THE STRAIN-RATE SENSITIVITY OF MARTENSITIC HIGH STRENGHT STEELS

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Abstract

Paper presents the analyses of high strength steels type of MnB5, widely used for auto-body passive safety parts. Different surface treatment towards to weldability optimization was subjects of performed experiments. Diffusion processes in surface layer due to variable heat treatment were observed as a substantial influence on strength of welding joints; prospective influence on microstructure and dynamic response outside heat affected zone was also examined.

Current development trends in this area lead to limitations for standard mechanical tests. Variable mechanical response of a particular constructional parts is required for energy flow during crash, so the local dynamic response including energy consumption during deformation and destruction needs to be analyzed. The rate-dependent behavior was examined at strain rates approaching operational relevant strain-rates, i.e. at strain rates ranging from quasi-static to 1000 s^{-1}. Behavior of steels in the sub-Hopkinson regime revealed the most influential strengthening effects, and also the higher sensitivity to phase heterogeneities. The present study employed servo-hydraulic tensile testing machine and the hammer loading system to obtain precise uniaxial loading and also decisive information about energy consumption.

Keywords: martensitic steels, dynamic fracture behavior, high strain rate

1. INTRODUCTION

Use of 22MnB5 high-strength martensitic steels has been increasing proportionally to requirements for improvement of car body passive safety. Boron alloyed steel reaches the strength during hot stamping process, material is formed in a thermo-mechanical process during anizothermal cooling from the austenization temperature into the specified shape and reaches a fully martensitic structure with strength higher than 1500MPa [1]. Besides weldability, another critical parameter of this steel is high energy consumption in fracture. Due to the application, the material response at deformation rate close to crash situations is significant. Critical factors are stability of ductile fracture mode, dynamic hardening tendency and steel sensibility to internal heterogeneity for metallurgical grade of steel.

Al/Si surface layer is applied to prevent oxidation during austenization over 900°C and next quenching. According to a number of studies, presence of this layer affects weldability [2]. In order to optimize the welding processes, the austenization processes are controlled which affect the internal structure of Al/Si layer [3, 4]. Eventual influence on dynamic hardening capacity remains a question.

The paper focuses on studying effects of alternative austenization procedures (and thus alternative structure of Al/Si layer) on dynamic hardening of steel and detailed study of such effect on weldability. The paper also presents results of experimental study of processes which affect the fracture behaviour in a specific metallurgical quality of material at the deformation rate of approximately 1000 s^{-1}.

2. METHODOLOGY OF EXPERIMENT AND PERFORMED ANALYSES

The subject of the study was martensitic high-strength steel 22MnB5; chemical composition is detailed in ***Table 1***. Reference samples with thickness of 1.2 mm were prepared for experimental analyses of influence of thermal mode on surface layer condition and subsequently on dynamic strength and weldability of martensitic steel, with the following austenization times: 300 seconds, 420 seconds, 660 seconds, 840 seconds. The austenization temperature was identical for all samples - 920 °C.

Table 1 Chemical composition of experimental steel [wt.%]

C	Mn	Si	P	S	Cr	Cu	Al_{celk}	Ti	B	N	O	H [ppm]
0.24	1.24	0.21	0.011	0.009	0.10	0.02	0.029	0.06	0.0030	0.0024	0.0020	2.3

Impact tensile tests were carried out for purposes of studying the dynamic hardening intensity at high deformation rates, corresponding to the working load in crash situations. The tests were concurrently carried out using two types of equipment: (i) fast hydraulic cylinder (AH 40-300, Kistler 9351B force sensor, Keyence LK-H 087 travel sensor), (ii) instrumented impact test hammer (Zwick/Roell BRA342038306). This enabled to check results up to the rate of 5.3 m/s. The intention of the equipment combination applied was to further verify possibility of minimizing samples for dynamic tensile tests. This requirement arises from the fact that the real condition of the subject material is given directly by production process of specific pressings of car body design safety elements. Broken shape and profile of these pressings do not allow preparation of samples in dimensions sufficient for standard tests, experimentally prepared material (with the aim to prepare sufficiently flat samples) cannot ideally simulate conditions of real production (hot stamping process). Therefore, the experiments carried out at the maximum loading rate of 5.3 m/s using the impact test hammer included compliance tests of special chuck, enabling sample testing with safe slip prevention at the impact moment. Validation of this equipment and of the entire testing methodology was based on concurrent testing at the same loading parameters using an electro-hydraulic cylinder with the above-mentioned measurement system at the maximum load of 15 m/s. Use of the impact test hammer enabled direct recording of the total energy consumed at sample destruction, the tests using an electro-hydraulic cylinder enable evaluation of the energy performance by calculation based on test records (force vs. movement).

