DYNAMIC FRACTURE BEHAVIOR OF THE MARTENSITIC HIGH STRENGHT STEEL AFTER SPOT WELDING

Schmidová Eva*, Culek Bohumil, Hanus Petr

University of Pardubice, Jan Perner Transport Fakulty, Studentská 95, 532 10 Pardubice, Czech Republic.

Abstract

Martensitic low alloy high strength steel grade of 22MnB5, used for automotive safety parts constructions, was subject of the experimental analyses of dynamic fracture behavior. The main purpose of the performed analyses was the qualitative and quantitative evaluation of heterogeneities due to the standard spot welding technology. The analyses also evaluate mechanical properties of the local heterogeneities. This enables computational prediction and also allows to sketch the influence of the strain rate on the weld joint load capacity. The dynamic resistance of heat affected zones compared to uninfluenced martensitic steel were the subject of suggested methodology for the evaluation of impact tensile strength; structural and fractography analyses were focused on an induced degradation process in terms of phase transformation and fracture mode.

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Keywords: Martensitic steel; heat affected zone; high strain rate; strain rate sensitivity

1. Introduction

Low alloy high strength martensitic steel is the key material in the design of safety parts of car body structures. Martensitic steel grade of 22MnB5 is one of the widely used AHSS steel grades, it is characterized by a martensitic matrix containing small amounts of ferrite and bainite. After the hot stamping process the components finally have a martensitic microstructure with a total strength of about 1500 MPa. The blank is formed and quenched simultaneously at a cooling rate of approximately 27 K/s. At a temperature of around 400 °C, a martensitic transformation is induced, which is finally resulting in high strength of the part [1].
Vehicle crashworthiness of high strength martensitic steel is greatly influenced by the fracture behavior of the weld joints [2, 3]. Critical part of the heat affected zone (HAZ) is sublayer of tempered martensite. The particular structural changes due to redistribution of carbon and final carbide precipitation are decisive for dynamic resistance of welded parts. The main problem for precise testing of this influence on dynamic strength is a presence of shear stress during the standard mechanical testing of welding joints. The strain rate over 1000 s^{-1} is often chosen for dynamic testing as a proportional to crash conditions. This presents highly non-linear deformation process. When the vehicle collides at the velocity of 60–80 km/h, the strain rate of the material can reach more than 1000 s^{-1}, leading to a significant change of the deformation behavior and energy absorption [4, 5]. The differences of strain rate sensitivity under influence of structural heterogeneities of HAZ of welding joints is substantially increased at this strain rate.

The dynamic resistance of HAZ compared to uninfluenced martensitic steel were the subject of suggested methodology for the evaluation of impact tensile strength of welded parts; structural and fractography analyses were focused on an induced degradation process in terms of phase transformation and fracture mode.
Simulation of the induced structural changes as a way to prepare homogeneous material for precise uniaxial dynamic tests was employed as the novel methods for the quantitative assessments of the heterogeneous microstructures in HAZ.

1.1. **Experimental procedure**

1.2. Microstructure evaluation and simulation of tempered zone

Applied welding technology has to be evaluated in terms of structural changes in HAZ. Primary martensitic microstructure with retained austenite after intensive thermo-mechanical treatment was observed in uninfluenced steel (Figure 1a). An essential degradation effect due to welding was found in the tempered zone; the presence of rough carbides along the grain boundaries (Figure 1b) can suppress the prior positive tendency to ductile high energy fracture. A drop of hardness by up to 12% compared to the primary state of high strength steel was measured in HAZ. This structural and mechanical heterogeneity is decisive for the position of initiated micro-cracks and, therefore, for the dynamic fracture resistance of spot welded parts.

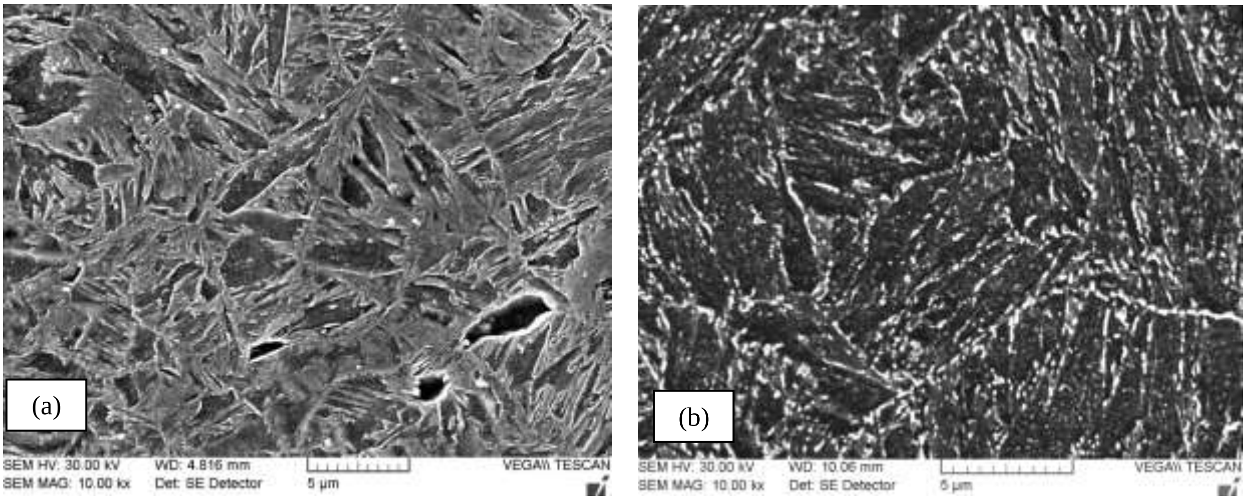

Fig.1. Uninfluenced microstructure of used martensitic steel (a) vs. microstructure of tempered zone (b).

