Al-Khwarizmi Engineering Journal, Vol. 5, No. 1, PP 33-41 (2009)

Al-Khwarizmi Engineering Journal

Investigation of Thermal Stress Distribution in Laser Spot Welding Process

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(Received 14 December 2008; accepted 19 March 2009)

Abstract

The objective of this paper was to study the laser spot welding process of low carbon steel sheet. The investigations were based on analytical and finite element analyses. The analytical analysis was focused on a consistent set of equations representing interaction of the laser beam with materials. The numerical analysis based on 3-D finite element analysis of heat flow during laser spot welding taken into account the temperature dependence of the physical properties and latent heat of transformations using ANSYS code V.10.0 to simulate the laser welding process. The effect of laser operating parameters on the results of the temperature profile were studied in addition to the effect on thermal stresses and dimensions of the laser welded workpiece which showed good correlations between analytical and numerical results. It was found that the temperature gradients during laser welding are usually very large and it was viewed that very high temperature at the center of the workpiece, and is decreased very significantly as propagating along the radial direction. Also it found that the thermal residual stresses around the laser spot due to plastic strains were very small and localized within 1.0 mm range. It is concluded that the laser welding process is effective to reduce the welding residual stress. The stresses along the lateral direction of the workpiece changed from compression at the spot under the laser beam and tension away from the spot at the end of welding to tension at the spot under the laser beam and compression away from the spot when it cooled, which are in a good agreement with the published results.

Keywords: Laser-spot welding, Residual stress, Non-linear thermal stress.

1. Introduction:

Laser welding represents a delicate balance between heating and cooling within a spatially localized volume to produce the liquid melt pool by absorption of incident radiation, allow it to grow to the desired size, and then to propagate this melt pool through the solid interface eliminating the original seam between the components to be joined. Laser beam welding has a number of desirable attributes. The heat affected zones are characteristically smaller and narrower than those produced using conventional welding techniques and distortion of the workpiece is reduced.

During laser spot welding, an intense beam is focused onto a small area. The material under the beam rapidly melts and may partly vaporise, leaving behind a small vapour filled crater, which enhances the absorptivity of the incident beam. The molten front extends more in the thickness than in the width direction if the laser power is sufficiently high. This can lead to a parallel sided molten pool and heat transfer occurs predominantly via radiative and convective modes through the vapour and molten material.

Numerical simulations of a laser welding process have been a major topic in welding research for several years. The results of simulations can be used to explain physical essence of some complex phenomena in the laser welding process explicitly and can be also used as the basis for optimization of the process. Simulations of the laser welding process enable estimation of transient stresses, residual stresses, and distortions. These can be used to evaluate structural misalignments and unexpected failures due to overstressing caused by the superposition of in-service loads and welding induced residual stresses. However, the simulation of the welding process is not an easy task since it involves interaction of thermal, mechanical, and metallurgical phenomena. For the study of stress distributions in laser welding process, early researches include the consideration of the thermoelasticity problem due to a moving heat source [1], development for the transient surface stress and displacement due to line heat sources in terms of Bessel functions [2], and the calculation of thermal stresses on an infinite slab caused by a moving square heat source on the surface [3]. More recently, an analytical solution for a semi-infinite plane subjected to a moving Gaussian heat source was obtained in terms of Bessel functions and exponential integrals [4]. An explicit formula for the shape of the deformed target surface under laser irradiation was obtained as a function of the deposited Gaussian energy distribution [5]. Furthermore, the numerical model of the thermal stresses generated by a moving elliptical weld pool in the welding of thin metal sheets were developed [6], and the stresses along the weld direction and the distortion of the workpiece from the laser welding process were evaluated using a Mellin-transform technique, where the considerations were restricted to the plane linear thermoelastic model in order to obtain the basic mathematical formula for the transient change in stresses, and the final results were expressed in terms of a convolution integral and illustrated by numerical calculations for the point heat source [7]. A number of analytical and numerical models of laser welding processes have been used to evaluate temperature and stress distribution during the welding process, as well as corresponding residual stresses and final distortions of structural components. These include analytical models [8], two-dimensional finite element models [9], and three-dimensional finite element models [10]. However, not all of parameters influencing the welding process, including microstructural changes due to phase transformation, heat flux simulation, and variation of thermal and mechanical material properties with temperature, were taken into account in the simulations listed above. [11], investigated the transient thermal and stress analyses of a laser spot-welded joint using nonlinear finite element method, and since the study was limited to the thermoelastic stresses, it was found that the stresses and deformations were overestimated.

