INPUT PARAMETERS INFLUENCE ON THE RESIDUAL STRESS AND DISTORTIONS AT LASER WELDING USING FINITE ELEMENT ANALYSIS

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În lucrarea de faţă a fost folosită analiza cu element finit pentru o îmbinare sudată cap la cap cu o singură trecere pentru a pune în evidenţă câmpul de deformaţii şi tensiuni reziduale în această sudură. Analiza termica elasto-plastică a fost folosită pentru a evidenţia tensiunile şi deformaţiile reziduale.A rezultat faptul că dacă se mareste puterea laserului, atunci tensiunile şi deformaţiile reziduale cresc. Pe de alta parte, cu cât creste viteza de sudare, tensiunile şi deformaţiile reziduale scad. Se observă o scădere a tensiunilor şi deformaţiilor reziduale cu marirea diametrului spotului laserului.

Finite Element Analysis (FEA) has been carried out on a single pass butt welding model to illustrate the distortion and residual stress field developed in the weldment. Thermo-elastic-plastic analysis has been used to find the residual stresses and distortion. It was found that the residual stresses and distortion values increase with of laser beam power. On the other hand, the distortion and residual stresses decrease as the speed increases. There is a reduction of residual stress and distortion values as the spot diameter increases.

Keywords: finite element analysis, thermo elastic-plastic analysis, residual stress, laser beam power.

1. Introduction

During laser welding, the parts are locally heated by intense laser beam followed by melting and solidification. Due to the non-uniform temperature distribution during the thermal cycle, incompatible strains lead to thermal stresses. These incompatible strains due to dimensional changes associated with solidification of the weld metal, metallurgical transformations and plastic deformation, are the main sources of residual stresses and distortion. The effect of welding residual stresses in the neighbourhood of the weld has a great influence

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on brittle fractures, fatigue crack propagation and structural instability strength. Traditionally, welding residual stress analysis uses non-destructive procedure or experimental methods which are time and resources consuming. Only the stress state on the surface of the structure can be determined using non-destructive methods, and even by destructive procedures; the whole three-dimensional stress field cannot be accurately described. For these reasons, a finite element modelling approach may be attractive in order to solve the residual stress problem.

Whereas finite element analyses for traditional welding processes have been successfully used, to some extent, in recent past, finite element analyses for laser welding processes are only at an initial stage of development.

The research on welding heat source models dates back to the early 1940s and Rosenthal [1] first proposed a mathematical model of the moving heat source under the assumptions of quasi-stationary state and concentrated point heating in the 3D analysis. A complete picture of the residual stress distribution in a general weldment is practically impossible to obtain by experimental techniques. Moreover, the results obtained for one particular weldment may not be directly applicable to other weldment.

FEA of residual stress in welding process have been studied by various researches. Yang and Xiao [2] proposed an analytical model to examine the residual stress distribution across the weld of panels welded with mechanical constraints. Furthermore, Ueda and co-workers [3], [4] presented a novel measuring method of three-dimensional residual stresses based on the principle which is simplified by utilizing the characteristics of the distribution of inherent strains induced in a long welded joint.

In recent years, advanced numerical analysis has been applied to solve these complex problems [5], [6], [7], [8]. The present study addresses the prediction of residual stress and distortion in laser welding process and discusses the effects of laser power and scanning speed on it. The distribution of residual stresses in and surrounding a laser welded joint is complex and depends on a number of factors, including material composition, thickness, applied restraint, and welding direction. Residual stresses and distortion in weldment have been calculated using thermo-elastic-plastic finite element analysis.

2. The geometry of joint and material's properties

It is argued that the three-dimensional model could accurately simulate the severe complexity of the phenomena involved in laser welding process. In this way, indeed, a more realistic three-dimensional transient thermal field can be applied to the model, which allows out-of-plane angular distortions of the plate to be calculated, a result not achievable by using simple bi-dimensional models.

The material employed in this work is AISI 304. A temperature dependency of material property has been used for the analysis.

3. The grid structure

The accuracy of the finite element method depends upon the density of the mesh used in the analysis. Sensitivity analysis of mesh density has been performed and a satisfactory mesh is adopted for further studies. The higher the values of heat input, the bigger the number of nodes necessary to accurately interpolate high temperature gradient. The finite element model used for the analysis is shown in Fig. 1. The model has a width 50 mm, length 100 mm and thickness 3 mm.

