LOCAL ELASTIC-PLASTIC RESPONSE OF WELDING JOINTS OF DOMEX700MS STEEL

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Abstract

The paper deals with degradation of the structural and mechanical parameters of DOMEX 700MC steel due to welding process. It is focused on evaluation of the mechanical heterogeneities influence at higher strain rate. DOMEX 700MC presents the micro-alloyed steel with the growing utilization. Especially for the lightweight construction of the transportation means. The precise characterization of material behavior at high strain rate is of great importance for reliable prediction of welded parts in that application.

Evaluation of the local mechanical parameters of experimental welding joints was performed. The three-point instrumented dynamic fracture analyses and instrumented indentation tests were employed to study the elastic-plastic response of critical weldments sublayers. The static vs. dynamic yield strength and energy consumption to fracture was compared in different stages of temper influence. Structural analyses brought the information about the conducted structural changes in tempered zone. Fractography analyses were focused on evaluation of local differences in fracture behavior influenced by real metallurgy quality. Based on the experimental results, the used combination of loading method is suitable to determine the local mechanical properties and enable the estimation of temper sensitivity of analyzed steel.

Keywords: DOMEX 700MC steel, dynamic fracture, indentation test, welding joint

1. INTRODUCTION

The use of high strength steels in railway applications has grown over the years. High strength steels, used for rail vehicles chassis, offer advantages such as reduced weight, reduction of fuel consumption and increased payload. However, the motivation to convert rail vehicles is currently substantially restricted due to the effect of welding. A comprehensive study of structural and mechanical changes caused by particular welding technology is necessary for successful adaptation of the improved steels grades.

Intensive structural and mechanical heterogeneity as a consequence of welding causes localised micro-plastic deformation during operational loading. Because of that, prediction of the actual degradation state requires an evaluation of the elastic-plastic behaviour of all the sublayers of the heat affected zone (HAZ). The limited reach of the crucial effects does not allow the usage of standard uniaxial mechanical tests for precise determination of the required mechanical parameters. The standard hardness measurement partially reflects the intensity of hardening or softening, but without giving detailed information about the elastic response of the material. The instrumented indentation test allows evaluation of the local mechanical parameters, including the residual plastic capacity of the crucial sublayers of welds [1]. It can provide the necessary information about re-precipitation processes even in connection with depletion of creep resistance [2].

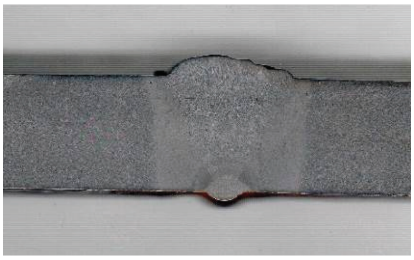
Domex 700MC, a thermo-mechanically hot rolled cold forming steel, characterized by a low carbon content and small addition of micro-alloying elements, was tested in this study. The steel grade of S355 was examined as comparative steel commonly used for the mentioned application.

2. METHODOLOGY OF EXPERIMENT

Experimental welding of Domex 700MC steel (chemical composition in **Table 1**) plates was performed by using shielded metal arc welding - see **Figure 1**. Electrodes of ESAB OK 78.16 were used in three layers with specific heat input of 4.2, 4.6 and 5.3 kJ/mm.

Table 1 Chemical composition of tested steels [wt. %]

	C	Mn	Si	P	S	V	Al	Ti	B
DOMEX 700MC	0.13	1.23	0.21	0.02	0.024	0.05	0.026	0.01	0.0005
S355	0.06	1.82	0.27	0.012	0.003	-	-	-	-



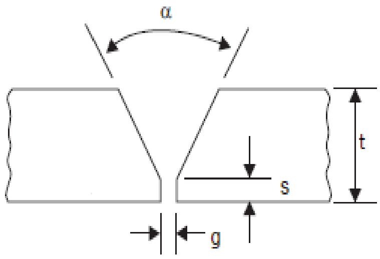


Figure 1 The weld geometry (α = 60°, t = 10 mm, s = 2 mm and g = 3 mm)

The induced degradation process was studied by a set of analyses after experimental welding:

- Instrumented impact tests were performed using the Zwick RKP 450 tester, impact energy 450 J, impact speed 5.23 m/s, at room temperature. The two most important parameters - a dynamic yield force F_{gy} (N) and energy consumption for destruction W_T (J) were monitored using instrumented three point bending. Different positioned V notch samples (in the basic material, head affected zone, fusion zone and weld metal) were tested at least three times.