Laser materials processing utilizes the high power density provided by the laser beam, which is focused on the workpiece. As a result, the workpiece material experiences heating, melting, and possible vaporization and re-solidification. Understanding the temporal evolution of the temperature field during laser material interaction is one of the most significant factors in achieving a desired quality of processing. The thermal history is required to determine dimensional changes in the machined part, the related stresses, phase transformations taking place, and the final metallurgical microstructures.

In order to achieve a satisfactory study of the laser welding process, it is first of all necessary to know the temperature distributions resulting from the irradiation of the laser beam. The next step that must be addressed is to use the fundamental equations of linear thermo-elasticity to arrive knowledge of the distribution of stress in the elastic material under certain boundary conditions. Once a combined understanding of the temperature and stress distribution is achieved it is possible to identify domains in which the stresses may have a value above the yield point of the material at a given temperature, as well as regions where possible phase changes can occur for the particular material.

2. Theoretical Aspects:

The coupling of laser radiation into a metal to produce the localized heating required for spot welding involved a delicate balance among many parameters. Some of these parameters, such as laser intensity, pulse shape, and beam polarization, are under the control of the operator, whereas others, such as metal reflectivity, thermal conductivity, and heat capacity, are not.

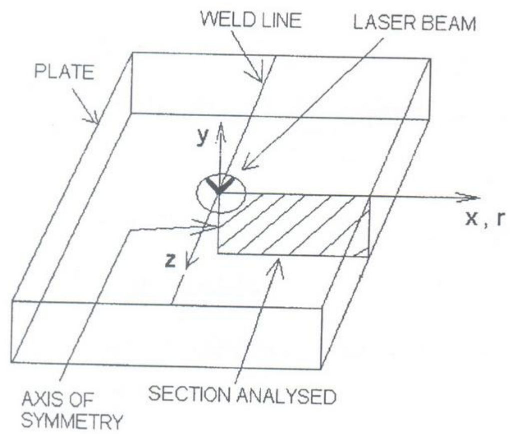


Fig. 1. Transverse Section of Thermal Model [13]

Under conduction limited conditions, the onset of surface melting can be estimated from the simple model (see figure 1). The temperature at the center of the beam focus(r =0) is:

$$T(0,t)-T = \frac{AI(0)w}{K(2\pi)^{1/2}}\tan^{-1}\left(\frac{8kt}{w^2}\right)^{1/2} \quad ... (1)$$

Where K is the thermal conductivity, k is thermal diffusivity, w is the Gaussian beam radius, T_0 is the ambient temperature, and t is time. If T (0, t) $=T_m$, the melting temperature, then the laser beam intensity, $I_m(0)$, required to produce melting in time t can be obtained with equation 1.

An estimate of the depth of penetration, z_m, of the weld pool under spot welding conditions in which melting is included can be obtained, when considered t_m as the time at which $T(z=0)=T_m$, as [12]:

$$z_m(t) \approx \frac{0.16AI}{\rho L_m}(t-t_m) \quad \ldots (2)$$

Where ρ is the density of the melt and L_m is the latent heat of fusion. Equation 2 will be strictly valid only when $t_m<8k/w^2$.

In order to account for the thermomechanical effect during the heating process, the energy transport equation for a deformable solid body can be written for the specific enthalpy as

$$\nabla.q = C_P\frac{\partial T}{\partial t} + \left(\frac{C_P\eta}{\alpha_e}\right)\frac{\partial}{\partial t}(\nabla.U) \quad \ldots (3)$$

The equation describing the energy transport due to electron-photon interaction can be written as

$$\nabla.q = K(\nabla^2.T) + \frac{C_P\lambda^2}{f}\frac{\partial}{\partial t}(\nabla^2.T) + I_{surf}\,\delta\exp(-\delta|x|) \quad \ldots (4)$$

Combination of equations 3 and 4 yields

$$\frac{\partial T}{\partial t} = \alpha\left(\nabla^2.T\right) + \frac{\lambda^2}{f}\frac{\partial}{\partial t}\left(\nabla^2.T\right) - \left(\frac{\eta}{\alpha_e}\right)\frac{\partial}{\partial t}\left(\nabla.U\right) + I_{surf}\,\delta\exp(-\delta|x|) \quad \ldots (5)$$

Equation 5 is the general energy transport equation, which includes the thermomechanical effect.