Evaluation of influence of the surface layer on dynamic strength of resistance spot welds was based on impact tensile tests at the rate of 15 m/s. Material static response in various conditions of thermal influence in connection with surface treatment, also owing to the weld cycle in critical zone of thermally influenced area, was evaluated by local indentation tests at variable load. Additional metallographic, fractographic analyses and chemical energy microanalyses provided information about local structure and mechanism of fracture in relation to achieved values of dynamic strength of martensitic steel, or of spot welds of such steel.

2.1 Experimental material

The initial analyses conducted included the surface layer condition analyses, focused on homogeneity and thickness of diffusion layer at the interface with the base material. On one hand, diffusion of Fe into surface layer results in the required increase in the layer hardness and resistance, but on the other hand, the previous analyses demonstrated a negative influence on material weldability. The problems are caused by change of resistance in connection with width of an interlayer enriched with Fe. Determination and continuous monitoring of limits are required for stability of fully automated process of resistance spot welding. With respect to the surface layer heterogeneity and uneven thickness of the individual sub-layers, measurement was carried out automatically in 10μm intervals, in 7 measurements altogether out of the total 10 measurement positions. Figure 1 (a) documents the internal surface layer structure after processing in 920°C/840s mode; (b) shows average values of the above-mentioned measurements.

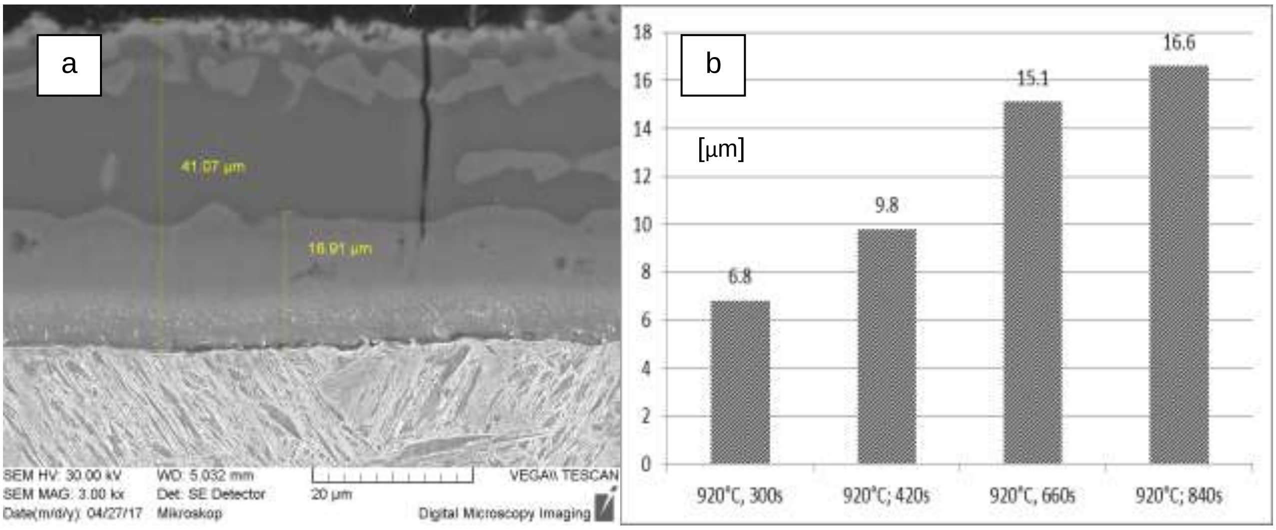

Figure 1 (a) A typical structure and (b) thickness of diffusion inter-layer of Al/Si coating

3. REFERENCES DYNAMIC STRENGHTENING INFLUENCED BY STRAIN RATE

Results of dynamic strength tests were supplemented by values of energy consumed into the accelerated crack propagation; this parameter was chosen to evidence the difference in deformation behaviour of samples under the load applied. A typical record of the test using instrumented hammer is presented in Figure 2 (a); character of the record (without evidence of spurious effects in form of, for instance, slip or higher vibrations at the moment of impact) confirms the measurement correctness.