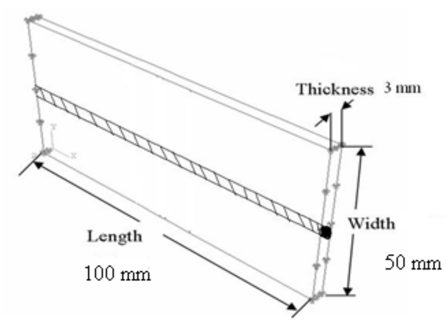

Fig. 1: Model used for the analysis

4. The distortion and Residual Stress Analysis

In this analysis the following assumptions have been considered:
1. The material is isotropic;
2. The material is stress free initially;
3. There is no influence of strain rate on the material's properties.

A non-linear structural analysis has been carried out using the temperature distributions. The thermal strains and stresses are calculated at each time increment. The residual stresses from each temperature increment are added to the nodal point location to determine the updated behaviour of the model before the next temperature increment. The material was assumed to follow the Von Mises yield criterion and the associated flow rules. The material properties that are required for the residual stress analysis are elastic modulus, plastic modulus, yield strength and thermal expansion coefficient. The solution domain for stress analysis is the same as that for heat flow analysis as shown in Figure 1. The boundary condition of stress analysis is shown in Figure 1. Displacements and rotations of the nodes at both ends are fully constrained (U(x,y,z,t)=0) as shown in Fig. 1. In this analysis, quasi-static equation of equilibrium is given by:

$$\Delta\sigma + F = 0 \tag{1}$$

where, $\Delta\sigma$ is the stress variation and F is the body force. Residual stresses are calculated by using the principle of virtual work. In this method, one considers infinitesimal nodes displacements $\{\delta\}$ imposed onto the body. This causes external total virtual work (equal to the total internal virtual work which is defined by stresses $\{\sigma\}$ and strains $\{\varepsilon\}$). By using FEM (finite element model), strain–displacement can be expressed briefly as follows:

$$\{\varepsilon\} = [B]\{\delta\}^e \tag{2}$$

where, $\{\varepsilon\}$ is the strain vector, [B] is the strain–displacement interpolation matrix and $\{\delta\}^e$ is the displacement vector for an element. The nodal displacement is obtained from

$$\{\delta\} = [K]^{-1}\left(\{R\}_T \{R\}_{P_1}\right) \tag{3}$$

where, [K] is the conductivity matrix, $\{R\}_T$, $\{R\}_{P1}$ is the resultant nodal displacements vector with respect to nodal temperature and laser beam power. The stress-strain relationship is defined as follows:

$$\{\sigma\} = [D](\{\varepsilon_e\}) \tag{4}$$

where, [D] is the Stiffness matrix and $\{\varepsilon_e\}$ is the elastic strain vector. For the deformation of metals, the Von Mises yield criterion is employed and the elastic strain is given by

$$\varepsilon_e = \varepsilon - \varepsilon_{pl} - \varepsilon_{th} \tag{5}$$

where, ε_e is the elastic strain, ε is the total strain, ε_{pl} is plastic strain and ε_{th} is the thermal strain.

In this analysis, the thermal element is a three-dimensional (3-D) structural element C3D8 [9]. This element has eight nodes with three degrees of freedom at each node. The analysis was performed for the time period between the start of welding and the end of cooling phase incorporating the thermal results. Within each time increment, the solution of the elastic-plastic problem was found by liberalizing the non-linear stress-strain relation in an incremental way. The analysis was performed and stresses and displacements were calculated by Newton-Raphson iterative process. The iterations were repeated until convergence is achieved. An important problem in the analysis of residual stress during welding is how stress develops in regions near the welding pool. When two sheets are joined by fusion welding, the material of the plates is heated to its melting point and then cooled again rapidly under restraint conditions imposed by the geometry of the joint. As a result of severe thermal cycles, the original microstructure and properties of the metal in a region close to the weld are changed. This part of the metal, or zone, is usually referred to as heat-affected zone (HAZ). The changes in the HAZ are also dependent upon the thermal and mechanical history of the metal. Therefore, after the welding process there will be different zones with different mechanical properties. In particular, there is a softening of the material in the HAZ, and there is a decrease of the mechanical properties of the material, i.e. yield strength, ultimate strength of the material, but the elastic modulus remains unaffected by the welding process.

