LASER BEAM WELDING OF STEEL-ALUMINUM JOINTS - INFLUENCE OF WELD METAL ELASTIC-PLASTIC PROPERTIES ON THE DISTORTIONS

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ABSTRACT

Great attention is focused nowadays on laser welding of dissimilar steel-aluminum joints in overlap configuration in key-hole mode. It was found that elastic-plastic properties of the weld metal exhibit strong difference to those of the base alloys and can be defined as a function of aluminum content in the weld metal. A developed Finite-Element simulation model allows prediction of the aluminum content as a function of welding parameters and subsequently the elastic-plastic properties of the weld metal as a function of the determined content. The main goal of the present study is to show the impact of the weld metal properties on welding distortions and residual stresses. For that purpose, a sensitivity analysis of the thermomechanical model was performed, where the distortions and residual stresses were computed as a function of welding parameters and therefore as a function of corresponding weld metal properties. The analysis showed that the influence of the weld metal is essential, and its properties should be taken into consideration in the models for better prediction accuracy.

Keywords: Laser welding, FEM, Distortions, Residual stresses, Dissimilar welding

INTRODUCTION

The application of hybrid lightweight structures, which possess good mechanical properties and lower weight, offers enormous technical and economic potential. Combinations of aluminum and steel are particularly interesting for modern lightweight design concepts. The joining of dissimilar metals within hybrid structures is still a challenging task.

Lately, the attention of researchers has been attached to the thermal joining processes such as brazing–welding-brazing [1], laser welding in conduction mode [2] and key-hole laser welding [3–6] of St-Al joints. In this work the keyhole laser welding is considered. In works [3–9] the researchers concentrated mainly on optimization of the welding parameters to increase the global tensile strength of the joints and on an investigation of the weld quality with respect to the formation of Fe–Al intermetallic compounds. It was found that the intermetallic phases at the weld – aluminum boundary is the weak spot of the joint which causes the fracture under subsequent loading. However intermetallic phases are formed on a micro level and therefore they do not affect another important issue such as distortions and residual stresses after welding.

It has been found that besides the formation of the IMC phases on the weld – aluminum boundary, the mechanical properties of the dissimilar weld metal itself undergo significant changes and differ strongly from properties of the both participating base metals. The authors [3–6] confirmed a strong increase in hardness and related this to the aluminum concentration in the weld. In the work [10] the weld metal was investigated with respect to its basic mechanical properties such as Young's modulus, yield stress, and strain hardening exponent. It was revealed that the yield stress of the mixed weld metal is significantly higher than the yield stress of the participating base alloys, however, Young's modulus and strain hardening exponent vary slightly with and remain almost on the same value as those of the steel. The weld dimensions are on the macro level and the strong changes in the mechanical properties of the weld metal can affect the overall behavior of the joint with respect to distortions and residual stresses. The method proposed in [10] for determination of the weld metal mechanical properties is time-consuming and required special equipment. Since mechanical properties of the mixed steel – aluminum weld metal can't be quickly determined, the following aspect becomes important for the welding FE simulation models. It is necessary to investigate how the change in the mechanical properties due to the mixing of liquid steel and liquid aluminum in the weld pool affects the distortions and residual stresses after welding.

Therefore, the main goal of the present study is to show the impact of the dissimilar weld metal and its mechanical properties on a calculation of welding distortions and residual stresses. First, the comparison between the distortions and residual stresses calculated with and without consideration of the change in the weld metal mechanical properties was performed. Second, the influence of the basic mechanical properties and their variations on the distortions was demonstrated by performing the full factorial sensitivity analysis.