To enable the study of dynamic response under defined loading conditions, a simulation of this critical sublayer was performed by controlled resistant heating process. Validation of the used simulation methodology was based on the structural evaluation, fractography evaluation and hardness measurement; the microstructure and static tensile fracture behavior were compared with the original welding joints. The samples with uniform dimensions and geometric parameters were prepared in the both states, i.e. after and without experimental heating (Fig.2).

2.2 Testing of strain rate sensitivity evaluation

The dynamic strength of the both states of martensitic steel was evaluated at different strain rates, with each step of the test adjusted to the real crash conditions. Different loading systems were used for the validation of results. The electro-hydraulic high speed loading system and the instrumented impact hammer system were employed under the same material and loading conditions. The main advantage of the impact hammer system is the direct information about absorbed energy as a distinctive parameter for passive safety application. A direct strain gauge measurement was used as the most precise evaluation of local strain development in a defined position of the loaded sample length during elastic deformation at strain rate over 10^3 s^{-1}.

The gradient of dynamic strengthening under a rising strain rate was estimated by the impact tensile tests for material conditions as follows:

- primary uninfluenced state of martensitic steel,

- tempered zone of welding joints, i.e. using the samples after simulation of mentioned degradation process,
- original welding joints.

Similar tendency of dynamic strengthening was found out for martensitic uninfluenced steel and welding points (Fig.2). More than two times increased maximal force of weldments and approximately the same increment of UTS was measured for basic material. Dynamic response of the material in structural state of tempered zone was partially influenced by structural degradation. This effect was observed mainly in the interval of strain rate from quasi-static up to 10^3 s^{-1} (Fig.3). Mentioned results indicate the slightly supressed intensity of dynamic strengthening in the zone of tempered martensite. It means the observed degradation process is emphasized by increasing strain rate.

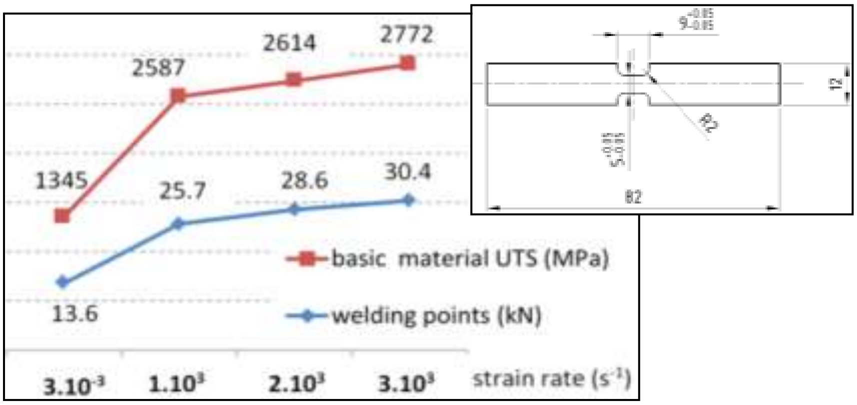

Fig. 2. Dynamic strengthening tendency of weldments compared to uninfluenced martensitic steel

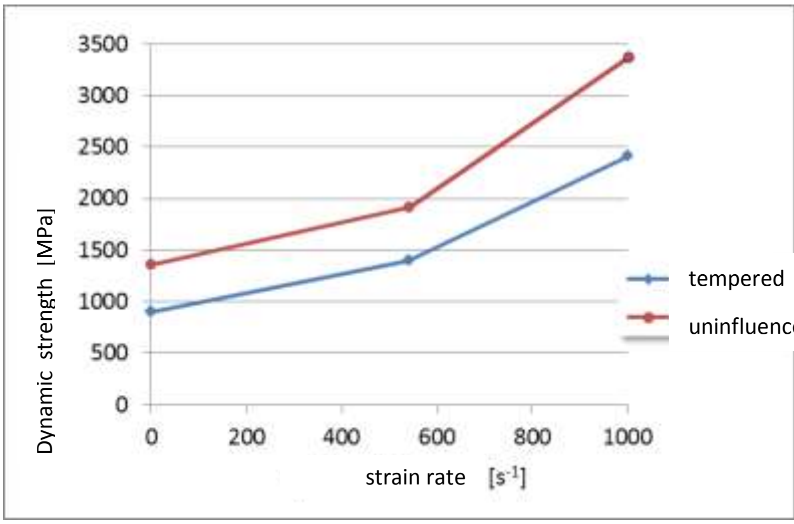

Fig. 3. Dynamic strengthening of simulated tempered zone compared to uninfluenced martensitic steel

In terms of fracture behavior, stable ductile fracture mode was observed for the both states – before and after simulation heat treatment during the whole range of testing strain rate (Fig.4). Locally suppressed plasticity was documented as an influence of carbide precipitation in tempered martensite - see positions pointed by arrows. Energy consumption to destruction was substantially lowered by simulation of the welding process, from 8,4J measured for uninfluenced steel to 4,10 J measured for tempered steel at the same strain rate of 10^3 s^{-1}.