5. Results and discussion

To obtain information from the simulation result and to find the effect of welding speed, laser power, and spot diameter on the residual stress and distortion, variables have been considered for simulation as shown in Table 1. The plate width, length and thickness are constant throughout the analysis.

Table 1

Process variables used for analysis

Sample	Laser Power [kW]	Welding Speed [mm/s]	Spot diameter [mm]
1	2.7	10	0.50
2	3.0	12	0.60
3	3.3	8	0.55

5.1 The residual stress and distortion analysis

Reducing the residual stresses in weld structures during an early stage of design and fabrication is of priority concern. For this reason, the effects of welding process parameter on the residual stresses are characterized in the following. This research investigates the effect of welding speed, laser power, and spot diameter on residual stress and distortion which have been obtained from the finite element elastic-plastic analysis. It is found that magnitude and distribution of residual stress is strongly affected by temperature gradient, temperature distribution through the thickness & length of the plates, thermal expansion coefficients of the materials and mechanical properties of material at elevated temperatures. According to the geometry and theory, larger residual stresses and distortions are expected parallel to the weld direction and closer to the weld zone. This behaviour is well evidenced from Figs. 2 to 23. Figs. 2 - 5 show the contours of residual stress and distortion for a laser power of 3.3 kW, 8 mm/sec travel speed, 100 mm work piece length and 3 mm thickness.

Figs. 6 - 23 show the graphical representation of residual stress and distortion for various laser power, speed, and spot diameter. All graphs are plotted by taking the values of each node along the direction perpendicular to the welding direction and 25 mm from the edge. Stresses acting parallel to the direction of the weld bead are termed longitudinal residual stresses, as denoted by the letters Sy. The longitudinal residual stress develop from longitudinal expansion and contraction during the welding sequence. The longitudinal residual stress distribution is shown in Figs. 3, 8, 14, and 20. It is worth mentioning that the residual stress distribution is strongly affected by the boundary conditions assumed.

The stresses acting perpendicular to the direction of the weld bead is known as a transverse residual stresses, denoted by the letter Sx. Figs. 2, 7, 13, and 19 represent the distributions of the residual stresses Sx along the X - direction. A very large tensile stress is produced near the surface of the plate. Owing to the locally concentrated heat source, the temperature near the weld bead and heat affected zone rapidly changes which leads to residual stress.

Fig. 2. Transverse residual stress, Sx

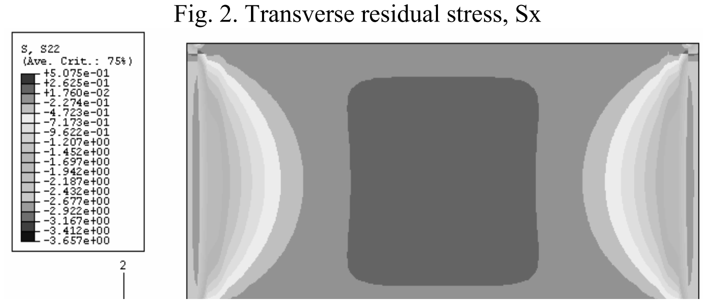

Fig. 3. Longitudinal residual stress, Sy

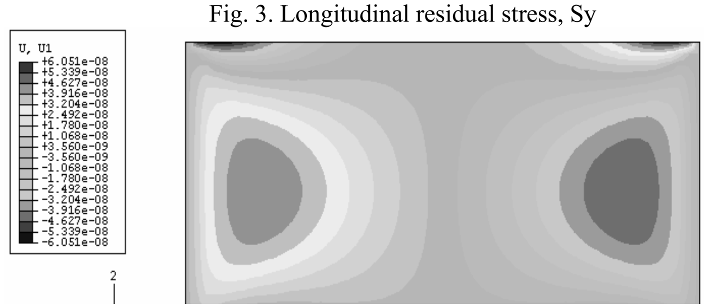

Fig. 4. Transverse displacement

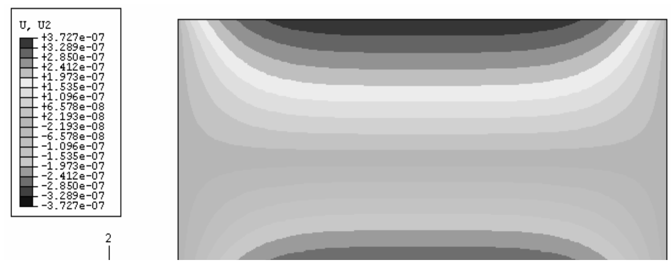

Fig. 5. Longitudinal displacement

5.2 The influence of laser beam power

Laser power is one of the most important process parameter governing the heat input which in turn controls the weld response. It is directly proportional to the energy supplied to the weldment. The most important characteristic of laser power is that it governs the cooling rates in welds, and thus affects the microstructure of the weld metal and the heat- affected zone. A change in microstructure directly affects the mechanical properties of welds. The effect of laser power on welding responses is evaluated by considering three different laser powers 2.7 kW, 3 kW and 3.3 kW. This evaluation has been carried out by considering the other parameter constants (welding speed = 8 mm/sec, length = 100 mm and thickness = 3 mm).

