MODELLING OF TEMPERATURE DISTRIBUTION IN LASER ASSISTED METAL-PLASTIC (LAMP) JOINING PROCESS

Francis Njihia, Bernard W. Ikua, Alphonse Niyibizi.

Abstract—Trends towards cost effectiveness, weight reduction and production flexibility in industrial production and manufacturing processes has led to a growing interest in hybrid components where two or more dissimilar materials are joined to achieve specifically optimized characteristics. Polymer and metals have become the most widely used combination of materials due to their superior characteristics. Polymers are lightweight and have a high degree of formability while metals have desirable properties such as high stiffness, high thermal conductivity and machinability. However, joining of these dissimilar materials presents challenges arising from their differences in chemical, mechanical and thermal properties. Joints are conventionally produced using adhesive bonds or glues, bolts, screws, and rivets. These conventional techniques have various limitation including low design flexibility, slow rate of joining and environmental restrictions. Laser Assisted Metal Plastic (LAMP) joining is a recently developed method that can adress such limitation. This technique is fast,easy to automate, and the joint is stable for a long period because of the direct utilization of a base plastic. However, the LAMP process has not fully been understood especially the thermal phenomena during the joining process. The need to predict the laser joining behaviour is very important because it forms a prerequisite for optimising the process parameters, thus improving the joint quality. This paper presents a model for prediction of temperature distribution in LAMP process, taking into consideration the different thermal properties of the materials. Finite element method (FEM) is employed for the model development. The heat transfer from the laser source is analyzed at the interface where the observation made will form a basis for further studies regarding the quality of the joints and important process parameters.

Keywords—LAMP, Temperature Distribution, Thermal Modelling.

I. INTRODUCTION

THErequirement of efficiency and innovation has led the manufacturing industries to a new level, where novel processes and products with enhanced properties are required. The increasing use of thermoplastics and thermoplastic based composites in different sectors, such as automotive, aerospace or electronics, has the potential to reduce costs and improve the production efficiency through the introduction of tailored materials with lower environmental impact [1]. However, technical plastics are often unable to substitute metals completely in industrial applications, especially in situations in which strong structural properties are required. Material hybridization can offer a compromise solution between all-metal structures and all-plastic components The main reason behind the integration of metal-polymer parts has been to complement the structural and non-structural needs of many products in a single customized solution [1]. Normally, metals have high strength-toughness ratio, high thermal and electrical conductivity, and high heat resistance. Plastic materials are principally used because of their light weight, high corrosion resistance and excellent form-ability. There are many cases of applications where plastics and metal parts have been joined.For example, Nylon/Polythene -Stainless steel for outdoor application where large bonded is subjected to constant vibration , impact, and temperature change [2]. Polycarbonate to Aluminum for battery housing application requiring heat and humidity resistance, high peel strength and high impact strength. Urethane to steel for outdoor use application subject to occasional impact , heavy static load and environmental exposure [2]. Metal to plastic joined-parts are normally fabricated by means of well-known techniques of mechanical joining such as riveting, bolting and screwing or adhesive joining like gluing [3]. Mechanical joints have limitations because of their poor flexibility in joint design and the rate of joining is low. Other limitations include increased component weight, evolution of stresses around fastener holes which consequently induces strength degradation and eventual corrosion related problems [3]. The major disadvantage of adhesive processes is that the volatile organic compound emissions are very toxic. The other factor limiting the use of adhesive bonding is the uncertainty in forecasting the long term durability of this joint alongside the fact that bonded joints often fails instantaneously instead of progressively [3]. It is therefore important to establish a joining technique for metal to polymer with unlimited design flexibility and faster fabrication rate as compared to adhesive joining and mechanical fastening. Laser assisted metal to plastic (LAMP) joining is a modern innovative technique used to join plastic to metals. The process offers unique fabrication opportunities and non-stringent requirements on surface preparation during the joining process [4]. Optically transparent plastics and opaque plastics can successfully be joined to a laser beam absorbent metal. The technology of laser joining presents advantages in design flexibility,precision, and fabrication rate. If compared to mechanical joining, the process flexibility is much higher. If compared to adhesive processes, direct laser joining is much faster and does not require special surface treatment. Overall, the joining process has shorter joining cycles and can effectively be used in cases of macro

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and micro components [5].The laser technology has expanded the application of polymer metal parts in the electronic and biomedical applications. Laser micro-joining technology has been used in packaging of MEMs.Also being a non-contact process, it eliminates concerns of contamination especially in manufacturing biomedical devices.

