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RESEARCH ARTICLE

Weldability of Al-Si Coated High Strength Martensitic Steel

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Abstract

Martensitic high strength steel type of 22MnB5 is increasingly used in transport industries for safety components. Al-Si based coating layer is applied to the steel surface to prevent oxidation during hot stamping process. The main objective of performed analyses is to study the differences in formation of the surface AlSi layer related to weldability of martensitic steels. The structure of sub-layers and changes of their chemical composition were studied as a result of different thermal conditions during heat treatment. Formation of silicon-enriched zones in connection with overheating during austenitization is discussed. Tendency for creation of brittle inter-metallic phases based on Al-Fe was revealed.

Keywords

weldability · martensitic steels · surface layer · fracture behavior

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1 Introduction

Hot stamping is a widely used method of preparation of high-strength steel for passive safety components. The material is formed in a thermo-mechanical process during anizothermal cooling from the austenitization temperature into the specified shape and reaches a fully martensitic structure with strength higher than 1500 MPa (Liu [1]; Heping [2]). The process enables production of stampings with reduced springback, with a great geometric accuracy and a high strength-to-mass ratio. The sections produced in this way are used in crash protection applications. Current research in this field is oriented around heat treatment with controlled cooling. Reaching an optimal combination of martensite and residual austenite leads to a desired increase of fracture toughness and energy absorption capability at high loading speeds (Bardelcik [3]; Dancette [4]).

Usage of precoated steels in hot stamping is one of the methods that improve the quality of high-strength stampings. The role of the coating is protection of the surface against iron scale and decarbonisation during hot forming and quenching in the die. A 30 – 40 μm layer based on Al-Si (90% Al) is preferred for martensitic low-alloyed steels. The benefit of a coating based on Al-Si is higher oxidation resistance at high temperature Karbasian [5]).

The structural changes in the surface layer produced by the thermal process reduce re-melting during welding, contributing to the preservation of the passivation effect. In addition, experiments have demonstrated a tendency to create a protective layer on the electrodes which increases their durability (Maggi [6]). At the same time, however, a tendency to melt into the weld metal has been observed, for example in laser-welded joints. A possible consequence is the creation of brittle inter-metallic phases based on Al-Fe and reduction of joint strength (Ehling [7]). Recent studies suggest a greater risk of this degrading process in "an overlap welded joint than in a butt welded one" (Choi [8]; Kim [9]). During laser welding of hot forming steel with an Al-Si coating, the coating is diluted into the weld zone, which results in Fe-Al intermetallic phase formation (Ehling [7]). The brittleness of the Fe-Al intermetallic phase weakens the strength of the weld joint. Even some of recent study suggest to remove the intermetallic coating for the reason of weldabilty (Fan [10]). The reason is presence of Al_2O_3 and surface oxides after coating cracking due to high temperature plastic deformation.

The presented study focuses on an analysis of the surface layer of low-alloy martensitic steel and detection of potential negative impacts of the surface layer on weldability. It specifies material parameters that present a source of dispersion of static and dynamic strength of joints within a standard manufacturing process of high-strength components of the bodies.

2 Experimental material, methodology of analyses

The experiments concerned various meltages of martensitic steels 22MnB5 after hot stamping. We analysed a set of six stampings of different shapes in which instable welding process occurred. The typical chemical composition of the welded materials is given in Table 1. The study of the material's metallurgical weldability was based on an analysis of internal homogeneity and micro-cleanness of the material. The evaluated effect of the surface layer on the weldability was based on the (i) analysis of the chemical composition of individual sub-layers in crosswise scratch patterns; (ii) evaluation of differences in morphology and chemical composition directly on the surface layer of the stampings.

Samples for the structural analyses were taken from flat areas specified for point-welded joints, because the shape differences of the tested stampings can cause uneven cooling speeds during stamping (Fig. 1). The scratch patterns were produced by standard methods, etched with a 3% Nital solution. The structural analyses were performed by light and electron microscopy (SE), the chemical composition was analysed by an energy microanalysis method (EDX analysis).

Tab. 1. Chemical composition of stampings [wt.%]

C	Mn	Si	Cr	Al_{total}	Ti	B
0.25	1.25	0.25	0.19	0.043	0.04	0.0035

Regarding the chemical composition, the entire tested series of stampings satisfied normative requirements for the 22MnB5 steel. Samples for the structural analysis and for the surface layers evaluation were taken from the same positions. All the evaluated stampings showed a martensitic structure with an approximately identical share of bainite and partially tempered martensite.