  Dynamic yield strength was obtained from dynamic test results [3];

$$R_{p0.2} = \frac{3F_{gy}W}{B(W-a)^2} \tag{1}$$

  where "F_{gy}" is general yield force, "$W = 7.5\ mm$" is the sample width, "$B = 10\ mm$" is the sample thickness and "$a = 2$" is the initial crack length.
- The local static properties of the weld critical sublayers were evaluated by comparative indentation test. Micro-indentation tests were conducted by use of a spherical indenter with diameter 1mm; the maximum load was chosen as 1kN to achieve fully plastic deformation. The elastic-plastic capacity of distinctive layers of welds, e.g. along the fusion line of the weld, was compared with the uninfluenced material by use of the representative stress and strain approach according to Tabor's formulae [4]. Static yield strength was extracted from force-depth indentation curves, where the constraining factor was chosen as equal to 3.
- Structural analyses were employed for identification of dominant heat-stress effect due to used welding technology.
- To find out the reach of the stress-strain zone of an indentation test, finite element analyses (FEM) were performed.
- As a validation of obtained indentation results, the tensile tests were carried out at strain rate lower than $10^{-3}s^{-1}$ using the standard round bar specimens of 6mm in diameter.

3. RESULTS AND DISCUSSION

The representative unfiltered standard force (N) - standard travel (mm) curves are documented in **Figure 2.** Primary micro-segregation of carbon together with local influence of impurities played a vital role in fracture response. Local defective fracture behaviour was much more frequent in basic material - see **Figure 2A** vs.

Figure 2B. From this point of view we can consider the heat input even as a partially positive effect; carbon redistribution has led to local homogenization of structure and so has suppressed the defective fracture. The influence of welding was observed as distinctive in the fusion zone. An intensive decrease of dynamic yield strain and absorbed energy is displayed in **Figure 3**. The lowered absorbed energy to fracture indicates that the overall decrease of plasticity worked together with lowering of onset of yielding. As the welded construction parts of transport means are often loaded by undefined impact load components, this influence of welding is important from the point of view of the operational safety.

