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Finite Element Modeling of Penetration Laser Welding of Sandwich Materials

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Abstract

In this paper, a modeling strategy for the penetration laser welding is presented. Both the surface heat and the heat generated within the keyhole are taken into consideration. For the estimation of the heat source, analytical and semi-empirical equations are used. The model is verified for the penetration welding of homogenous materials, and the simulation results meet the experimental ones with good accuracy. However, the penetration welding of sandwich materials is prohibited due to their tendency to delaminate. In this work, the simulation is exploited for selecting process parameters that will not harm the internal layer of the sandwich material. Based on the experimental verification, strategies and guidelines for the successful welding of such materials are discussed.

Keywords: Processes, Modeling; Laser Welding; Sandwich material

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1. Introduction

Sandwich composites with viscoelastic core are currently used in load-bearing components, in buildings and naval structures due to their high strength to weight and stiffness ratios, excellent thermal insulation, and ease of manufacturing. Such composite materials are also used in automotive manufacturing due to their excellent vibration absorption properties. It is known that the constituent properties of the sandwich composites are greatly influenced by the temperature and moisture fields. For example, extreme temperature changes, such as those created during the laser welding process as well as the humid environmental conditions can significantly degrade the stiffness and strength of the viscoelastic core.

Sandwich structures, composed of stiff outer layers, connected by a relatively low-density core, result in high specific strength and stiffness, which may lead toward substantial design advantages. Properly designed steel sandwich panels offer a substantial resistance to static and dynamic loads, due to their relatively high stiffness and inherent energy absorbing capacity. To that end, the steel sandwich construction has a great potential to be used in the automotive industry, for ships, buildings, and bridge structures. They perform especially well in situations of hazard reduction owing to their high energy absorbing potential. The steel sandwich construction has other

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advantages as well. Lok and Weng [1] have listed several; such as accurate construction, less surface distortion, rapid construction practices, better retention of pressure and water leakage, greater flexibility and ease of material transportation. Although difficulty in fabrication and reliability of the face-sheet/core connection has been a continual problem, laser welding of the face sheet to the core with the use of a stake weld could possibly overcome this problem. Assessments of the weld's fatigue resistance as well as connection details are essential to the implementation of laser welded steel sandwich panels. Bampton [2] patented the laser welding of sandwich structures through the control of the depth by applying the energy in stages, in order to weld layered materials starting from the inner layers.

The study of the relevant literature has revealed the lack of simple theoretical models able to describe the laser welding process of such sandwich materials. However, a large number of papers investigating the laser welding processes of monolithic materials have been published. Over the last years, the theoretical papers are focusing on the simulation of the process with the use of the finite element analysis. The outcome of these works can also be adapted to the simulation of the sandwich materials.

In this paper, the simulation of the laser welding process of sandwich materials is presented. The main concern is that laser welding be achieved without incurring any negative results on the middle layer of the sandwich material or to its general behavior. Based on the experimental verification, strategies and guidelines for the successful welding of such materials are discussed.

2. Theoretical Analysis of laser welding of monolithic materials

2.1. Analytical Modeling

During the laser welding process, while the laser beam impinges on the material's surface, a portion of the beam is reflected because of the material's emissivity. The remaining energy is absorbed by the material and is transferred to the material's molecules causing them to move and resulting in a temperature raise and heat transfer [3]. At the beginning of the process, the energy absorbed by the material causes a local temperature rise at the material's surface. Continuing because of the conduction, the temperature in the area surrounding the laser spot, rises and reaches that of melting. The melted pool is then created and the temperature continues rising until the material's evaporation (sublimation). A "keyhole" is formed because of the internal gases' pressure and keeps existing during the laser welding procedure following the laser beam. The laser welding process is simulated by two heat sources, a surface and a volumetric one both, following the Gauss distribution for the load intensity. While there is a great amount of heat concentrated on the area where the laser welding process occurs and the temperatures of the material may reach 3000 K, the supporting table and the surrounding air have the environment temperature. This extreme temperature difference cause the heat loss by convection. Convection occurs from all the surfaces of the metal sheets, horizontal and vertical ones.