However, LAMP technology is yet to be fully understood and deeper investigations are being carried out in order to optimize the process and hence properties of the joints [6] . The joining process present challenges arising from large differences in thermal properties between metals and plastics, and different varying laser process parameters. The distribution of the thermal energy from a laser source at the plastic metal-interface is very influential in the development of a reliable joint. Inconsistent temperature distribution may lead to polymer degradation in case of excessive heat or uneven melting of the polymer. Therefore, the prediction of temperature distribution during the joining process is very crucial in understanding and predicting important welding attributes.

A. Joining Mechanism

LAMP joining mechanism is a complex physical process involving an interface thermal interaction of a laser-beam transparent plastic and the metal. The physical process is still under investigation but according to [1] it occurs as follows:

- The metal to polymer joint interface is heated up by the incident laser beam and melting temperature is attained in the plastic material in a narrow region adjacent the interface as shown in Figure 1 a.
- The resulting high temperature initiates bubble formation close to the interface into the melting plastic as shown in Figure 1 b.
- The bubbles spread across the interface, consequently increasing seam dimensions as shown in Figure 1 c.
- The bonding occurs in the molten solid interface between the plastic and the metal

Based on experimental evidence,the bonding mechanism is due to the combined influences of chemical bonding between the metal oxide film and the carbon atoms of polymers alongside physical bonding resulting from Van der Waals forces and mechanical bonding [1]. The physical phenomenon occurring during the welding process necessitates the overlapping joint configuration in this joining technique . Due to the low thermal conductivity of plastics, the heat remains concentrated in the material interaction zone and the heat behavior depend on the optical properties of the plastic as a function of its molecular composition i.e., color of plastic and wavelength of incident beam [4]. In the case of optically transparent plastics, laser metal plastic joining occurs only if the laser beam absorption is localized at the interface and its commonly referred to as laser transmission joining. On the other hand, for optically opaque plastics, the laser beam must be focused on the external surface of the metal component. Heat transfer is via conduction from the heated metal component to the plastic component which heats up and consequently melts [4].

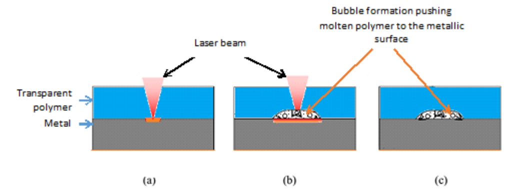

Fig. 1. Sequence of laser joining mechanism

The work proposed in this paper is to further evaluate the mechanism of joining occurring at the metal-plastic interface by modelling the heat transfer and predicting the thermal distribution at the interface.Temperature distribution during the joining process is important in understanding and predicting key welding attributes.

II. Materials and process

The ideal combination of materials to be joined in a LAMP welding process includes one absorbing and one transparent part. A direct laser beam laser irradiates and penetrates through the top transparent part and absorbed by the absorbing part. The laser energy is converted into heat in the absorbing part due to electron-phonon interaction at the surface thus causing localized heating of the material and subsequently induces local melting in the joining region.

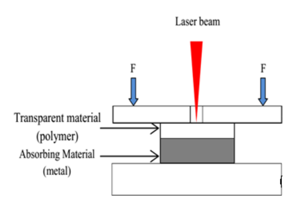

Fig. 2. A typical laser joining system.

The materials considered in this study are 1 mm thick PET (Polyethylene Terephthalate) overlapped on 1 mm stainless steel plate type S30400 . Physical properties for the materials are as indicated in Table 1. The joining of the materials are simulated with an Nd:YAG laser beam with constant laser power of 65 W and welding speed of 30 mm/min. PET is a typical engineering plastic with high laser transparency. Its excellent wear resistance, high flexural modulus, superior dimensional stability, and low coefficient of friction make it a multipurpose material for designing mechanical and electromechanical parts. PET can also be used in LAMP to produce strong joints with various metallic materials and some joint parts could resist heat cycle tests according to the previous research [2]. Thus it was thought that PET was one of the best plastics suited to dissimilar metal joining. Stainless steel is a laser absorbent metal with high strength and toughness, and is among the popular metals in application in the engineering industry.

III. Finite Element Modelling

The model developed is based on $COMSOL^R$, which is a Finite Element Analysis software package that allows the user to develop 3D models with associated boundary conditions.The solution are uniquely defined provided that appropriate initial and boundary conditions are given. The major assumptions on which the model is based are as follows:

- The laser beam has a Gaussian distribution in pulsed mode.
- Thermo-physical and optical properties are constant and uniform.