VALIDATION OF THE FE MODEL

EXPERIMENTAL SETUP

Prior to the sensitivity analysis, the developed simulation model was validated. The validation took place on geometrically simple components. Instrumented laser beam welding of two metal sheets in steel on aluminum overlap configuration served as an initial set up (Fig. 1). The sheets for the trials were austenitic steel X5CrNi18-10 (1.4301) with 1.5 mm sheet thickness and hardenable 6082-T6 Al alloy of the same thickness. The sheets were fixed on both sides by the clamping claws so that the optical access to the lower surface for the displacements measurements was available. The displacements of the sheets were determined optically, based on stochastically distributed gray value patterns on the underside of the sample. No special pre-processing of the welding surfaces was done prior to the joining.

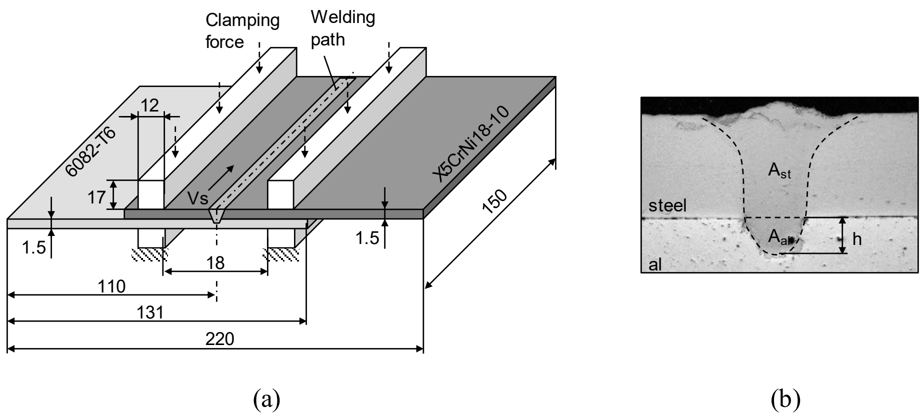


Fig. 1 Scheme of the welding (a), typical St-Al joint (b)

A disk laser was applied for the welding. The welding parameters were experimentally determined to obtain defect-free joint. The final parameters were set to laser power P = 3,75 kW, welding velocity V_s = 4,8 m/min. The selected welding parameters lead to stable process conditions. Two welding trials were performed in cooperation with Laser Zentrum Hannover e.V. (LZH). The cross section of the St-Al joint is shown in Fig. 1. *h* is the weld penetration depth, the ratio A_{st}/A_{al} defines the dilution.

FE MODEL

For the lap joints, the complete geometry of the plates must be considered, as there is no symmetry due to the different material properties and asymmetric configuration of the plates relative to the welding line. The meshing strategy is shown in Fig. 2. A coarse mesh was adopted for the region far from the weld area. The element type for thermal process analysis with FE-Code ANSYS® is the eight-node hexahedral element SOLID70 and the four-node surface contact elements CONTA 173 and TARGET 170 for modeling the overlap region (thermal and mechanical contact). The full model consists of approximately 210 000 nodes and 240 000 elements. Element size lengths in zone 1: 0.15 × 0.5 × 0.15, in area 3: 0.25 × 1 × 0.25 and in the range 5: 2 × 2 × 0.5 mm. The transition areas 2 and 4 consists of pyramidal elements. The meshing strategy allows to save a CPU time, achieve high accuracy and get rid of bad shaped elements, which can be a source of the unconverged solution during the thermomechanical simulations. The material thermophysical properties can be found elsewhere [11]. The change in thermophysical properties of the weld metal due to the mixing in the weld pool was not considered for the thermal simulation. The heat losses into the ambient were considered as the heat exchange through convection and radiation under the assumption of distinct film coefficients for steel and aluminum. The special thermal contact between the plates was defined. With regard to details about the thermal model, readers can refer to [12].

