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Experimental Stress Analysis

FEM simulation of pulsed laser seam welding

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Abstract: Welding simulations became very popular in last years because they can provide us with much interesting information about the internal material processes or heat source – material interactions. Usually continual seam welding was simulated. Since the pulsed laser welding systems were developed and disseminated, the need of pulsed welding simulations came out. Finite element SYSWELD welding simulation tool was adapted to model and simulate pulsed laser seam welding, also called spot overlapping welding. This paper describes basic principles of such simulation and shows some of its possible outputs.

Keywords: Pulsed laser seam welding, Numerical simulation, Intensity function

1. Introduction

Laser welding is a high power density technology which works with relatively small but highly focussed energy [1]. In comparison to the conventional welding processes less heat is absorbed by the material. Very precise amount of energy can be delivered in a very short time in pulsed laser welding [2]. By the consecutive pulses landing at simultaneous movement of the heat source towards the work piece continuous weld seam can be produced. Such weld has much smaller heat affected zone and also lower final distortions in comparison to the weld produced by continual systems. Therefore usually used techniques of more conventional continual welding can not be applied for simulation of welding with a pulsed laser.

1.1. Principle of pulsed welding simulation in SYSWELD

Simple non-proportional scheme of pulse generation waveform is depicted in Fig. 1, where t represents pulse duration, t_f inverse value of pulse frequency, P average laser power and PP peak power.

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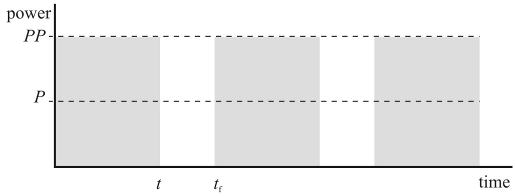


Fig. 1. Scheme of laser pulses generation.

We used this model and made our simulated laser source work this way. We used predefined 3D conical gaussian heat source (Fig. 2) which represents thermal load to the material described by the fortran time-space function [3]. Power density distribution of this kind of a source corresponds to the power density distribution of laser beam used for the welding [4]. Power density in a point with coordinates (*x*,*y*,*z*) can be expressed as follows.

$$Q(x,y,z) = Q_0 \exp(-\frac{r^2}{r_0^2(z)}) \qquad (1)$$

where

$$r = x^2 + y^2 , \qquad (2)$$

$$r_0(z) = r_e - \frac{r_e - r_i}{z_e - z_i}(z_e - z) \qquad (3)$$

where Q_0 is maximal power density and the meaning of gaussian parameters r_e, r_i, z_e and z_i results from Fig. 2.

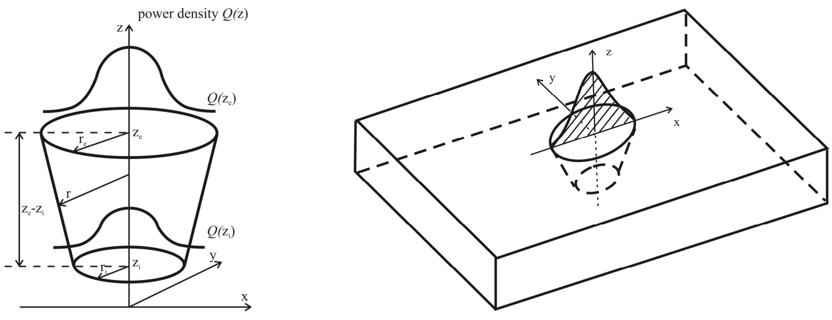


Fig. 2. Gaussian heat source applied to the material.

We modified original heat source by means of the time dependent source intensity function. This SYSWELD function is primarily supposed to define a ramp at the entry of the weld joint which is caused by the fact that only a part of geometry shape of the heat source is in the material yet [4]. This idea of changing the intensity of a heat source during the welding corresponds to the pulse welding principle.

According to the pulse generation cycle presented in Fig. 1, periodical time dependant intensity function was introduced. It is a piecewise linear function defined by a couple of values (*a*,*b*), where *a* is the time point and *b* is the value of the corresponding intensity function to multiply heat input given by 3D conical source described above. Thus *b* is equal to 1 during the pulse duration *t*. It means that heat source fully works during this time interval. On the other hand, *b* is equal to zero during the period between the end of the one pulse and beginning of the next one $t_f - t$. The source has no impact at this moment. Then, intensity function periodically continues.