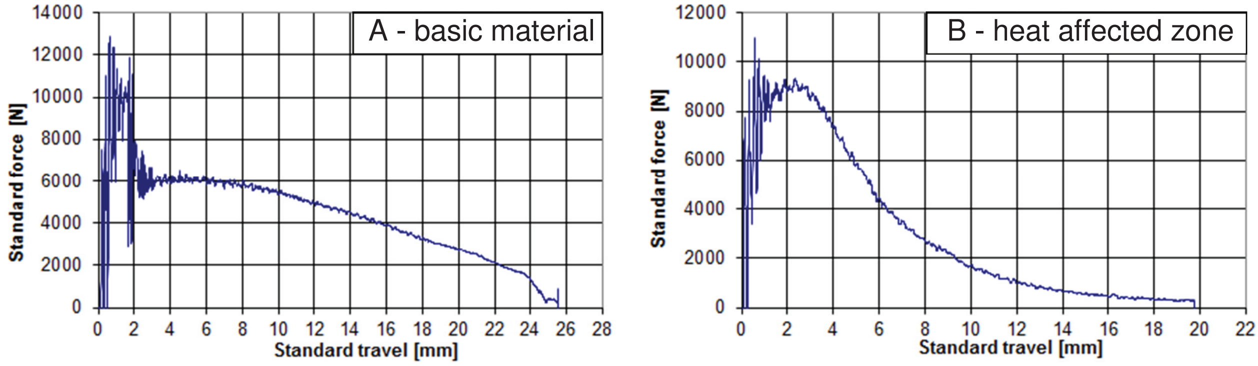


Figure 2 Dynamic response of Domex700MC steel

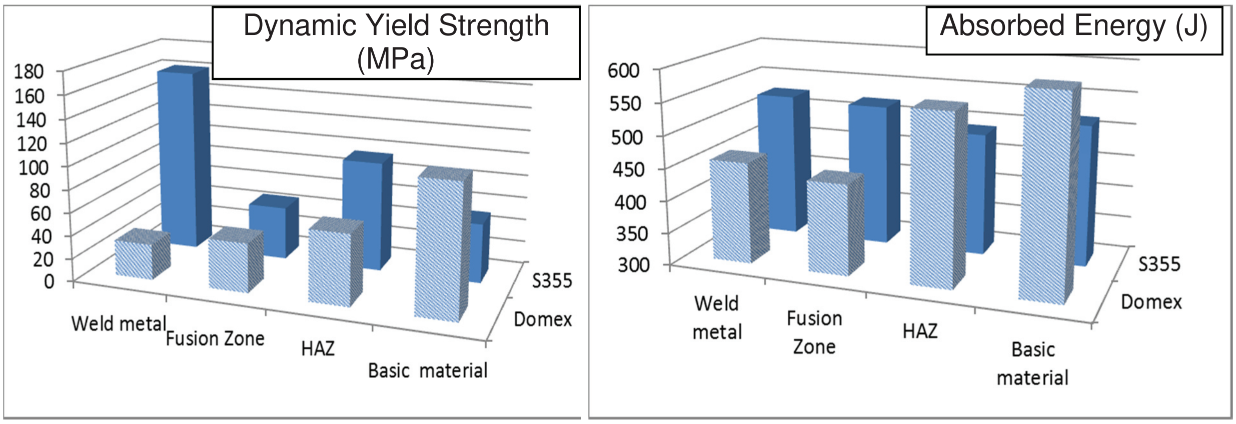


Figure 3 Comparison of influence of the welding on dynamic parameters of Domex700MC vs. S355 steel

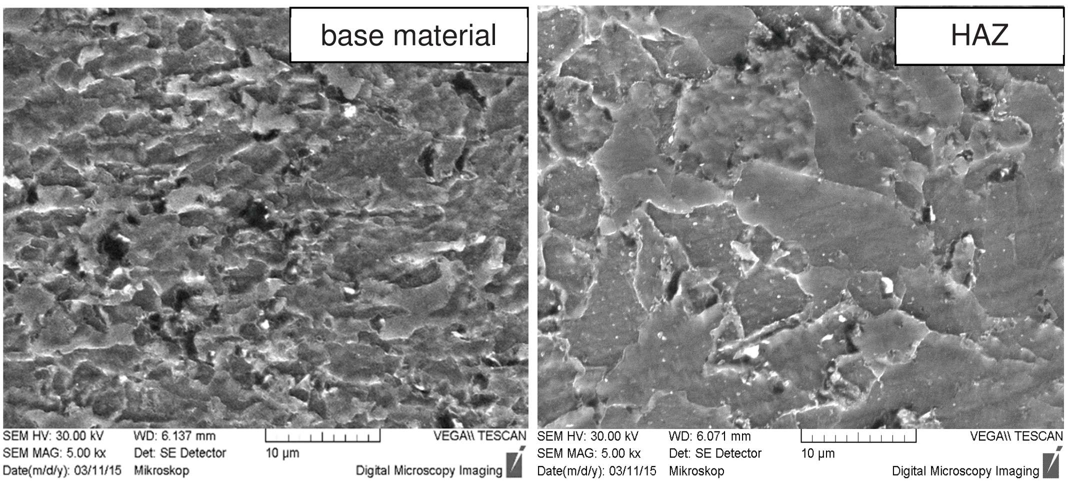


Figure 4 Microstructural changes due to welding

Structural analyses revealed the source of measured difference in local dynamic resistance. The layer along the fusion zone was identified as distinctive for the final strength of weld. The reprecipitation of carbides of Domex700MC steel was predominant and together with grain coarsening decreased the initial strength of parent steel substantially. The above-mentioned structural effects are pictured in **Figure 4**.

Micro-indentation tests were focused on the critical degradation process of Domex700MC steel. The typical indentation load-indentation depth curves for compared positions of experimental weld are presented in **Figure 5** Substantial decrease of comparative yield stress $\sigma_{y(ind)}$ due to the welding process was measured - see **Table 2.**