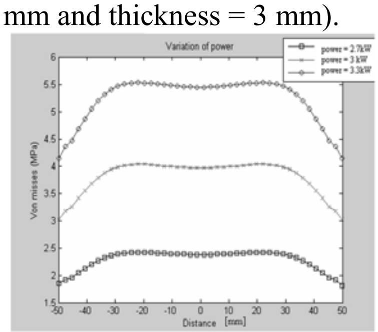

Fig. 6.Von Mises stress

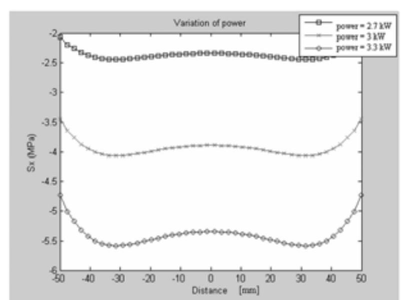

Fig. 7. Transverse residual stress

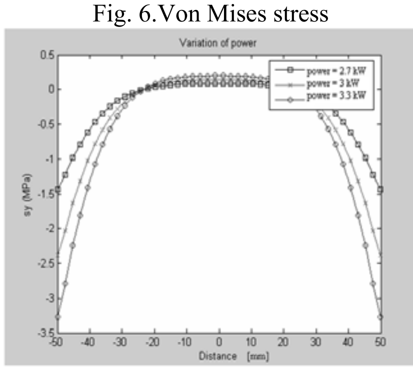

Fig. 8. Longitudinal residual stress

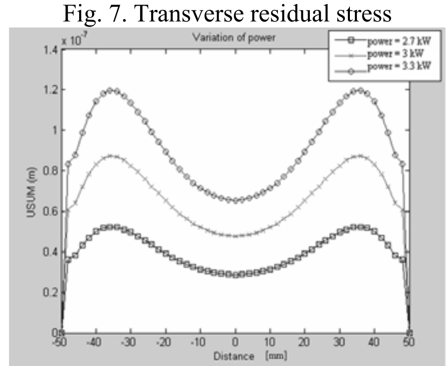

Fig. 9. USUM displacement

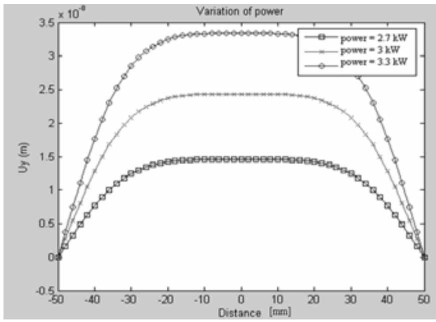

Fig. 10. Transverse displacement

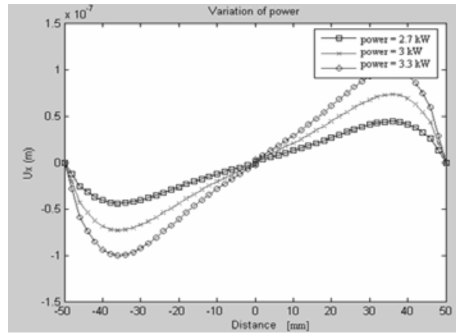

Fig. 11. Longitudinal displacement

The effect of varying laser power on the thermo mechanical responses is illustrated in Figures 6 -11. When the laser power increases, the responses such as residual stress and distortion also increase. This is due to increased supply of heat by the laser beam which results in slower cooling rate. Figure 10 shows that transverse displacement is more sensitive to laser power as compared to other directional displacements. Maximum Von Mises stress for power 3.3 kW is 5.5 MPa whereas for 2.7 kW it is 2.2 MPa. A 10% reduction in power leads to 50% reduction in Von Mises and 55 % reduction in transverse displacement. The maximum displacement occurs along cross section 30 mm from the weld line, as one can see in Fig. 9.