I.C's: t=0, T=0 and U=0,

Since the laser pulse length and heating duration are short, there is no convection or radiation losses are considered from the surface, therefore

B.C's at t>0 and at the surface, $\left.\frac{\partial T}{\partial x}\right)_{surface} = 0$,

at t>0 and x = y = z = α, T= 0 and U= 0.

During laser materials processing, the heating is localized and therefore, a very large temperature variation occurs over a small region. Owing to this temperature gradient, large thermal stresses are generated in the substrate, which can lead to the defects in the material such as the formation of cracks and fractures in the material. The stress is related to strains by [14]:

$$\{\sigma\}= [D]\,\{\varepsilon^e\}, \quad ... (6)$$

Where {σ} is the stress vector, and [D] is the elasticity matrix.

$$\{\varepsilon^e\}= \{\varepsilon\}-\{\varepsilon^{th}\}, \quad ...(7)$$

Where {ε} is the total strain vector and $\{\varepsilon^{th}\}$ is the thermal strain vector.

Equation 7 may also be written as

$$\{\varepsilon\}=[D]^{-1}\{\sigma\}+\{\varepsilon^{th}\} \quad \ldots (8)$$

But $\{\varepsilon^{th}\} =\alpha_e\Delta T= \alpha_e(T-T_{ref})$ ... (9)

Where T_{ref} is the reference temperature at t=0.

The principle stresses (σ_1, σ_2, σ_3) are calculated from the stress components by the cubic equation. The Von Mises or equivalent stress, σ', is computed as

$$\sigma' = \sqrt{\frac{1}{2}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2]} \quad \ldots (10)$$

The equivalent stress is stress is related to the equivalent strain through

$$\sigma'=E\,\varepsilon' \quad \ldots. (11)$$

Where ε' is the equivalent strain.

The boundary conditions for stresses are: since there is no surface tractions are involved in the problem under consideration the corresponding boundary and initial conditions are introduced:

at t=0, σ=0,
at t>0 and at surface, $\sigma_{surface}=0$,
at t>0 and x=y=z=α, σ=0.

3. Finite Element Modeling Procedures:

The form of the representation used for the laser beam has a significant effect on the results of numerical models of the laser beam welding process. A Gaussian representation of the laser beam, assuming heat input only on the top surface of the material, may not lead to correct results, especially for high power lasers that penetrate rapidly some distance into the material thickness, resulting in welds of high depth to width ratio. The present work is thus aimed at a heat transfer analysis following the double ellipsoidal representation of the laser beam, as this typically incorporates volumetric heat input from a heat source. The temperature dependence of the material properties, phase change phenomena, and convective and radiative heat losses from all the surfaces of a sheet are considered. The heat transfer analysis is therefore axisymmetric, with the y axis defined as the axis of symmetry. The volumetric heat input due to the laser is represented by adapting equation (12) for a stationary heat source [13],

$$q(x,y) = \frac{6\sqrt{3}Q}{a^2 b\pi^{3/2}} \exp(-3\frac{x^2}{a^2}) \exp(-3\frac{y^2}{b^2}) \quad .... (12)$$

Where Q is taken to be the incident laser power multiplied by the energy transfer efficiency (absorptive), a is the focal radius of the laser beam, b is the sheet thickness.

The FE analysis was carried out in two steps:

1- Non- linear (material properties depend on temperature) transient thermal analysis using three modes of heat transfer: conduction, convection, and radiation; was conducted first to obtain the global temperature history generated during and after welding process.

2- Stress analysis was then developed with the temperatures obtained from the thermal analysis used as loading to the stress model.

The general purpose FE package ANSYS V10.0 was used for both thermal and stress analysis performed sequentially. The mesh used in the stress analysis was compatible to that in the thermal analysis. Figure 2 shows model geometry and the representative mesh.