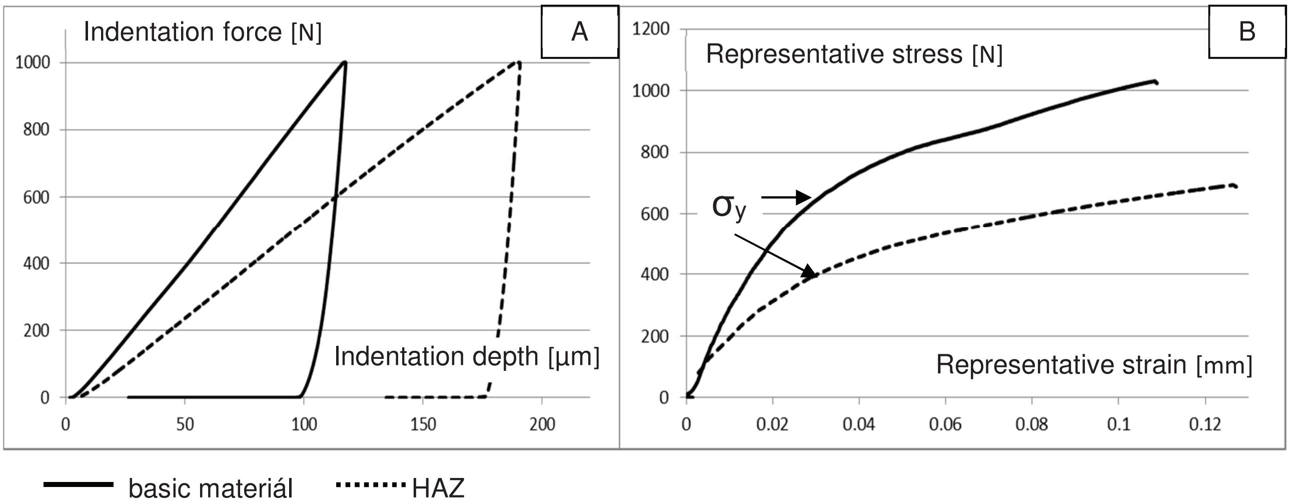


Figure 5 Representation of indentation test procedure (A - indentation curves, B - representative stress-strain characteristics according Tabor´s equations)

Yield strength was detected from representative stress - strain curves; a directive of the curve slope was decisive for the chosen evaluation. The onset of macro-plastic deformation was defined as a point at a decrease of 10% slope. The results for weld metal and HAZ compared to uninfluenced material are presented in **Table 2**.

Comparison of the parent materials indentation yield stress $\sigma_{y\,(ind)}$ showed the corresponding values with the yield stress measured by standard tension test. The deformation hardening effect expressed by representative stress-strain curves differs from the values obtained from true stress-strain curves at equivalent strain interval. This is due to the nature of Tabor's formulae, which average the large volume of strained material with the different level of actual hardening [5].

Table 2 The effect of welding on the yield point identified by indentation

Position/No.of measurement		1	2	3	4	5	$\sigma_{y(ind)}$ [MPa]	σ_y [MPa]
Domex700MC	Weld Metal	860	862	864	871	868	865 ± 4.0	-
	HAZ	326	329	321	331	328	327 ± 3.4	-
	Basic Material	681	691	698	687	685	688 ± 5.8	630± 2.3

The used model for yield point determination assumed a homogeneous material within the whole loaded volume in every tested position. The local microstructural differences and so the gradient of mechanical parameters should be considered in the HAZ; at least the difference between the coarsened sub-layer and the rest of the influenced volume. The thickness of this layer in ratio to the size of the loaded volume plays a vital role in mechanical response measured by indentation. The measured volume must not exceed the reach of decisive degradation mechanisms. Even the principle of similarity loses its validity when the size of the loaded volume becomes comparable with the size of structural heterogeneity [6]. To interpret the reach of the stress-strain field induced by indentation, finite element analyses (FEM) were conducted. The ANSYS software was used for the FEM model. The quadratic hexahedral volume elements were used and the indentor body were defined as rigid.

The contact system between the specimen and the indentor was consider as a frictionless (frictional with the zero frictional coefficient). The tested material was assumed as isotropic with the mulitilinear isotropic hardening plasticity model based on the experimental work-hardening curve. True stress-strain behaviour of tested material was obtained by linear extrapolation after conversion of the engineering values with assumption of volume conservation during deformation. The extent of total deformation compared to residual plastic deformation (**Figure 6**) showed the restrictions of the used indentation test parameters for this application. The distinctive for chosen test parameters is reach and substance of structural heterogeneities. In this case the metallurgy imperfections in the parent steel require a wider zone for testing, contrary to the critical sublayer of HAZ, which requires a much thinner zone for testing. The advantage is the possibility to control multiaxial inhomogeneity of mechanical behaviour [7]. The actually detected zone was more than 1 mm in width in this case; that means the attacked zone exceeds the reach of the grain coarsening effect along the fusion zone. On the other hand, the attacked zone is comparable with the zone at the top of the notch tip according to the standards for 3-point dynamic bending test. Because of that, we can consider the used combination of testing procedures as suitable for this application.