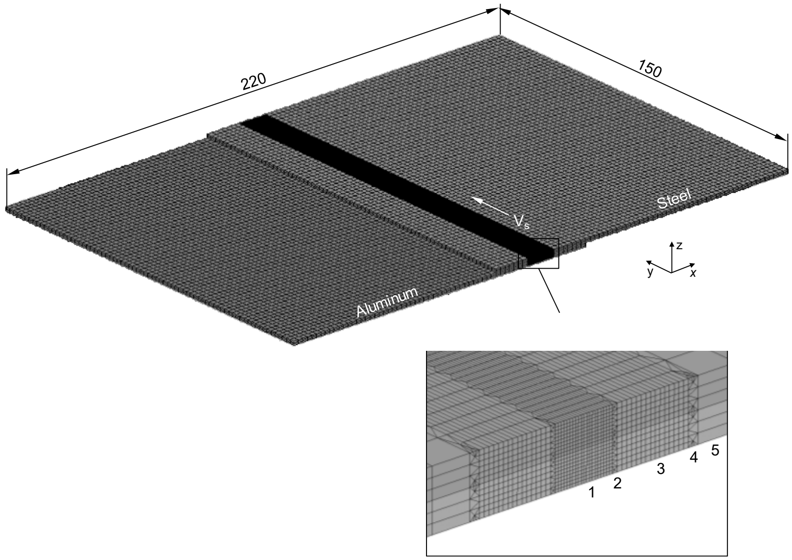


Fig. 2 Meshing of the FE model.

For the thermomechanical simulation, the ideal elastic plastic material model for steel, aluminum and weld metal was implemented. The steel and aluminum alloys were extensively examined in the work [11]. The properties of the dissimilar steel – aluminum welds were determined in the work [10]. The softening of the steel and aluminum in heat affected zone were considered as a function of maximal temperatures. The hardening of the weld metal due to the mixing was implemented as a function of the average aluminum concentration in the weld, which is calculated automatically after the temperature simulation, based on the ratio of melted steel and aluminum elements. The research [10] showed that the aluminum concentration and mechanical properties within the weld metal are quite homogeneous. Therefore, for the simulation, the homogeneous weld metal material model was assumed. The properties of the weld metal were taken from the study [10]. Yield stress σ = 950 MPa, Young's modulus E = 200 GPa. For the thermal expansion coefficient, a linear mixture is assumed, derived from the area fraction values presented in Fig. 1. The thermal expansion coefficient of the weld metal was assumed as a linear mixture, derived from the area fraction values. The user subroutine for an accurate description of the materials properties was implemented directly into the ANSYS code. Modeling of the clamping jaws and contact conditions between them and the sheets brings additional complexity to the model. It requires more computational time and often results in convergence problems. To avoid application of the contact elements the influence of the jaws was approximated with the spring elements. The nodes which belong to the area of contact between the jaws and the sheets, get the non-linear spring elements. The springs act in plane of the sheets and representing the friction forces. On the upper side the normal forces to these nodes represent the clamping force. On the underside the displacement on the nodes is blocked. The mechanical contact between plates was set to exclude the penetration of the sheets. The bonding temperature was set to the melting temperature of the aluminum alloy.

Transversal shrinkage (X), longitudinal shrinkage (Yst, Yal) and out of plane distortion (Zst, Zal) (Fig. 3) were calculated and compared to the measured values. The results are summarized in Table 1. According to Table 1, the calculated and measured transverse and longitudinal shrinkage is in an excellent agreement. The deviation between the calculated and measured out of plane distortions Zst and Zal arise possibly due to the approximation of the jaws by the normal forces acting at nodes. It should be noted that the measured and calculated displacements are very small, and therefore some deviations can arise due to the inaccuracies of the measurements. In general, it can be concluded that the developed model allows the correct prediction of the distortions after welding.