Pulsed laser welding can be simulated this way. The only necessary condition is to have the mesh fine enough so as several time point calculations are included within the one pulse duration and also within the period when source is no effective. The number of these points is individual but always must be high enough to ensure reliable results. A big disadvantage of this procedure resulting from great number of integration points is a very long computing time. Suitable compromise between computing time and detail results with respect to reality the must be always found.

2. Experiment and example of welding simulation

Weld dimensions are the input parameters for each accurate model and welding simulation. Therefore, they had to be determined first. Then, we can use them to fit model heat source power.

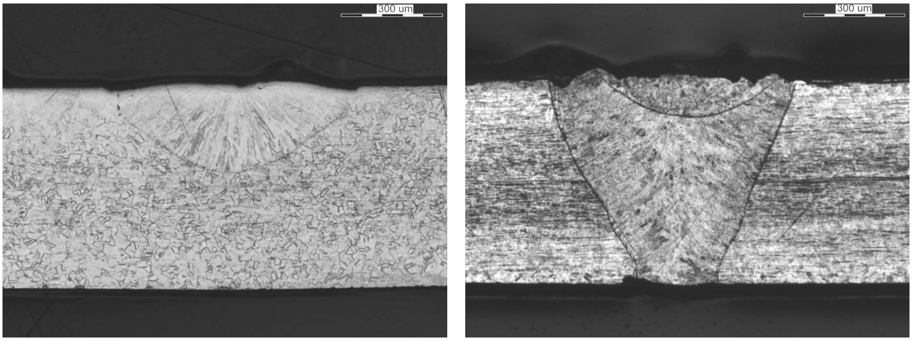
2.1. Experiment

First, welding experiments were conducted. Laser power was the only parameter which was changed during the experiments. All the other process parameters were set to be constant. Stainless steel AISI 304 0.6 mm thick 50 mm x 15 mm sheets were butt welded using pulsed Nd:YAG laser LASAG with 63 % of pulse overlap. Such overlap is quite small but good for the demonstration of differences in pulsed and continual welding. Welding itself was realized 4 mm under the focal plane to ensure the sufficient beam diameter on the specimen which was 0.85 mm. Cleaned degreased weld pieces were fixed in a mounting jig. Pure argon gas at coaxial 8 $l.min^{-1}$ flow rate was used to protect the weld pool against its oxidation. Two different energies were applied to demonstrate conduction and penetration mode welds. An overview of applied processing parameters and computed average and peak powers can be found in Table 1.

Table 1. Applied processing parameters

Sample no.	Beam energy (J)	Pulse frequency (Hz)	Pulse duration (ms)	Welding speed ($mm.s^{-1}$)	Average power (W)	Peak power (W)
1	4.4	13.0	3.4	4.0	57.2	1294.1
2	5.9	13.0	3.4	4.0	76.7	1735.3

Completed welds were cut perpendicularly to the welding direction and metallographic specimens of weld cross sections were prepared. Polished specimens were etched by the mixture of hydrochloric and nitric acid to highlight weld borders and microstructure (Fig.3). These are typical overlapped pulsed laser conduction and penetration mode welds. Usually more pulses impacts the area of one spot which can also be seen in Fig. 3. Each pulse affects different depth within one cross section because its intensity distribution is not uniform along beam cross section. Each previous pulse acts as a pre-heating factor and each following one has probably an annealing function in the case that the previously melted material solidified or it contributes to its melting. The temperature of pre-heating as well as the temperature field distribution can be estimated on the basis of welding simulation results.



a) b)

Fig. 3. Typical overlap pulsed laser weld cross sections a) conduction mode (4.4 J), b) penetration mode (5.9 J).

Table 2 presents measured width, depth and the area of each weld cross section. Penetration depth naturally increases with increasing laser power. Full penetration was achieved at sample no. 2 since the laser peak power exceeds 1.7 kW. Weld width is almost the same within both samples. Certain differences are probably caused by the effect of energy and cross section position because circular beam shape was applied with relatively small pulse overlap.

Table 2. Welds dimensions

Sample no.	Weld width (mm)	Weld depth (mm)	Weld cross section area (mm^2)
1	0.780	0.27	0.131301
2	0.741	0.60	0.302002

To set the appropriate power and to prepare a model corresponding to the real weld, weld width, depth and generally visual aspect must be known. Therefore, real weld and its analysis must forestall each simulation.