5.3 The influence of welding speed

Welding speed represents the distance travelled by the laser beam along the weld line per unit of time. The heat input is inversely proportional to the welding speed. Therefore, when the welding speed increases the heat input rate decreases. Three different speeds 8, 10 and 12 mm/sec were used in this simulation. All other parameters are kept at constant value (laser power = 3.3 kW, length = 100 mm and thickness = 3 mm).

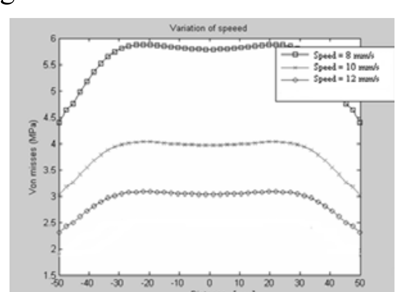

Fig. 12. Von Mises stress

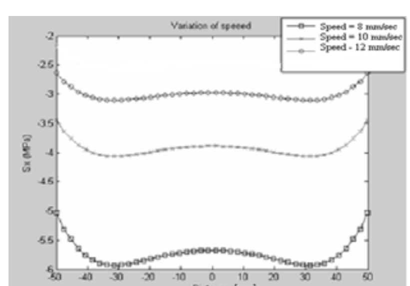

Fig. 13. Transverse residual stress

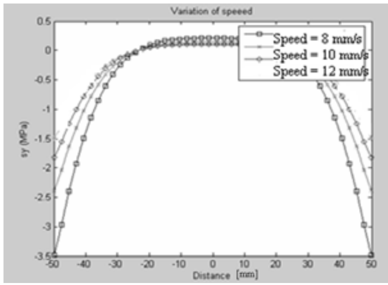

Fig. 14. Longitudinal residual stress

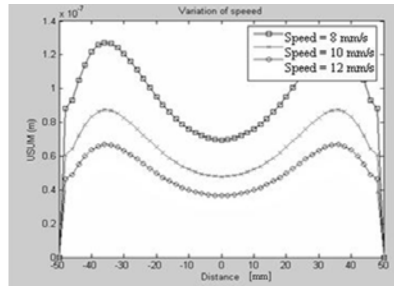

Fig. 15. USUM displacement

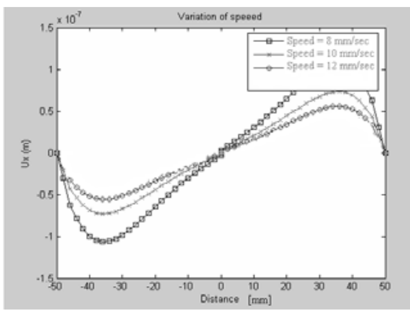

Fig. 16. Transverse displacement

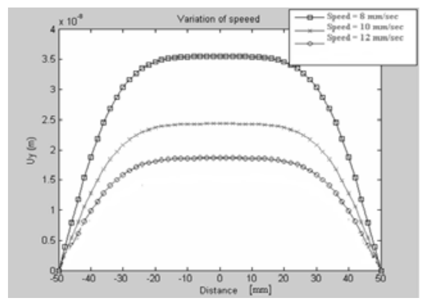

Fig. 17. Longitudinal displacement

Figs. 12 – 17 show the effect of various welding speeds on residual stress and displacement. As the welding speed increases, the displacements and stresses decreases. This trend was expected since laser power is inversely proportional to welding speed. It is noted that the faster the welding speed, the less heat absorbed by the base metal, which leads to a decrease of residual stress and distortion. This is because the increases in scanning speed reduce the interaction time of laser beam with the base metal. Therefore the heat input reduces, which leads to less volume of the base metal being melted. Moreover an important difference lies in the fact that the higher speed welding technique produced a slightly narrower isotherm. This isotherm's width influences the transverse shrinkage of butt welds, accounting for why faster welding speeds generally result in less residual stresses. A reduction of 50 % of the welding speed, for instance, causes a decrease of 60 % of Von Mises stress and 66 % of transverse displacement.

5.4 The influence of spot diameter

The effect of spot diameter on residual stress and distortion is found out by performing the analysis with three different spot diameters i.e. 0.5, 0.55 and 0.6 mm. From Figs. 18 – 23, the effect of variable work piece thickness is well evidenced. As the spot diameter increases there is a reduction of residual stress and distortion. A decrease of spot diameter from 0.6 mm to 0.5 mm causes an increase of Von Mises stress from 1.5 MPa to 8.5 MPa respectively.