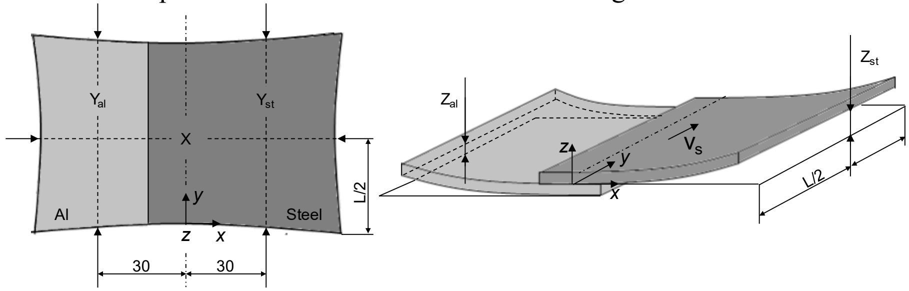


Fig. 3 Distortions of the lap joint. *L* is the length of the sheets.

Table 1 Validation of the model. Calculated and measured distortions (in mm)

Distortions (Fig.)	P= 3,75 kW, V_s = 4,8 m/min		
	Exp 1	Exp 2	FEM
Transverse shrinkage *X*	-0.04	-0.057	-0.0474
Longitudinal shrinkage of steel Y_{st}	-0.02	-0.01	-0.0187
Longitudinal shrinkage of aluminum Y_{al}	-0.03	-0.031	-0.027
Out of plane distortion of steel Z_{st}	0.25	0.32	0.45
Out of plane distortion of aluminum Z_{al}	0.44	0.54	0.78

SENSITIVITY ANALYSIS

Sensitivity analysis aims to describe how much model output values are affected by changes in model input values. In this study the mechanical properties of the dissimilar steel – aluminum weld metal serve as the input parameters and the distortions as output responses. A full factorial design was chosen in the current work for the sensitivity study. Such an experiment allows the investigator to study the effect of each factor, as well as the effects of interactions between factors on the response variable. From the CPU point of view, the model was reduced to 50 mm in length (Fig. 4). For the sensitivity analysis, the longitudinal shrinkage Yst and Yal differ from the ones shown in Fig. 3. Yst is the shrinkage along the welding line on the top and Yal along the welding line on the bottom (Fig. 4). Transverse shrinkage X and out of plane distortions Zst and Zal are the same as presented in Fig. .

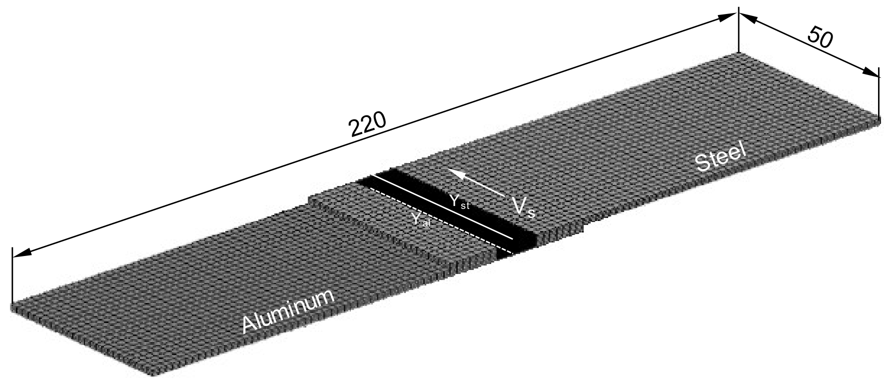


Fig. 4 Reduced model for the sensitivity analysis.

The first step of the sensitivity analysis involves an identification of the important input variables and their suitable working range. Due to the ideal elastic plastic material model assumed for the simulation, the strain hardening exponent plays no role. The following parameters were considered as input parameters: yield stress σy, thermal strain coefficient α and Young's modulus E. The input parameters were divided into discrete levels. The upper limit of a factor was coded as +1, the lower one was coded as −1. Simulation runs are made for all combinations of parameter levels. In the current study, three input parameters gives 8 simulations to be performed. The input parameters with their coded levels as well as the assumed properties of the real weld are listed in Table . The lower and upper values of the yield stress and Young's modulus were chosen based on the estimated accuracy of the indentation technique for the determination of the mechanical properties of the weld [10]. The lower level for the thermal expansion coefficient was chosen as the one of the steel and the upper limit was chosen as for the weld metal containing twice more aluminum than the real weld. A full factorial design contains all possible combinations of low/high levels for all the factors (Table 4).