3 Analyses of surface layers

An example of a typical composition of the surface layer is presented in Fig. 1, 2. The thickness of metallographically distinguishable sub-layers was measured on etched crosswise scratch patterns (positions 1 to 4 in Fig. 2). For each stamping, three samples from a specified flat area of the stamping were evaluated. The compared result for each sample represents an average value from at least three measurements in various positions on samples. The length of scratch patterns was 20 mm.

A difference of the diffuse - inter-metallic layer thickness was detected (in the measured parameter No. 2 in Fig. 2). In two stamping shapes, the thickness of the diffuse inter-layer was over 13 μm, i.e. about double (or twice) compared with the other stampings with a thickness of the inter-metallic layer of 6 – 9 μm. In addition, a different structure of heterogeneities in the volume of the coating was observed in these stampings. Unlike the remaining set of stampings with typically scattered isolated volumes of these heterogeneities, in stampings with higher intermetallic layer, another continuous "inter-layer" was formed in the volume of the coating (see Fig. 3 (a) in comparison with Fig. 2). The analyses of local differences in the chemical composition focused on these areas.

Fig. 1. Test stamping No.1

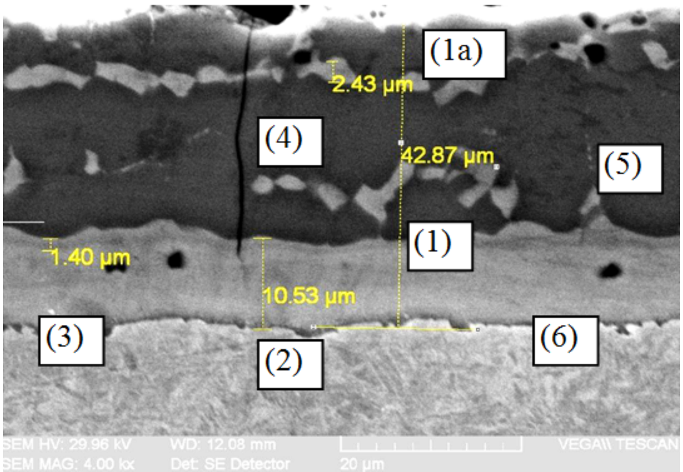
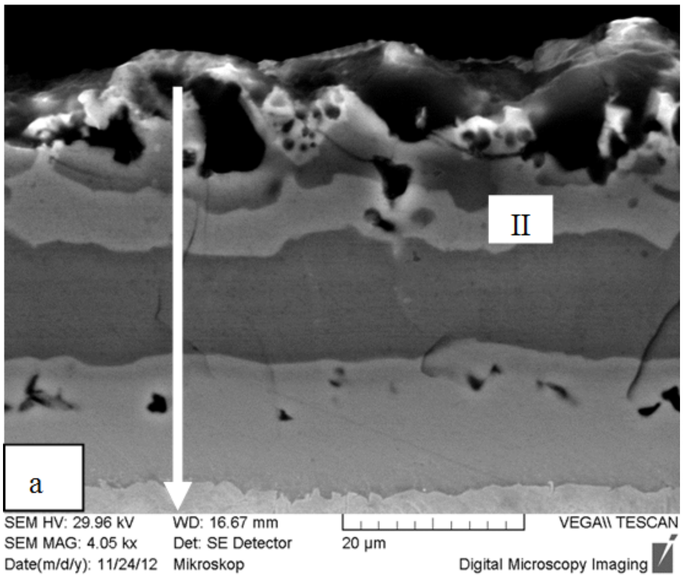


Fig. 2. Typical structure of surface layer

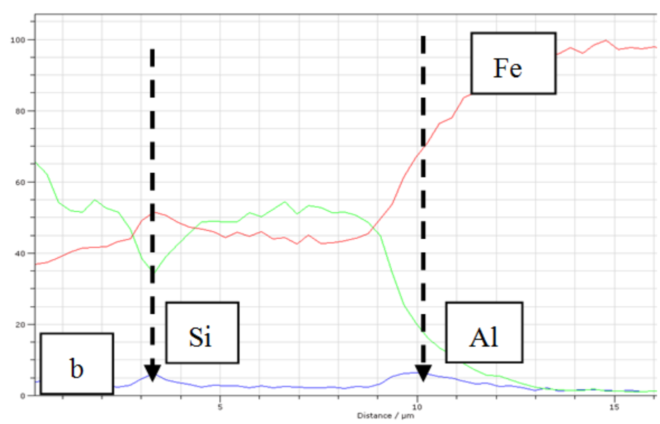
The chemical composition of the sub-layers was evaluated on scratch patterns. The positions of individual measurements correspond to measurements of the sub-layer thicknesses and is presented in Fig. 2: (1a) immediate surface layer; (2) diffusion layer bordering martensitic steel; (3) border between the diffusion layer and the remaining volume of the coating; (4) heterogeneities in the coating beyond the area of the diffusion layer; (5) homogenous area of the coating beyond the diffusion layer; (6) surroundings of hollows in the diffusion layer.