A. Governing Equation

The thermal model is based on the heat transfer modes occurring during the joining process of the dissimilar materials. Heat conduction is one of the major heat transfer modes which involves the heating of the absorbent metal by a laser beam and the transfer of heat to the polymer by conduction. The main purpose of this study involves the heat conduction analysis to determine the temperature profiles and heat flow within the joint. Fouriers law of heat conduction states that the heat flux (q) within an object is proportional to the temperature gradient in the direction of heat transfer. For a 1D plane wall, this equation can be written as [7]

$$q_x = -k_x \frac{\partial T}{\partial x} \tag{1}$$

where k_x is thermal conductivity along the x direction, and T is temperature distribution function.

The general heat conduction equation defines the temperature distribution within a body based on the energy conservation law, which balances the rate of the internally generated heat within the body, bodys capacity to store this heat, and the rate of thermal conduction to the boundaries (based on Fouriers law). A general heat conduction equation in three-dimensional Cartesian space can be expressed as follows [8]

$$\frac{\partial}{\partial x}(k_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k_y \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(k_z \frac{\partial T}{\partial z}) + Q = \rho(T)c(T)\frac{\partial T}{\partial t} \tag{2}$$

where k_x,k_y,and k_z are thermal conductivities. $\rho(T)$ is the density,$c(T)$ is the specific heat, t is time,and Q the heat source.

B. Heat Flux

The heat generation for the present study is due to a laser beam interaction at the plastic-metal interface after the beam has passed through the transparent plastic material. The heat generation is defined in terms of the laser power flux change caused by the absorption of the laser beam energy by the metal part and is a function of laser power, material absorption properties, laser-beam cross-section dimensions, laser beam scanning speed, and laser-beam power flux distribution. This heat generation term varies with x y z and time. It is modeled with a Gauss-shaped heat flux whose intensity varies with the beam radius. For the case of Gaussian power distribution, the equation for the incident heat flux q $(\frac{W}{m^2})$ can be expressed as [9]:

$$q = \frac{2AP}{2\pi r} e(-\frac{2r^2}{r_0^2}) \tag{3}$$

where A is the absorption coefficient of the absorbing material, P is the laser beam power, r_0 is the laser beam radius, $r = \sqrt{(x^2{}_s + y^2{}_s)}$ is the radial distance of any point from beam center on the surface of the material, where x_s and y_s are the Cartesian coordinates of that point.

C. Initial and boundary conditions

At the initial condition when time = 0 sec, the work piece has uniform ambient temperature. The environmental temperature is chosen as 293 K (20C). As the laser beam heats the cross-section, all the surfaces exposed to air transfer the energy by the convective heat transfer mode. This convective heat flux q_c is expressed by Newton's law of cooling [10]

$$q_c = Ah(T_s - T) \tag{4}$$

,where h is convection heat transfer coefficient, T_s is surface temperature, and T is ambient temperature. All the surfaces of the geometry except the top surface, bottom surface and the symmetry plane are assumed to transfer heat by natural convection to the environment since they are exposed to the surroundings.

D. Material Properties

In the development of a thermal model, material properties input determine the accuracy of the numerical results. The key material properties required for any heat transfer evaluation include, thermal conductivity, specific heat capacity and the densities of all the materials involved. The thermo-physical and optical characteristics in this study are assumed to be constant.

TABLE I
Physical properties of the material properties [11]

MATERIALS	Glass Transition Temperature K	Melting Temperature K	Specific Heat Capacity, $Jkg^{-1}K^{-1}$	Thermal Conductivity, $W/m^{-1}K^{-1}$
PET	353	472-528	1000	0.24
SUS304	-	1399-1454	500	16.2

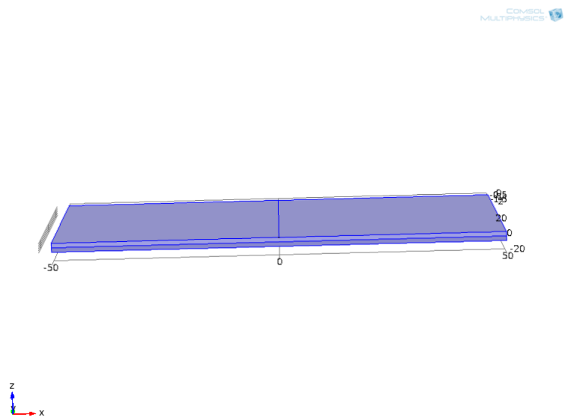

Fig. 3. Model geometry

E. Creating model geometry

The model geometry selection involves two domains representing the transparent plastic part and the metal part as shown in figure 3. Both domains are evaluated at the laser beam symmetry where the laser energy heats at the interface.