Table 2 Summary of the input parameters and their levels

Input variables	Code levels		Assumed properties of the real weld
	-1	+1	
Yield stress, MPa	800	1100	946
Thermal expansion coefficient, $10^6 k^{-1}$	18.3	19.9	19.12
Young's modulus, GPa	180	220	200

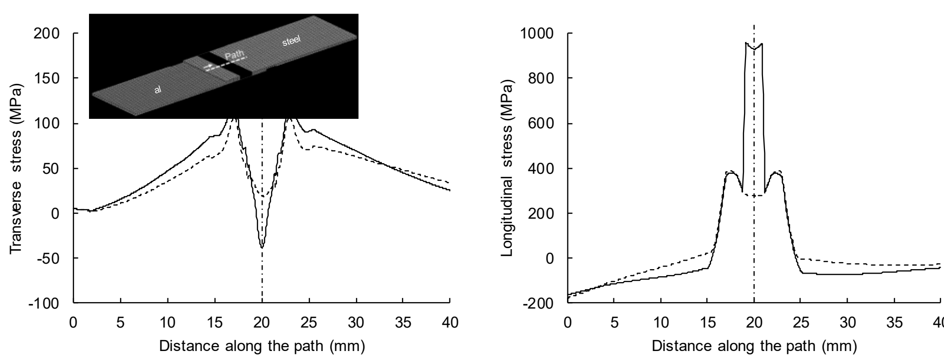
RESULTS AND DISCUSSIONS

In Table 3 the calculated distortions with consideration of the weld metal mechanical properties (computation 1) is compared to the calculated ones, where the properties of the steel were assigned to the weld metal (computation 2). In brackets, the deviation from the reference value is shown for each type of distortion. The reference value implies the distortion when the mechanical properties of the weld are considered (computation 1). It is obvious from Table 3, that the most affected response values (compared to the reference) are the longitudinal shrinkage Yst and Yal. However, it is important to note that the absolute values are extremely low. The relative deviation of the out of plane distortion Zst and Zal from the reference value is less, however, the absolute difference is higher and therefore this deviation can be crucial if the dimensions of the structure become larger. The results indicate that the implementation of the additional material model for the weld metal is important with respect to the distortions after welding and can't be neglected or approximated by assuming the properties of steel for the weld metal.

Table 3 Comparison of the distortions calculated with and without consideration of the weld material model

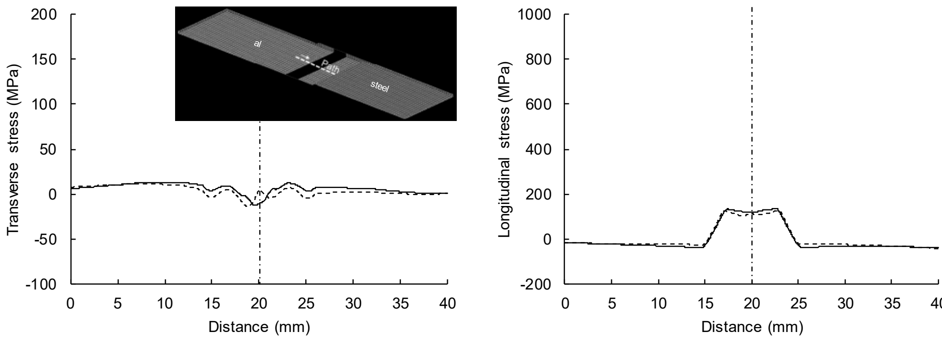
Computation	Input parameters			Response values (in mm)				
	σ	α	E	X	Y_{st}	Y_{al}	Z_{st}	Z_{al}
Weld model included (1)	946	19.12	200	-0.0430	-0.0126	-0.0167	0.537	0.712
Weld model excluded (2)	265	18.3	200	-0.0428 (-0.5 %)	-0.00887 (-29.6 %)	-0.00989 (-40.7 %)	0.566 (+5.4%)	0.72 (+1.1 %)