Changes in concentration of essential elements (Al-Fe-Si) in the sub-layers of the coating in a line perpendicular to the surface of stamping No.2 are presented in Fig. 3. Proportions of

Si-Fe-Mn elements in individual sub-layers were evaluated in succession to the detected geometric differences in the structure of the coating in the tested series of the stampings. Differences of Al/Si in the individual sub-layers are considered particularly important as regards the evaluated effect on the weldability. The results showed a twofold increase of Al/Si proportion in the basic volume of the layer, for example in stampings No.2 compared to No.1, i.e. the stampings where the deviation in the internal structure of the surface layer was detected. The non-compactness of the immediate surface layer (the 1a area in the mentioned measurement) did not allow a definite evaluation of the chemical composition in the crosswise scratch patterns. For this reason, the measurement was supplemented with a direct measurement from the surface. The measurement showed again an increase of the Al/Si proportion in stampings with identified deviation in the thickness of the inter-metallic layer.



(a) Measured along the arrow as a ratio of each elements



(b)

Fig. 3. Different structure of surface layer after intensive Al-Si-Fe redistribution

The results of the monitored relations are given in Fig. 4. Twofold increase of the proportion of Al/Si on the surface and in the volume of the coating (layer 5) occurs together with stabile proportion of Al/Si in layers bordering the basic material (layers 2, 3). This redistribution was thus produced by an increase of an inter-metallic layer and, at a certain stage, by the formation of a new inter-layer in the volume of the coat with an approximately identical Fe/Al/Si proportion. The increased Al/Si proportion on the surface of the stampings coincides with the measured parallel decrease of Al in the formed secondary inter-layer. According to the measurement, the increased thickness of the inter-metallic layer was accompanied with increased Fe concentration in the secondary inter-layer.

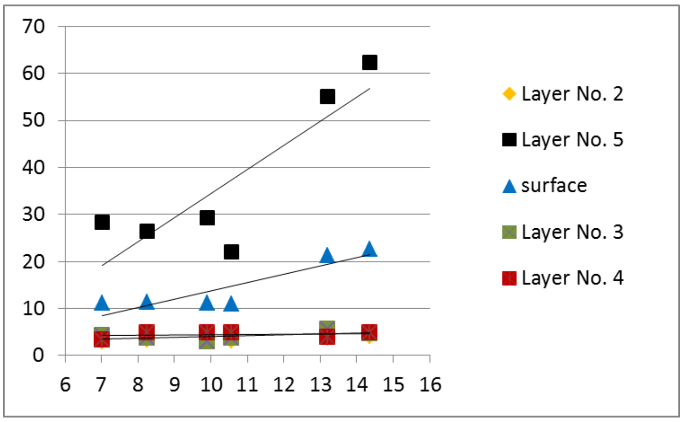


Fig. 4. Change of the Al/Si proportion [%] in relation with the thickness of the inter-metallic border of the coating

The mutual interconnection of the detected deviations in the internal composition and the Al/Si proportion manifest the dispersion of the performed heat treatment, particularly the differences in temperatures and the heating period during austenitization. This fact leads to differences in intensity of the diffusing processes that lead to the observed differences in the internal structure of the layers. The source of the undesired dispersion of weldability particularly comes from a tendency to form a secondary inter-layer with an increased Fe and Si content (zone II in Fig. 3). The measurement results suggest that these secondary layers are formed in combination with a thickness of an inter-metallic layer exceeding ca 13 μm.

The marked border in Fig. 4 corresponds to the detected limit thickness of the inter-metallic layer. Exceeding this limit leads to creation of another "secondary" layer enriched with Fe, thus an undesired effect on the weldability. A layer of oxide on the surface of the stampings increases with the growing heating period of austenitization. The changes of thickness in the layer of oxide on the surface of the stampings produce different surface colouring caused by interference. Stamped sections with detected diffusion redistribution of the monitored elements in the formation stage of a new "secondary" layer enriched with Si and Fe showed a certain distinction in the surface colouring within the tested series of stampings (difference in the blue-grey colouring intensity). The undesirable changes of the internal structure of surface layer can thus be indicated by a change of surface colouring.