It identified decrease in dynamic strength with increasing austenization time. Results presented in Figure 2(b) shows the effect of tested material conditions on dynamic response at the loading rate of 4.1 m/s. Huge scatter of results is related to characteristics of the steel structure and phase. Quantity and distribution of precipitates were found to have the critical influence on fracture behaviour at the rate above 10^3 s^{-1}. The above-mentioned influence increases with increasing loading rate, and so does the scatter of the reading.

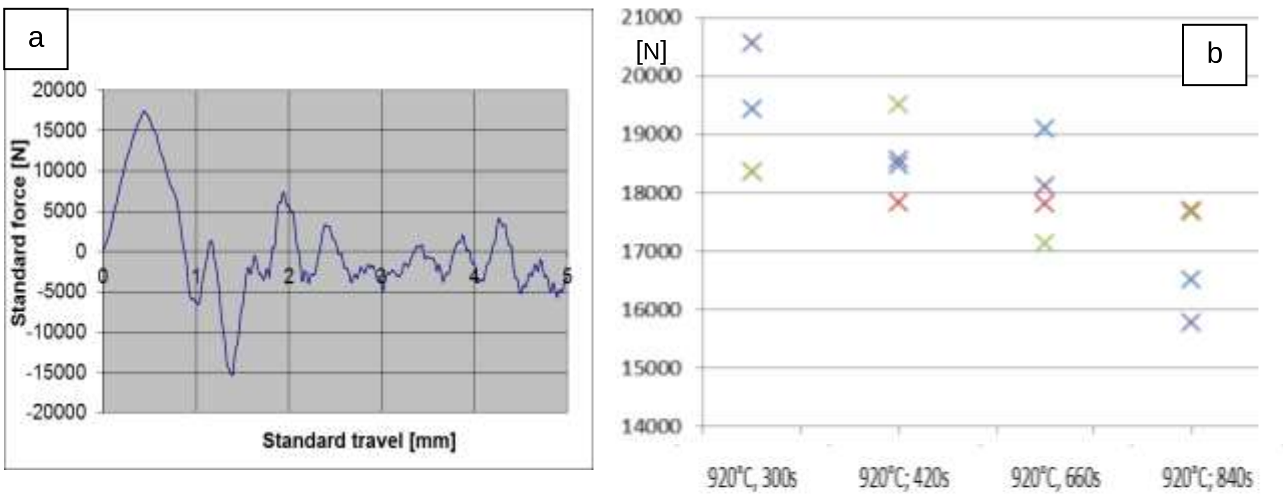

Figure 2 (a) A typical record and (b) results of dynamic test at 4m/s.

Fractographic analyses demonstrated ability of the material to maintain ductile mechanism of fracture even at the maximum loading rate tested. Major negative effect influence on fracture behaviour was identified in connection with presence of secondary particles on the basis of Niobium and Titanium. Figure 3 (a) documents the defective fracture areas where the influence of rows of the above-mentioned particles became evident. The defective area detail in Figure 3 (b) proves presence of the initial discontinuities around particles, developing by load during the dynamic tensile test. The details document characteristic orientation of shear bridges inside such formations - parallel to the fracture plane. So these are initial discontinuities, copying the forming direction when final separation of only partly interconnected surfaces occurred in the test. It is obvious that areas at the interface of distribution of these particles regulated by forming and metal matrix may work as Hydrogen traps at the same time. Sensitivity of this steel to presence of Hydrogen increases with the deformation rate.