2.2. Joint model and welding simulation

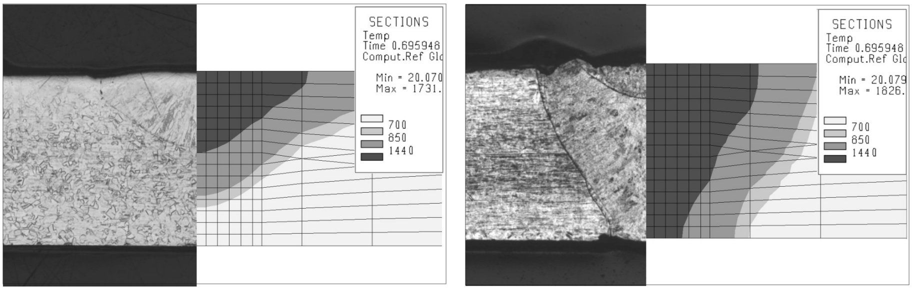
Tools of finite element software SYSWELD were used to prepare a 3D model of components to be welded. Geometrical model of a butt weld with the very fine mesh was generated. High mesh refinement is required because of simulating of pulsed welding. In this case, according to the processing parameters, minimal required node distance was 0.06 mm. This results in a great number of nodes which corresponds to a great number of particular computations which means long computing time as well as high demands on computing storage and processor of used computer. Therefore it is quite problematic to maintain real size of the components in the model. Usually only a part of the weld is modelled but must represent the whole system enough. In order not to obtain misrepresented data, border conditions must be set in a proper way.

In our model, real weld length was reduced to only 5 mm which is enough for the demonstration of about 16 pulses touching the material surface. Time step of the intensity function was set to be 0.7 ms so as the computation in 5 nodes could be accomplished within the one pulse duration at given welding speed. According to the pulse duration, in subsequent 105 nodes intensity function is equal to 0 and then periodically continues. Such model contains 54 796 nodes and thermal analysis took 8 hours. Output data file included almost 60 GB. All this computation represents only 1 s of the real welding time.

Number of nodes is the main difference between the continual and spot overlapping welding model because much more detailed mesh is required. It results from the principle we applied to adapt the software primarily designed for simulation of continual welding to simulate laser welding with pulsed laser.

Heat input into the material was set so as modelled weld cross section shape and dimensions corresponds to the real weld ones. The procedure of heat source fitting is quite time consuming but must be conducted to find the power really absorbed by the material. The knowledge of the amount of power which has to be absorbed by the material to prepare the weld of required size is very desirable. Comparing this simulated absorbed power to the power delivered by the beam, losses caused by the surface reflection or heat conduction in the material can be computed and the efficiency of the welding process can be evaluated [5].

An example of modelled weld shape and its comparison to both real weld cross sections presents Fig. 4. To achieve these weld shapes, simulated absorbed power P_a had to be approximately one half of laser peak power. This means that about 50 % of incident power represents energy losses due to surface beam reflection and heat exchange inside the material and between the material and surroundings. Absorbed power can be computed by integration of power density Q given by Eq. (1) thorough the volume of the heat source and material intersection. Applied heat source parameters can be found in Table 3.



a) b)

Fig. 4. Modelled and real weld cross section shape, a) sample no. 1, b) sample no. 2.

Table 3. Heat source parameters

Sample no.	r_e (mm)	r_i (mm)	z_e (mm)	z_i (mm)	Q_0 ($W.mm^{-3}$)	P_a (W)
1	1.00	0.25	0	-0.18	3300	590
2	0.65	0.20	0	-0.60	3000	929

AISI 304 is a mono-phase austenitic stainless steel. From the SYSWELD point of view there is no metallurgical difference between the basic material and the weld metal. To be able to display weld metal a fictive phase with the same properties as the base austenitic phase was introduced. Fig. 5 presents phase images of central longitudinal cross section of sample no. 2.

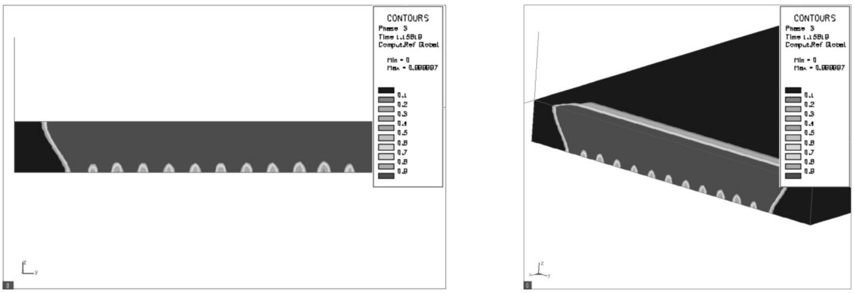


Fig. 5. Phase images of the central longitudinal cross section of sample no. 2.