4 Experimental welding

An experimental series of 25 spot welding joints was produced to evaluate the effect of the detected diffusion processes on the weldability. The experiment was based on a comparative evaluation of static strength and fracture behaviour of the welded joints, combining materials with extremes of the detected differences in the structure of surface layer. The selection of the welding parameters was based on a preceding optimisation of the technological welding process. The detected difference of static strength was 22 kN (in joints combining materials with a minimum thickness of the inter-metallic layer) vs. 17.6 kN (in joints of materials with the maximum thickness of the inter-metallic layer). This difference was connected with a differing position and curve of the fractures.

The curve of the fracture decisively affected the strength of the resistance spot-welds. Higher strength was achieved in a situation where the fracture was initiated in a zone of tempered martensite. Lower strength was connected with initiation of the fracture on the fusion line. The welding thermal cycle in this particular type of martensitic steel causes a local softening. The position and extent of this critical zone decisively affects the fracture behaviour and strength of the spot welds. The detected differences in the structure of surface layer affect the current flow during the spot welding. With a view to the stable characteristics of the remaining parameters in the tested series (the chemical composition, the micro-structure, micro-cleanliness, etc.), it is possible to connect the differences in the reach and intensity of the thermal impact during welding with the detected deviations of the coating.

4.1 Evaluation of the samples based on the scope of thermal effects

Current flow during spot welding is influenced by surface layer condition. Influence of diffusion processes in surface layer was evaluated by analysis of heat affected zone.

To assess the influence on the range of thermal effects there was evaluated:

1) the distance of the fusion zone

2) the distance of the softening zone

Representative samples for experimental welding were prepared from materials in the same state of the surface layer. After the static test, the scratch pattern was created and subsequently also the microhardness was created for determination of the heat affected zone (see Fig. 5).

The comparison showed that the differences in the diffusion zone did not produce measurable differences in regard of the positions of those layers. A comparison of the intensity of thermal effect on the material showed no difference in level of microhardness, but a measurable effect on the wide of tempered zone was observed. There was also found a tendency of precipitation of carbides along austenite grain boundaries. But in the reviewed cases, this trend did not lead to any negative effect on fracture behavior. Only ductile fracture mechanisms was observed, no intergranular fracture.

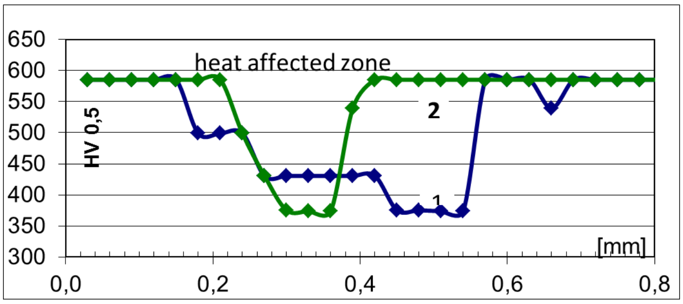


Fig. 5. Microhardness of compared sample (1-material with higher intermetallic layer, 2- material with lower intermetallic layer)

4.2 Creation of brittle inter-metallic phases

The quality of spot welding of the safety auto body parts can be decisively influenced by nonhomogeneous fusion zone. Specific heterogeneity was observed in some samples of operational weldments inside the weld metal. Energy microanalysis was conducted to investigate the chemical composition of the intermetallic layer in Fig. 6. Creation of brittle inter-metallic phases based on Al-Fe as a consequence of welding process was found out. Aluminum and silicon had melted in the Al-Si layer and were diluted into the weld metal during the cooling stage of welding. Both of these elements are soluble in iron and were homogenously distributed inside the solid solution but partially precipitated as an intermetallic phase along the fusion line.

Fracture behavior at different microstructural state of spot welds was analysed. A tendency to the brittle fracture mode instead of a ductile fracture was observed as a consequence of inter-metallic phase along fusion line (Fig. 7). Crucial effect mainly on the dynamic strength can be presumed (Paščenko [11]).

5 Conclusion

The presented results led to detection of basic tendencies in the formation of the internal structure of the surface layer in connection with deviations of the introduced heat treatment of martensitic steel 22MnB5. Coating by AlSi is applied during the heating phase (to the temperature range of $880-950°C$ for times of 5-10 min). The applied heat treatment leads to modification of the surface layer and at the same time diffusion of iron into the surface layer and surface oxidation of the layer.

The heat treatment creates a layered sub-structure with uneven distribution of Al-Si-Fe. The performed analyses document diffusion redistribution of Al-Si-Fe elements in the surface layer in connection with changes in the geometry of the internal structure of the layer. Increase of the temperature and the heating period leads to an increase of the thickness of diffusion layer and diffusion of Fe into the AlSi coating. Together with the rising Fe/Si, Fe/Al proportion, the volume of heterogeneities enriched with iron increases and the share of Al/Si rises in the immediate surface zone. Forming of a continuous "secondary" inter-metallic inter-layer in the volume of the coating with prevailing Al is particularly important for its impact on weldability. The share of Fe/Si, Fe/Al elements, i.e. the intensity of the impact on the current flow during welding, rises with the austenitization period in this secondary layer.