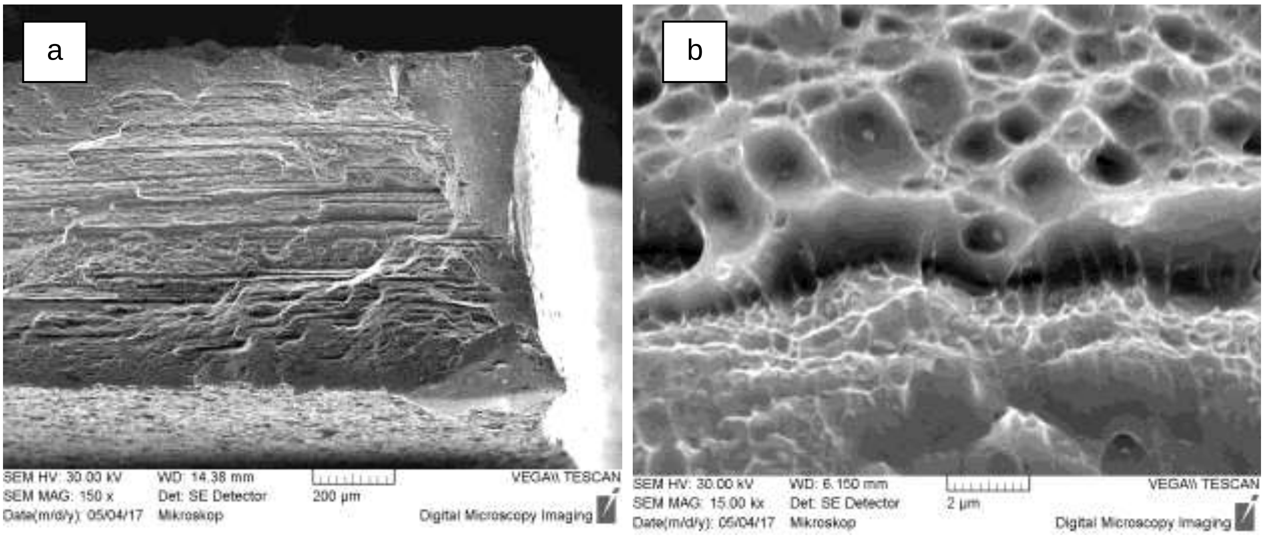

Figure 3 (a) Defective fracture mode due to precipitation.

4. DYNAMIC STRENGTH OF WELDING JOINTS

Influence of the surface layer condition or, as the case may be, of the diffusion interlayer thickness, on dynamic strength of resistance spot welds was tested on the same experimental alternatives of martensitic steel, i.e. material after the same austenization modes. Results are presented in Figure 4, decrease in strength is apparent with increasing austenization time and increasing diffusion layer thickness. The huge scatter of results was caused by micro volumes of the Al/Si surface layer material melted. With respect to influence of the softening zone on the austenization temperature interface, the influence of tempering of original martensitic structure was evaluated by indentation tests for all tested heat treatment alternatives. Instrumented indentation tests using a Vickers indenter were performed according to standard ISO 14577-1. Elastic versus plastic response ratio was applied to the comparison tests (η_{IT}(W_{elast} /W_{total}).100[%]). Differences within the experimental set of steels cannot be considered significant; substantial difference of elastic-plastic response was found in the softening zone.7) as compared to material outside the thermally affected area of welds (η_{IT} = 117.8).