F. Meshing

Both domains of were meshed with a normal mesh on the surfaces that were least to be affected by the laser energy. The path of travel was meshed with a fine mesh as shown in figure 4.

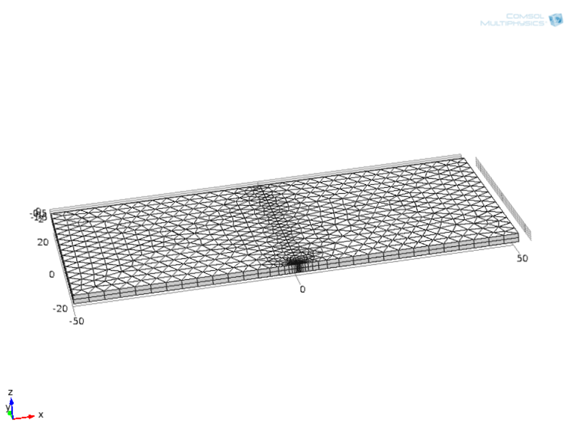

Fig. 4. Domains Meshing

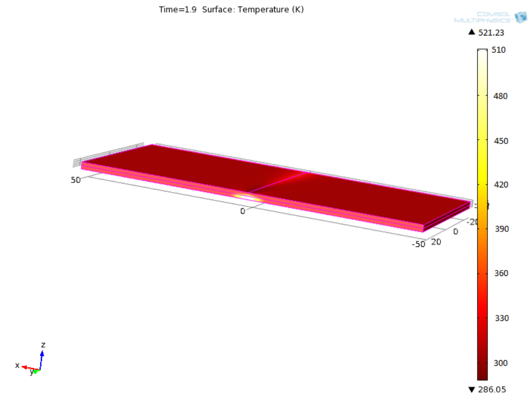

Fig. 5. Laser heating at the domains interface

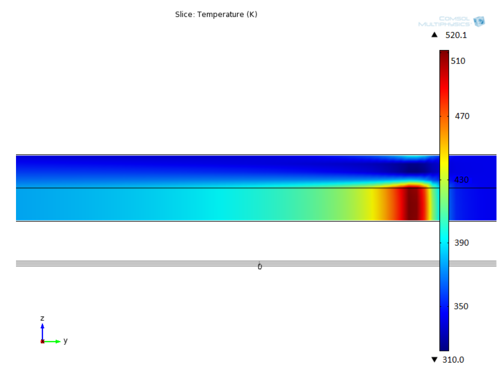

Fig. 6. Temperature Contour at the (Y-Z) plane at time 1 s

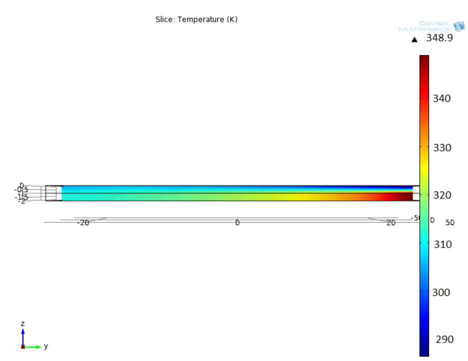

Fig. 7. Temperature Contour at the (Y-Z) plane at time 2 s

IV. Results and Discussion

A. Thermal simulation of temperature field

The simulation involving a moving heat flux on PET-SUS 3040 is shown in Figure 5. The laser beam passes through the transparent PET plastic and get absorbed in the stainless steel. Heat generation occurs at the interface and is conducted to the polymer surface.

Figure 6 and figure 7 shows the temperature field at the joint interface along symmetry plane Y-Z at 1 s and 2 s respectively . It is clearly seen that the temperature distribution of the both domains changes quickly with time and space. The laser beam passes through the transparent polymer and it is absorbed by