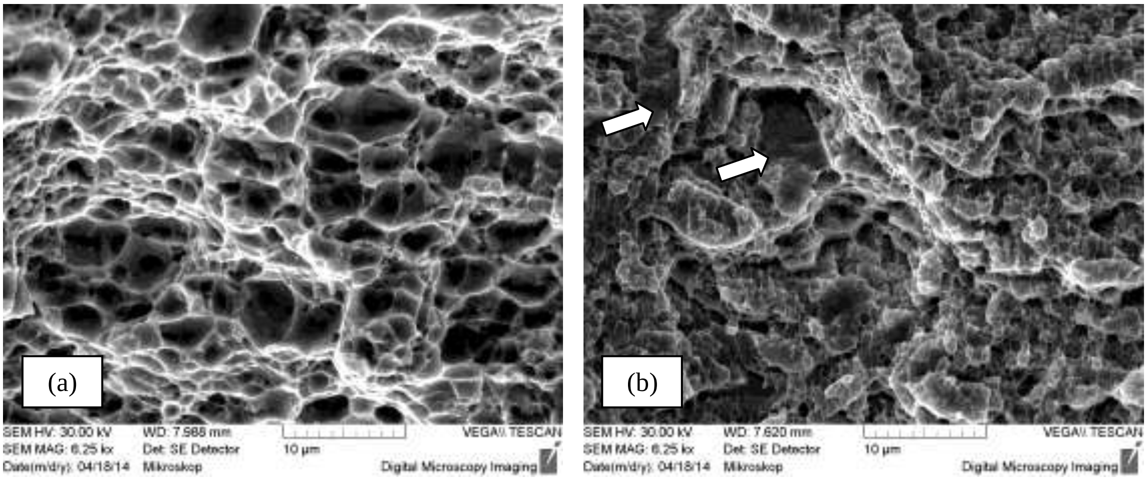

Fig.4. (a) Fracture morphology of uninfluenced martensitic steel after loading at strain rate 10^3 s^{-1}; (b) Fracture morphology of tempered martensite steel after loading at strain rate 10^3 s^{-1}.

2. Conclusions

The dynamic fracture behavior of spot welding joins of martensitic high strength steel type of 22MnB5 is primarily influenced by unstrengthening processes in HAZ. The softening of the tempered HAZ sub-layer is the decisive process determining the fracture position and finally the dynamic fracture mode. Structural effects in the sub-layer under the influence of 700°C are more limited than the generally critical fusion zone. Different stress-strain conditions for welding joints testing, compared to the standard uniaxial impact tensile tests, are the main obstacle for the desired direct evaluation of induced mechanical heterogeneities.

Dynamic strengthening tendency of martensitic steel grade of 22MnB5 was evaluated with a focus on the influence of the degradation process of the used spot welding technology. Carbide precipitation in the tempered zone was identify as the decisive process towards to decreasing of strength and toughness. The new methodology for assessment of local mechanical heterogeneity was suggested. Simulation of tempered zone enabled the uniaxial impact tensile tests of HAZ and the uninfluenced parent martensitic steel at same stress conditions.

During the tensile tests, the strength of steel sheets is mainly determined by comprehensive function of the strain hardening, the specimen size variation and the effects of strain rates sensitivity and adiabatic temperature rise softening. During deformation under adiabatic conditions, there are two opposing effects, namely work hardening and work softening, the former being dominant at low strains and the latter more of an influence at higher strains [6]. The dislocation movement is hindered owing to the intertwining of dislocation, which causes the strain hardening. The of dynamic hardening process is strongly influenced by primary cooling rate, i.e. by primary microstructure [7]. At high strain rates, however, the plasticity is restricted. According some experimental analyses [8], both the high density dislocation and the twinning in martensite block the dislocation motion so that the work hardening and strain rate hardening effect of the martensite is limited.

A high sensibility to the strain rate was observed for the both states of microstructure – after and before experimental heat treatment. The samples after softening process due to tempering of martenzite displayed partially lowered strengthening effect, it means the degradation effect is emphasized by increased strain rate. Intensive strengthening effect was measured for the both state up to strain rate of 10^3 s^{-1}. in contradiction to research.

Ductile fracture mode was observed for the both conditions at the whole interval of testing strain rates. Tested steel shows a great potential for energy absorption at high strain rate such as 3.10^3 s^{-1}.

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