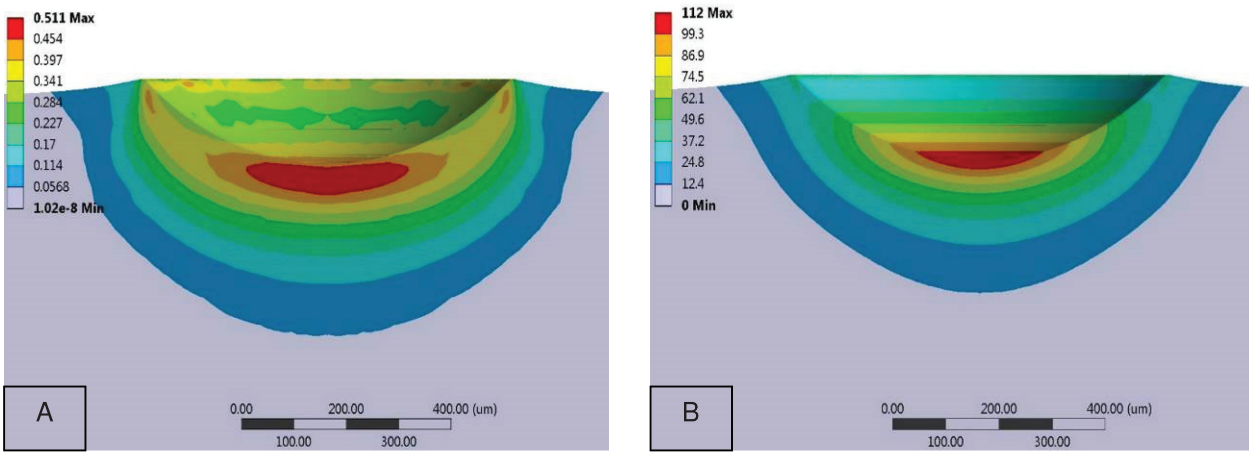


Figure 6 The extend of the equivalent total strain (A) vs. total deformation (B) at maximal load

4. CONCLUSION

Two methods for prediction of the welding influence on elastic-plastic response of the Domex700MC steel were performed: a dynamic three point bending instrumented test and micro-indentation test. Metallography analyses and the supporting FEM analyses of the indentation allowed estimation of the reach of the degradation mechanisms vs. the reach of the indentation strain field.

Based on performed analyses we can conclude that the yield point obtained from indentation is consistent with the tensile test data for the used type of steel. Spherical indentation can be generally used for estimation of elastic-plastic behaviour of materials, but not as a substitution of the standard tensile tests because the indentation loaded volume is different and loading is not uniaxial. It allows an evaluation of local mechanical response and so to consider the inequality of the mechanical properties for welded parts design.

The degradation process of the Domex700Mc steel due to welding process was evaluated with the focus on the sublayer near the fusion zone. Instrumented static and dynamic tests were employed to find out the real difference of the mechanical response in the critical layers of the welds. Drop of the static and also the dynamic resistance to plastic deformation together with decreased energy consumption to dynamic destruction has confirmed the justified requirements for precise testing of the used welding technology. Observed structural effects along the fusion zone can substantially change the propagation of micro-plasticity and so the relaxation of stress induced by welding. Mainly a decrease of the absorbed energy is crucial from the point of operational safety welded construction parts.

Based on the performed analyses, it can be concluded that the used combination of methodology enables the evaluation of the degradation process in the critical part of the weld mainly for advanced thermomechanical treated steels. FEM analyses are suitable as a validation of measured volume, which is necessary to control the ratio to required width of the measured layer. In such a case, the analyses can provide information about the real restrictions of the used indentation test parameters.

ACKNOWLEDGEMENT

This work has been supported by the "Competence Center of Railway Vehicles", Project No. TAČR TE01020038.

REFERENCES

[1] YAN, J., KARLSSON, A.M., CHEN, X. Determining plastic properties of a material with residual stress by using conical indentation. *International Journal of Solids and Structures,* 2007, vol. 44, pp. 3720-3737.

[2] MOHYLA, P., FOLDYNA, V.Improvement of reliability and creep resistance in advanced low-alloy steels. *Materials Science and Engineering A,* 2009, vol. 510-511, pp. 234-237.

[3] HARTWIG P., New Method for Fracture Toughness Determination on Railway Wheels, Valdunes S.A.S., Unpublished Rpt., 2005.

[4] TABOR, D.: *The Hardness of Metals. 1st ed.* Oxford, Clarendon Press, 1951, 123p.

[5] HAUŠILD, P., MATERNA, A., NOHAVA, J. On the identification of stress-strain relation by instrumented indentation with spherical indenter. *Mater. Design, 2001, vol.* 37, pp.373-378.

[6] MENČÍK, J. Limitations of similarity principle in indentation testing of small samples. *Key Engineering Materials, 2014,* vol. 586, pp. 51-54.

[7] SONG, W.S., KIM, S.G., KIM, I.CH., KWON, D. Use of Spherical Instrumented Indentation to Evaluate the Tensile Properties of 3D Combined Structures. *Journal of Electronic Materials*, 2015, vol. 44, no. 3, pp. 831-835.