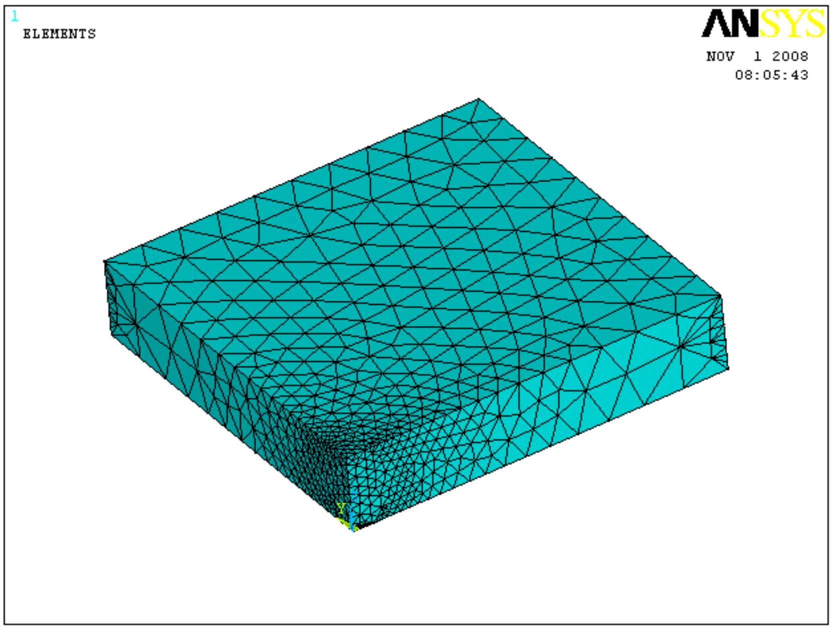
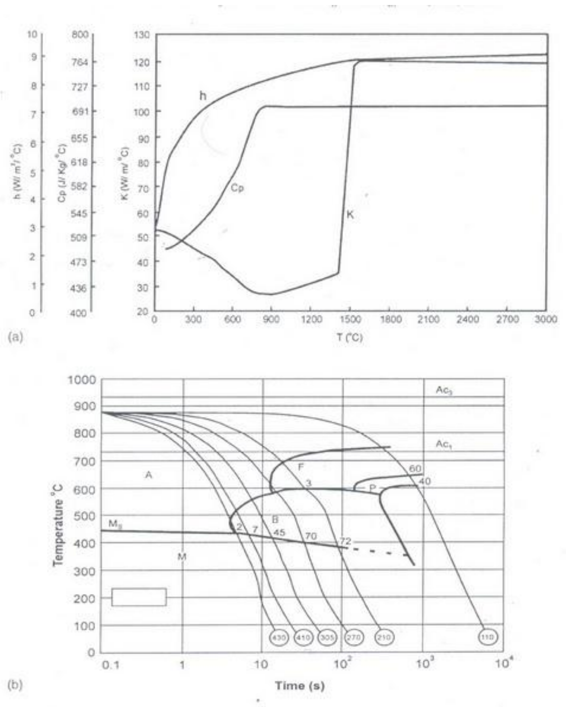