The distribution of the residual stresses along the path at the upper surface of the joint is shown in Fig. 5. It is clearly indicated that the higher stress concentration exists in the weld, especially the longitudinal stresses when the weld metal material model is included. The distribution of the residual stresses along the path at the bottom surface is presented in Fig. 6. The difference between computed residual stresses is not significant since the path does not cross the weld metal.



(a) (b)

Fig. 5 Stress distribution along the path at the top: transverse stress (a), longitudinal stress (b). Full lines correspond to the stress computed with the weld material model and the dashed lines without weld model.



(a) (b)

Fig. 6 Stress distribution along the path at the bottom: transverse stress (a), longitudinal stress (b). Full lines correspond to the stress computed with the weld material model and the dashed lines without weld model.

The results of the sensitivity analysis are presented in Table 4**Table** . The analysis of the relations between input variables and transverse shrinkage X shows that the thermal expansion coefficient had the most significant effect; the yield stress had less effect; Young's modulus had the least effect and basically, the variation of this parameter within the defined boundaries does not affect the transverse shrinkage. For the longitudinal shrinkage Y_{st}, the analysis shows that the yield stress is the most significant parameter; the thermal expansion coefficient is less important; the change in the Young modulus can be neglected.

Table 4 Results of the sensitivity analysis

#	Input parameters			Response values (in mm)				
	σ	α	E	X	Y_{st}	Y_{al}	Z_{st}	Z_{al}
1	-1	-1	-1	-0.0426	-0.0088	-0.0160	0.540	0.724
2	-1	-1	+1	-0.0428	-0.00876	-0.0159	0.535	0.728
3	-1	+1	-1	-0.0477	-0.00671	-0.0158	0.587	0.768
4	-1	+1	+1	-0.0449	-0.00666	-0.0158	0.578	0.774
5	+1	-1	-1	-0.0411	-0.0186	-0.0170	0.504	0.654
6	+1	-1	+1	-0.0413	-0.0185	-0.0173	0.490	0.658
7	+1	+1	-1	-0.0432	-0.0165	-0.0170	0.545	0.697
8	+1	+1	+1	-0.0434	-0.0165	-0.0173	0.529	0.700

For the longitudinal shrinkage $Y_{al,}$ the most significant parameters are the yield stress and the interaction of the yield stress and Young's modulus; Young's modulus itself and especially the thermal expansion coefficient of the weld metal do not affect the shrinkage Y_{al}. The out of plane distortions of the steel Z_{st} and aluminum Z_{al} sheets are affected mostly by the changes in the yield stress and thermal expansion coefficient; Young's modulus had less effect. Considering the distortions Z_{st} and Z_{al} the following observations can be made. In the dissimilar steel – aluminum lap joints, the increase in the yield stress of the weld metal leads to the decrease of the distortions Z_{st} and Z_{al}. The increase of the thermal expansion coefficient of the weld metal results in the increase of the distortions. According to the obtained results, the calculation of the distortions is sensitive to the variations of the input parameters within the defined boundaries.

CONCLUSION

In this study, the influence of the mechanical properties of the dissimilar steel – aluminum weld metal on the residual stresses and distortions after welding was analyzed. The following conclusions can be drawn:

- The change in the weld metal mechanical properties due to the mixing in the weld pool significantly affects the distortions and residual stresses after welding. The additional material model for the weld metal should be implemented in the simulations for a more accurate prediction.
- The distortions are sensitive to variations of the yield stress and the thermal expansion coefficient and less sensitive to variations of Young's modulus of the weld metal. Therefore, the accurate determination of yield stress and thermal expansion coefficient prior to simulation is necessary and Young's modulus can be approximated as those of steel.

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