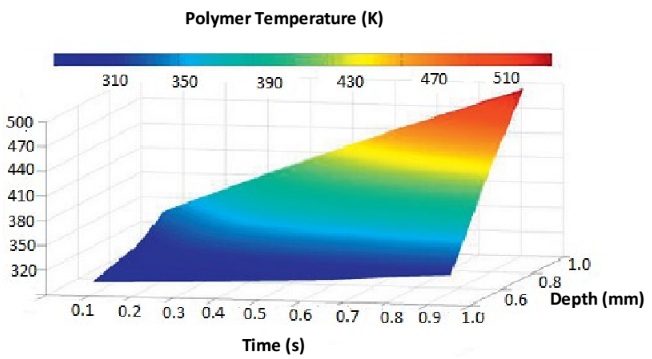

Fig. 8. Temperature Distribution on the interface along the irradiation path

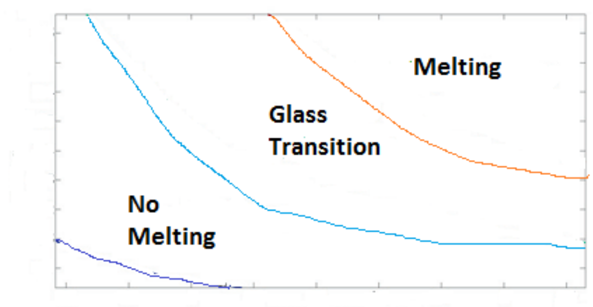

Fig. 9. Melt pool formation at the interface

the metal part where heat generated at the surface is transferred to the polymer by conduction.Due to the low conductivity of polymers as compared to metals, the heat transfer in the polymer domains occurs at the region close to the interface where melting occurs. However, the maximum temperature achieved at the interface is far below the melting temperature of the metal.Therefore, it can be concluded that only the polymer melts during the process,taking into consideration the melting temperature of PET, which is between 470-520 K.

Figure 8 shows the temperature distribution on the polymer side at the interface along the irradiation path and along the thickness of the polymer. From the graph, it can be deduced that maximum temperatures occurs at the interface where the laser energy is absorbed by the metal. As observed, the plot in brown color shows the temperature required to melt the plastic is achieved. The thermal field changes as the laser source moves along and with distance away from the interface. Figure 9 shows the melt pool formation as depicted from figure 8. It is therefore noted that the polymer domain undergoes melting at the interface where the bonding occurs with the metal as cooling takes place. .

V. Conclusion

A three dimensional finite element model for prediction of thermal process in LAMP has been developed. The model has been able to predict the temperature distribution occurring during the joining of the plastic-metal materials in consideration. It involved a moving heat flux that is distributed across the laser travel-path cross-section. The results show that the temperatures at the joint interface can be predicted at each point or time during the process. This model can be used for selection of optimum parameters, thus providing the parameter window for appropriate interface temperature with good accuracy, and thus, reduce notably the need for trial and error experiments. In addition, the model will help us to predict the molten pool dimension of the plastics in relation to the distribution of the laser energy from the interface. This is part of an ongoing work and in a later publication, the model will be validated using available experimental data to establish the correlation between the model simulation and experiments.

References

[1] Katayama S. , Kawahito Y. , "Laser direct joining of metal and plastic," *Scripta Materialia*, vol. 36, pp. 1247–1250, 2008.

[2] Weber A., *New Techniques for Joining Plastic to Metal*. www.assemblymag.com/articles/92408-new-techniques-for-joining-plastic-to-metal.

[3] Cenigaonaindia A., Libana F. , Lamikiz A. , Echegoyen Z , "Novel strategies for laser joining of polyamide and aisi 304," *Physics Procedia*, pp. 92–99, 2012.

[4] Kah P., Suoranta R., Martikainen J., Magnus C., "Techniques for joining dissimilar materials:metals and polymers," *Rev.Adv.Mater.Sci*, vol. 36, pp. 152–164, 2014.

[5] Farazila Y. , Fadzil M. , Hamdi M. , "A brief review: Laser joining of polymer metal structures," *Invited Paper*, 2012.

[6] Fortunato A.,Cuccolin G. , Ascari A. ,Orazi L. , Campana G. , Tani G. , "Hybrid metal-plastic joining by means of laser," *Int J Mater Form*, vol. 3, pp. 1131–1134, 2010.

[7] Carslaw H. S. and Jaeger J., *Conduction of Heat in Solids*. Clarendon Press Oxford, 2001.

[8] Rosenthal D., "Mathematical theory of heat distribution during welding and cutting," *Welding Journal*, vol. 20, pp. 220–234, 1941.

[9] Rodrguez-Vidala E. , Lambarria J. , Sorianoa C. , Sanza C. , Verhaegheb G. , "A combined experimental and numerical approach to the laser joining of hybrid polymer metal parts," vol. 56, pp. 835–844, 2014.

[10] Dowden J. M. , *The Mathematics of Thermal Modelling-An Introduction to the Theory of Laser Material Processing*. Chapman and Hall/CRC.

[11] Farazila Y. , Miyashita Y. , Wang Hua, Mutoh Y. , Otsuka Y. , "Yag laser spot welding of pet and metallic materials," *Journal of Laser Micro/Nanoengineering*, vol. 6, pp. 69–74, 2011.