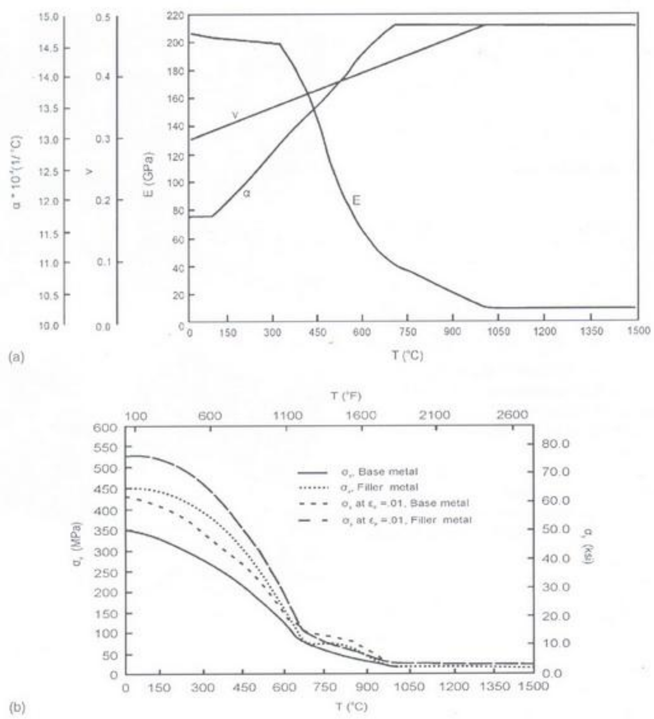
Fig.2. Model Geometry and Meshes

4. Results and Discussions

The present study is based on calculated geometric and material data for laser spot welds in a single sheet. The heat source was a laser with a beam spot diameter of 1.0 mm focused normally onto the top surface of a 2.0 mm thickness low carbon steel sheet. Three levels of beam power, namely 1.0, 1.5, and 2.5 kW, and on-times varying in the range 0.15 – 2.65 s were considered. To model the results, a rectangular region of 15 mm (width) by 2 mm (thickness) is finely discretised (meshed) into divisions of 0.1 mm along the thickness direction. Along the width direction, a division of 0.1 mm is used up to a distance of 5 mm, beyond which a division of 0.2 mm is used for the remainder of the length. 3-D 20-node elements are used. The time span of the transient analysis includes the on-time of a single laser pulse and the subsequent cooling stage. The analysis is carried out through a number of small time steps, each time step being 0.001 s. Within each time step, a number of iterations are performed to achieve a convergence criterion of 1% (the difference in nodal temperature between two successive iterations). Figures 3(a,b) show the temperature dependent thermal and mechanical material properties used in the calculation. During the analysis, whenever the temperature of a node exceeds the boiling point of the steel (2800°C), it is allowed to remain in the mesh at the boiling temperature and is not considered further in the analysis until cooling starts after removal of the laser beam.

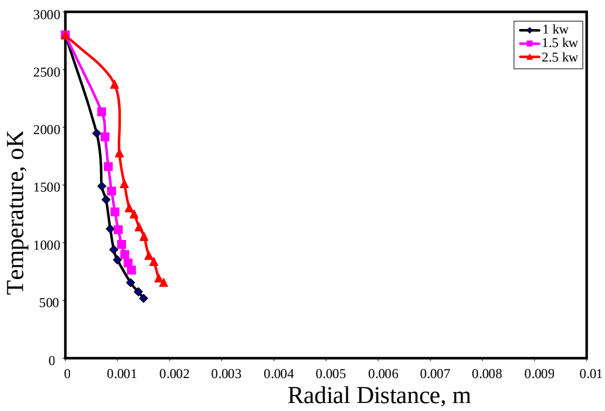


-a-

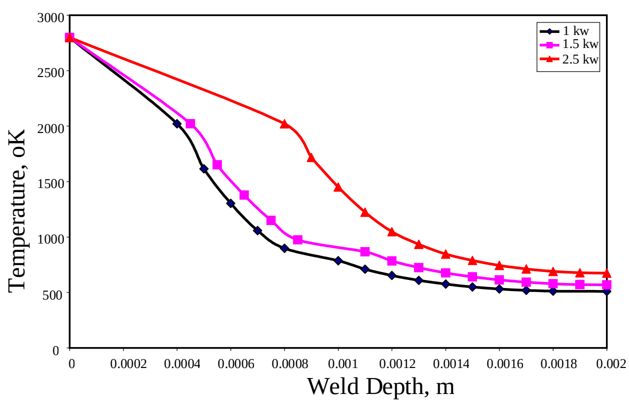


-b-

Fig.3. [15] Material Properties with Temperature a- Variation of Thermal Material Properties with Temperature. b- Variation of Mechanical Material Properties with Temperature



