tests (Fig. 15, 16). The discrepancies between the diagram of the real tensile tests and that of the numerical simulation involving the standard test pieces with 100% laser beam penetration resulted from the simplification consisting in ignoring the HAZ in the previous calculations. The implementation of this phenomenon in the material numerical model is planned in further research works.

The coincidence of results obtained in the numerical simulations and those received in the real tests makes it possible to use the numerical model of the parent metal and the weld in simulating complex structures, e.g. in collision tests of cars. The models developed contribute to the increase in the passive safety of vehicles enabling the simulation of behaviour of supporting structures subjected to laser processing of surface layers.

Summary and Conclusions

According to the "Foresight of leading technologies for processing the surface properties engineering and biomedical materials" the possibility of manufacturing materials having properties required by the user is presently expected by customers. Selective laser strengthening meets such expectations and offers the possibility of affecting the mechanical properties in the end product manufacturing process. The use of the technology for strengthening thin-walled elements of the vehicle supporting the structure enables the control of the car body behaviour during collision. The locally hardened elements enable the obtainment of local stability loss in car body elements in previously anticipated areas.

The research enabled the determination of the mechanical properties of the DP600, TRIP700 and 22MnB5 steels subjected to laser strengthening as well as the preparation of virtual models of strengthened materials. This provides the possibility of further works concerned with the application of the technology for thin-walled load-bearing elements.

The tests demonstrated the laser strengthening treatability of the DP600, TRIP700 and steels. The conclusions are the following:

- 70%/105%/140% for DP600/TRIP700/22MnB5 respectively - increase in the weld microhardness in relation to that of the parent metal,

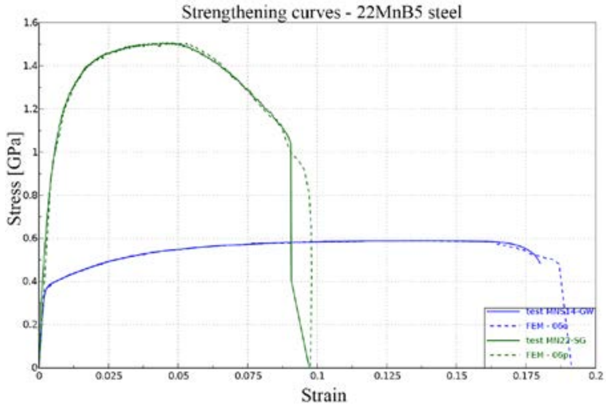

Fig. 15. Strengthening curves for the 22MnB5 steel for the parent metal (standard test piece and for the weld (micro test piece with laser beam penetration) – the comparison of the results obtained in the real tests and numerical calculations

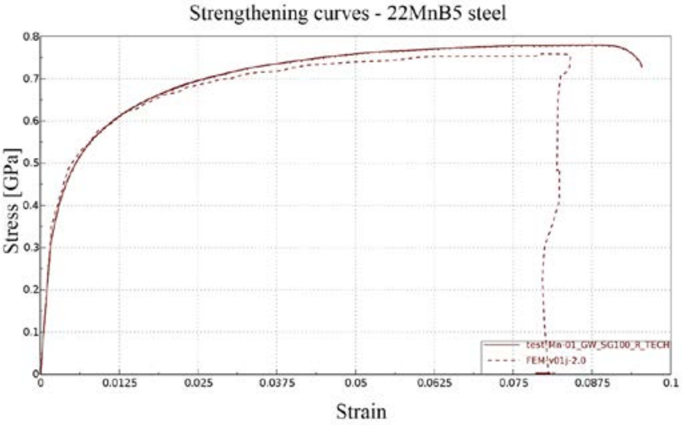

Fig. 16. Strengthening curves for the 22MnB5 steel (standard test piece with 100% penetration using the laser beam) – the comparison of the results obtained in the real tests and numerical calculations

- 10%/20/30% for DP600/TRIP700/22MnB5 respectively – increase in the strength of the laser penetration strengthened material with the simultaneous reduction of the maximum elongation by 25%/50%/50% for DP600/TRIP700/22MnB5 respectively,
- similar values of maximum uniform strains for the material not subjected to the strengthening and for the material variants strengthened by 30%, 40%, 100% penetration.

The strength increase with the simultaneous minimisation of permissible deformability losses can be obtained by the appropriate strengthening arrangement. In the hard zone area there must be the appropriate soft zone content.

The project was co-founded by the European Union within the confines of the European Regional Development Fund no. WND-POIG.01.04.00-02-067/12

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