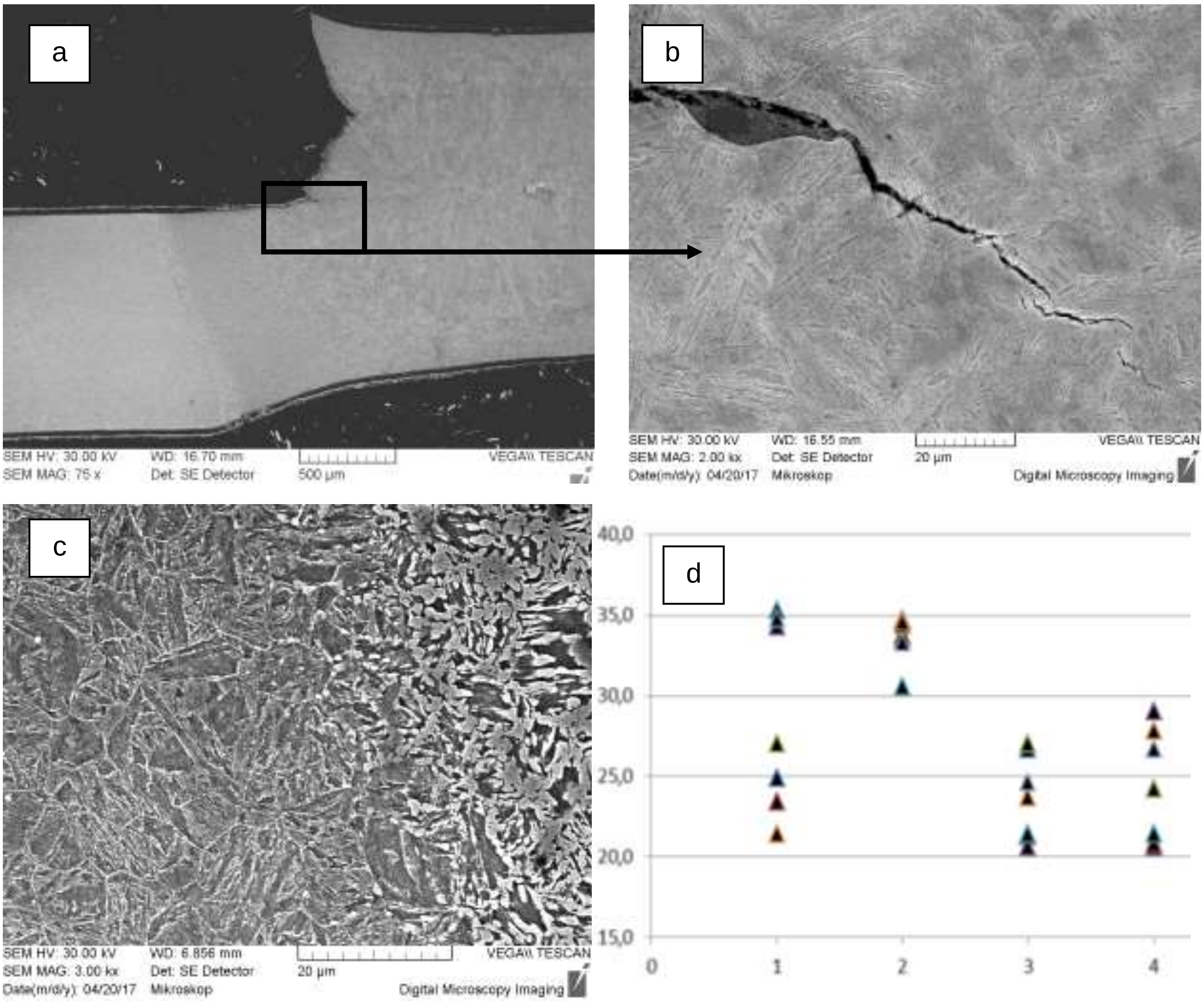

Figure 4 (a) A typical macrostructure of 22MnB5 spot weld (b) crack initiation at Al-micro-volume in weld metal (c) a typical microstructure of tempered zone (d) dynamic strength of spot weld.

5. CONCLUSION

Study of dynamic strength increase depending on deformation rate showed the highest intensity of dynamic hardening of the given steel type within the deformation range of up to 5 m/s. The results also indicate that a substantial effect on response stability at the loading rates close to real conditions of crash situations is presence of precipitates in possible interaction with Hydrogen. These effects increase with increasing loading rate, intensification of this effect was identified above the deformation rate of 1000s-1.

Influence of diffusion interlayer enriched with Fe on weld strength has already been proven by a number of experimental works. Accepted is the connection with influence on transition resistance during welding [5], thus on range of smelted volume of material, based on which the limits are determined for thickness of this layer for ensuring the process stability. Another effect that intervenes in the weld failure process is the material condition in fusion zone. At the moment of shock load transition, the critical parameter is the elastic-plastic response at the weld nugget interface. For the given material type and Al/Si layer, the critical role is played by two processes here, whereas the intensity of their influence de facto competes with the generally accepted “limited interlayer thickness - optimized connection strength” dependence.

The first effect mentioned is the tendency towards melting away of the Al/Si layer to the weld metal in the least positive case (under influence of microscopic mixing of material) of tendency towards formation of micro volumes containing Aluminium along the fusion line**.** The situation definitely results in fracture initiation along the fusion line when the dynamic strength is controlled only by the material condition along the fusion zone in line with the established relations in welding process optimization [6,7].

Another significant process is strength decrease in the zone at the austenization boundary. Energy consumption during material destruction is significantly higher in the zone. The indentation tests indicate that the elastic-plastic capacity of material in this layer is not significantly affected by the tested differences in surface layer condition and the corresponding differences in heat transfers during welding. A significant difference from response of not affected material was measured. Contrary to a number of other applications, the local heterogeneity of material mechanical response is a desirable effect in this case which enables preferential initiation of fracture in the decreased strength zone. These situations result in maximum weld strength achieved. Intensity of both effects increases with the loading rate, and thus with the deformation rate. Interaction of all effects mentioned above then causes huge scatter of results and increases requirements for correct interpretation, in particular, of crash tests of welded assemblies.

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