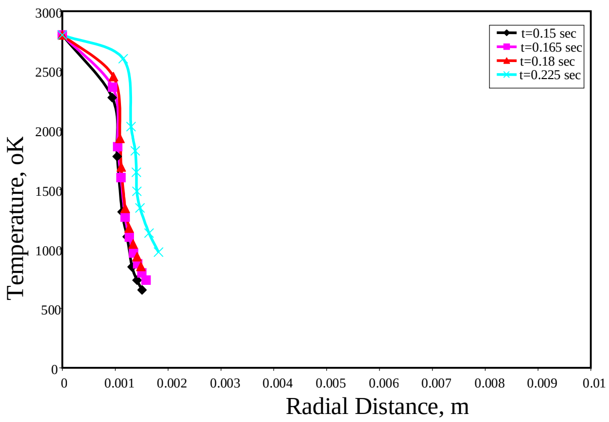
-a- Along Radial Distance



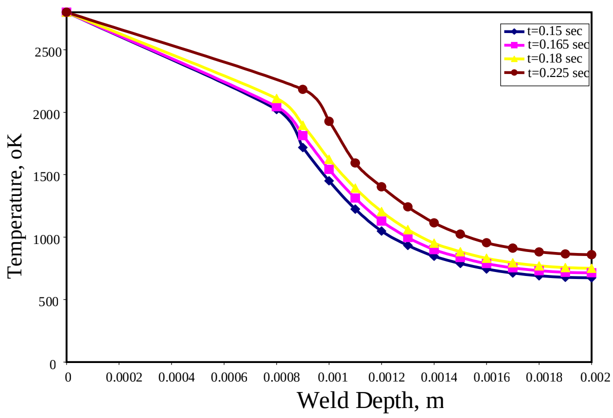
-b- Along Weld Depth

Fig.4. Temperature Distribution

In figures 4(a,b) the maximum temperature for laser powers of 1.0, 1.5, 2.5 KW and an on-times of 0.15 sec are compared. The weld width and penetration are estimated along the horizontal and vertical direction respectively. It can be shows that the weld dimensions do not changes significantly as the laser power is increased from 1.0 to 1.5 KW for an on-time 0.15 sec. In contrast, an increase in laser power to 2.5 KW shows a marked increase in penetration from approximated 0.5 mm (both at 1.0 and at 1.5 KW) to 1.0 mm at (2.5 KW). This is further evident as the on-time is increased from o.15 to 0.225 sec at 2.5KW laser power (see figure 5).



-a- Along Radial Distance



-b- Along Weld Depth

Fig.5. Temperature Distribution

The temperature gradients during laser welding are usually very large, due to the high power density, and small local area provided by the laser. Figures 6 and 7 show the large temperature gradient at the workpiece radial distance at a laser power of 2.5KW, and it can be viewed that very high temperature occur at the center of the workpiece, and is decreased very significantly as propagating along the radial direction, and for nodes that more1.5 m.m away from the center, the temperature drop down to very close to room temperature indicating that most of the heat affected zone are localized within the 1.5 m.m range.