At the same time, the Al/Si proportion on the surface of the stampings rises, the surface oxidation becomes more intensive and porosity of the immediate surface layer increases. The rise of porosity and the content of oxides on the surface contribute to the instability of the welding process. A higher amount of pores leads to their random collapse, thus changing the current flow. The higher layer of oxides on the surface of the stampings affects the current flow.

The study of the crucial tendencies in diffusion re-distribution of the Al-Fe-Si components in connection with formation of undesirable "inter-layers" was based on an evaluation of local concentrations of these elements in relation to the thickness of the inter-metallic layer. Based on the performed experiments, the maximum limit thickness of the inter-metallic layer has been specified as 13 μm as the limit stage of these changes with a view to the researched impact on the spot welds' quality. Higher value by dispersion of the austenitization period causes instability of the welding process in the random combinations of the weldments.

The experimental evaluation of the weldability revealed the differences in softened zone. The formation of wider zone of tempered martensite was accompanied by the intergranular carbide precipitation. Regarding the fracture behaviour, the harmful effect on the fracture toughness can be estimated mainly in the case of more intensive precipitation. Formation of Al-Si inter-metallic phase along the fusion line was observed as the most harmful effect on the fracture behaviour.

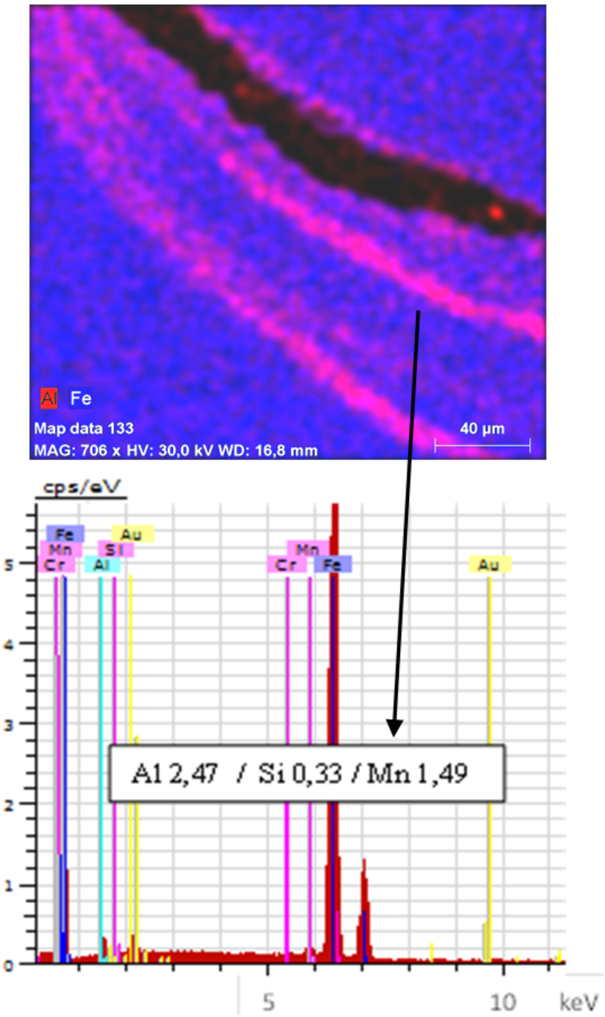


Fig. 6. Inter-metallic phase along the fusion line

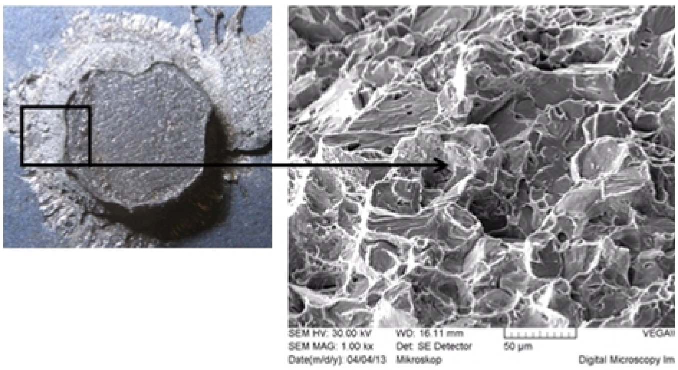


Fig. 7. Defective fracture mode due to the Al-Si phase along the fusion line

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