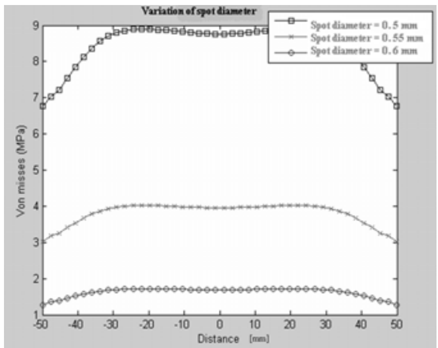

Fig. 18. Von Mises stress

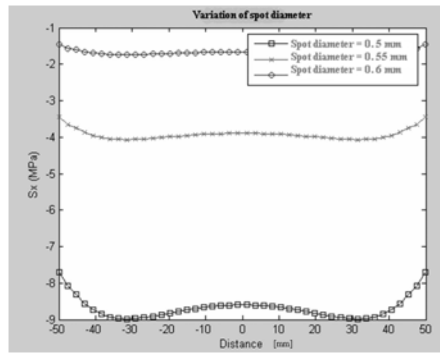

Fig. 19. Transverse residual stress

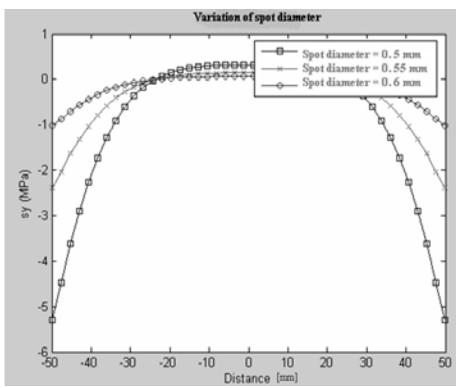

Fig. 20. Longitudinal residual stress

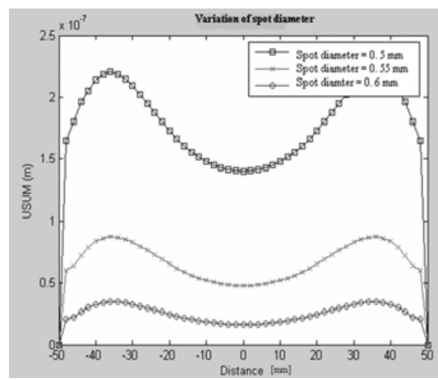

Fig. 21. USUM displacement

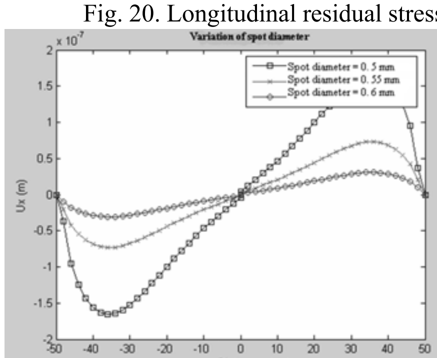

Fig. 22. Transverse displacement

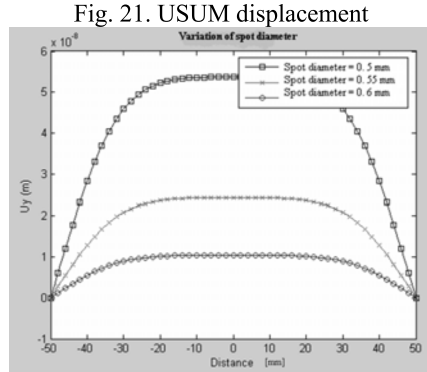

Fig. 23. Longitudinal displacement

6. Conclusions

The following conclusions can be drawn from the simulation results:

• Based on the simulation results, distortion or shrinkage of the weldment can be predicted. Thus, the experimental analysis, which might be costly, can be avoided.

• Laser power, welding speed, and spot diameter have a significant influence on the residual stress and distortion values.

• The transverse residual stress is high near the weld and decreases as it moves further. This is because yield force is very low immediately after welding and a part of the specimen near the bead deforms plastically under very low external load.

• When the laser beam power increases, displacements and residual stress values also increase.

• Displacement and residual stress decreases as the speed increases.

• There is a reduction of residual stress and distortion as the spot diameter increases.

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