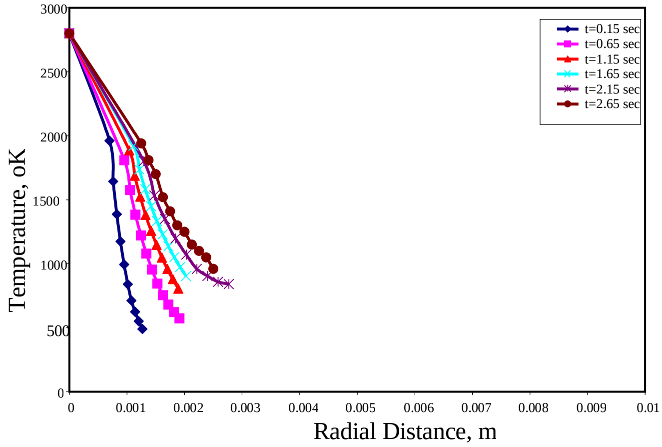


Fig.6. Temperature Distribution Along Radial Distance

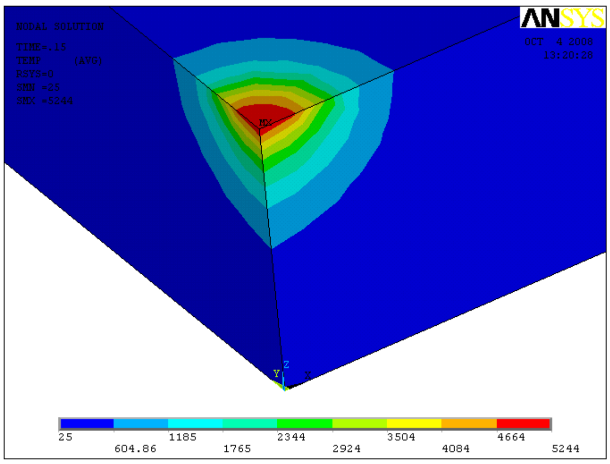
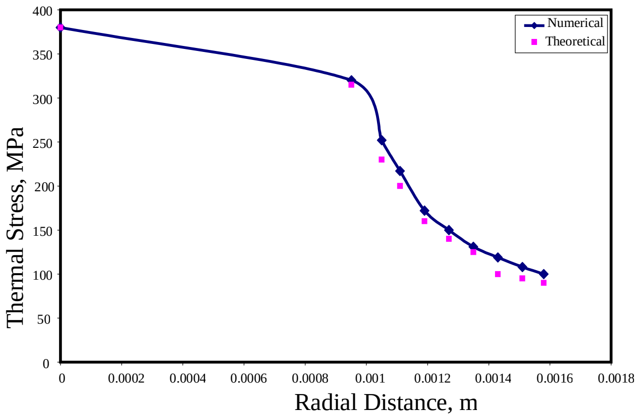
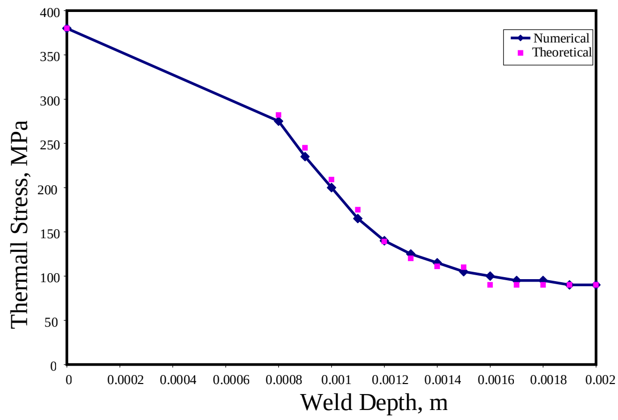


Fig.7. Temperature Distribution During Laser Spot Welding

For stress calculation, the temperature fields at the various time steps are then used as an input to the mechanical analysis, Von Mises stress was calculated. The maximum Von Mises stress was about 380 MPa, while the yield strength of low carbon steel is about 290 MPa, indicating that the workpiece would undergo plastic deformation. The thermal residual stresses around the laser spot due to plastic strain can be calculated from figure 8 at yield strength value. It was found that the residual stresses were very small and localized within 1.0 mm range in radial distance and 0.5mm range in depth; these values are very small compared with 4 mm range in radial distance for resistance spot welding process[16].



-a- Along Radial Distance



-b- Along Weld Depth

Fig.8. Von Mises Thermal Stress Distribution After Laser Spot Welding

In laser spot welding, a weldment is locally heated by intense beam which focused on small area. Due to 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 deformations, are the sources of residual stresses. The stresses along the lateral direction of the workpiece changed from compression at the spot under the laser beam and tension away from the spot at the end of welding (t=2.65 sec) to tension at the spot under the laser beam and compression away from the spot when it cooled (t=400 sec), which are a good agreement with the published results[11,15], see figure 9.