Temperature field distribution is one of the main outputs of the thermo-metallurgical simulation of the welding. Time evolution of local temperature can be analyzed. Let us focus on sample no. 2 (Fig. 6 and 7). Temperature – weld trajectory position curves for three different time points corresponding to the point of temperature maximum of each pulse are represented in Fig. 6. The maximal achieved temperature during the welding was about 1760 °C. It is shown that each ensuing pulse remelts the area maximally affected by the previous one. This area temperature decreased to about 650 °C before the next pulse land the material surface. Another ensuing pulse only reheats this area to about 1200 °C. Contour image of temperature field at time point 0.772989 s is shown in Fig. 7.

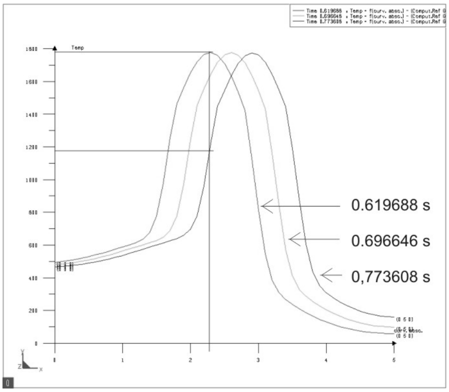


Fig. 6. Temperature – weld trajectory dependence for three different time points.

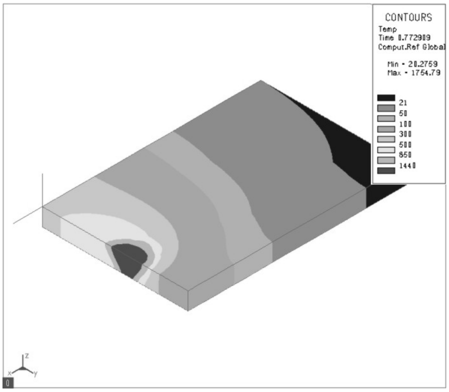
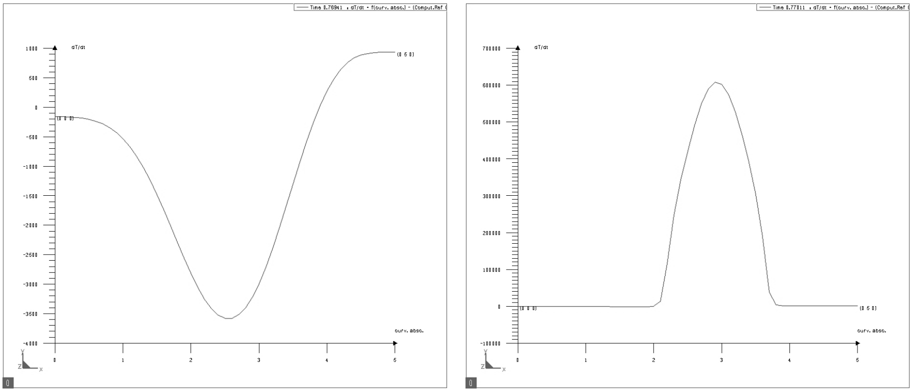


Fig. 7. Contours image of temperature field distribution in 0.772989 s time point.

Analogically temperature rate and many other outputs can be displayed. Temperature rate expresses the heating or the cooling speed at given point. The maximal heating speed reached in this simulation was 665 069 °C.s^{-1}. Maximal cooling speed was 322 000 °C.s^{-1}. Cooling is expressed by negative value of temperature rate. Fig. 8 presents temperature rates along the welding trajectory at two consequent time point at the moment just before the pulse lands material surface and at this moment. Such a high heating and cooling speed results in a very narrow heat affected zone which even was not detected by optical microscopy.



a) b)

Fig. 8. Temperature rate along the welding trajectory for time point a) 0.76941 s, b) 0.77011 s.

3. Conclusion

Nd:YAG pulsed laser welding experiments were conducted. On the basis of these experiments results, geometrical model of the weld and the heat source was prepared. Finite element software was adapted for pulsed laser welding simulation by means of time dependant intensity function implementation. Some of possible simulation outputs were presented.

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