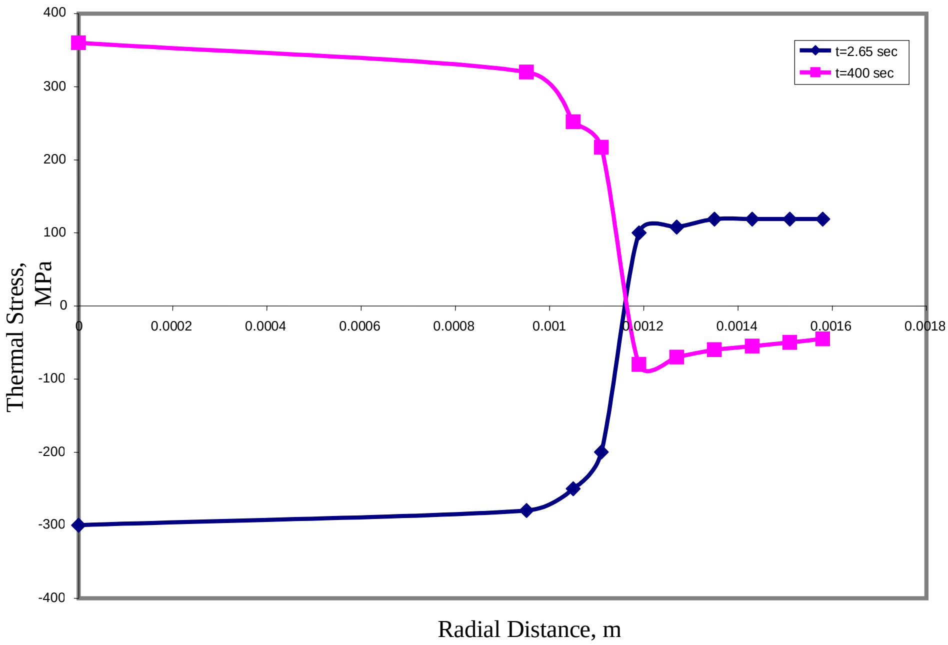


Fig.9. Thermal Stress Distribution During and After Laser Spot Welding

5. Conclusions:

An analytical and finite element analyses have been investigated to simulate the laser spot welding process on a low carbon steel sheet. The analytical analysis was focused on a set of equations representing interaction of the laser beam with materials. The numerical analysis based on 3-D finite element analysis of heat flow during laser spot welding taken into account the temperature dependence of the physical properties and latent heat of transformations using ANSYS code V.10.0. The effect of laser operating parameters on the results of the temperature profile, thermal stresses, and dimensions of the laser welded workpiece were studied which showed good correlations between analytical and numerical results. We conclude that:

1- The temperature gradients during laser welding are usually very large and it was viewed that very high temperature at the center of the workpiece, and is decreased very significantly as propagating along the radial direction.

2- The thermal residual stresses around the laser spot due to plastic strains were very small and localized within 1.0 mm range.

3- Laser welding process is effective to reduce the welding residual stress.

4- Stresses along the lateral direction of the workpiece changed from compression at the spot under the laser beam and tension away from the spot at the end of welding to tension at the spot under the laser beam and compression away from the spot when it cooled.

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أستقصاء توزيع الأجهادات الحرارية في عملية اللحام النقطي بالليزر

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الخلاصة

يهدف هذا البحث الى دراسة عملية اللحام النقطي بالليزر لصفائح الكاربون المنخفض الفولاذية تحليليا و عدديا. الجانب التحليلي أعتمد على مجموعة ثابتة من المعادلات التي تمثل التفاعل بين شعاع الليزر والمعدن. أما الجانب العددي فقد أستند على تحليل عنصر ثلاثي الأبعاد لتمثيل الحرارة المتولدة أثناء عملية اللحام النقطي أخذين بنظر الأعتبار أعتماد الخصائص الفيزيائية والحرارة الكامنة على درجات الحرارة بأستخدام برنامج ANSYS 10.0 متعدد الأغراض. تم في هذا البحث دراسة تأثير متغيرات شعاع الليزر على توزيع درجات الحرارة، الأجهاد الحراري، وأبعاد منطقة الليزر. لقد لاحظنا من خلال النتائج وجود أرتباط جيد بين الجانبين التحليلي والعددي. وقد تم ملاحظة حصول أرتفاع كبير جدا في درجات الحرارة أثناء اللحام بالليزر في مركز البقعة ثم يبدأ بالتناقص بصورة كبيرة كلما أبتعدنا بالأتجاه الشعاعي. كذلك تمت ملاحظة تولد أجهاد حراري متبقي حول بقعة الليزر بسبب الأنفعال اللدن موزعا في منطقة ضيقة جدا لاتتجاوز 1.0 ملليمتر وهذا يدل على أن عملية اللحام بالليزر فعالة لتخفيض الأجهادات الحرارية المتبقية نتيجة عملية اللحام. ايضا تم الأستنتاج بأن الإجهاد على طول الإتّجاه الجانبي للقطعة الملحومة قد تغيّر من الأجهاد الأنضغاطي في البقعة تحت شعاع الليزر وأجهاد شد بعيدا عن البقعة في لحظة نهاية اللحام إلى أجهاد شد في البقعة تحت شعاع الليزر وأجهاد أنضغاط بعيدا عن البقعة عندما برّدت، وهذا يتوافق مع الأدبيات المنشورةالتي لها علاقة بالموضوع.