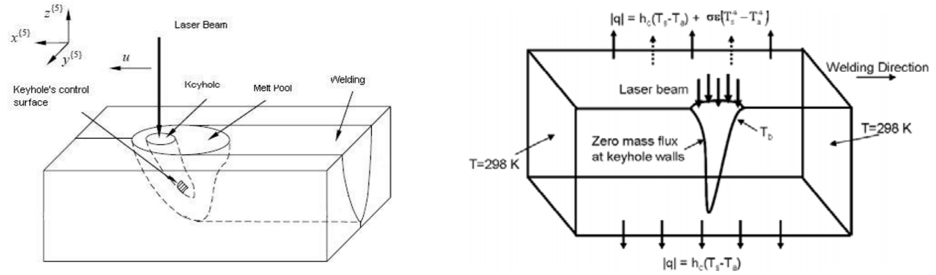

Fig. 1. (a) Butt laser welding; (b) laser welding process physics

The keyhole's geometry can be estimated using the equations derived by Solana and Ocana [4]. Their comprehensive analysis took into consideration the heat conduction, the ablation loses, the evaporation effects at the keyhole open surfaces and the Fresnel and inverse- Bremsstrahlung energy-absorption mechanisms. The keyhole length is calculated from equation:

$$H_{\Lambda} = \frac{nP_L}{h(T_B - T_0)\left(f_1 + \frac{f_2}{2}Pe + \frac{f_3}{3}Pe^2 + \frac{f_4}{4}Pe^3\right)} \tag{1}$$

Where the Peclet number is estimated from:

$$Pe = \frac{u_{weld}\, w_{weld}}{2\mu_k\left(\beta_1 e^{-\lambda_1 Pe} + \beta_2 e^{-\lambda_2 Pe} + \beta_3 e^{-\lambda_3 Pe}\right)} \tag{2}$$

Additionally, the keyhole's radius is estimated using the following equation:

$$R_{\Lambda} = \frac{2\mu_k Pe}{u_{weld}} \tag{3}$$

The temperature field, generated because of the laser beam's impact, can be determined using finite elements. However, in order to model the conditions of the welding, several factors have to be calculated. Free convection (fig. 2) factors for each surface of the sheet, as well as the convection and radiation on the interface of the two sheets, were calculated using the equations found in table 1. These thermal coefficients were estimated using the Nusselt numbers.

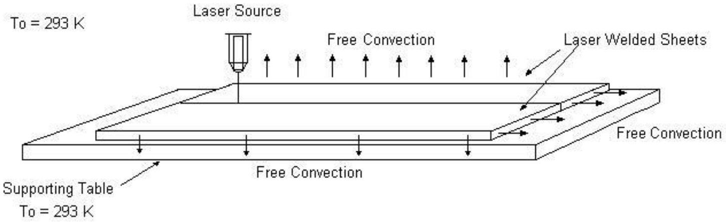

Fig. 2. Free convection during laser welding

Table 1. Free convection coefficients

Free convection coefficient at	Equation
Bottom areas	$N_{u_L} = 0.27 Ra_L^{1/4}, 10^4 \le Ra_L \le 10^7$
Top areas	$N_{u_L} = 0.54 Ra_L^{1/4}, 10^4 \le Ra_L \le 10^7$
Vertical areas	$N_{u_L} = 0.68 + \frac{0.67 Ra_L^{1/4}}{\left[1 + \left(\frac{0.942}{\mathrm{Pr.}}\right)^{9/16}\right]^{4/9}}, Ra_L \le 10^9$

Further to the free convection, forced heat convection occurs at the top areas due to the jet of air from the laser machine that can be calculated by the following equation:

$$Ra_x = Gr_x \Pr = \frac{g\beta}{va}(T_s - T_\infty)x^3 \tag{4}$$

Where

$$Gr_L = \frac{g\beta(T_s - T_\infty)L^3}{v^2} \quad \text{and} \quad \Pr = \frac{v}{a} = \frac{viscousdiffusionrate}{thermaldiffusionrate} = \frac{c_p \mu}{k}$$

The surface load, resulting from the laser source, was calculated after having considered a Gaussian distribution of the laser beam's intensity using equation [5]:

$$q(r) = \frac{n_L P_L}{r_b^2 \pi} e^{\frac{-r}{r_b^2}} \tag{5}$$

Simultaneously, a volumetric load is considered to exist due to the keyhole formulation that can be determined by the following equation:

$$q(r,z) = \frac{2 n_L P_L}{\pi R_k^2 H_k} e^{1-\left(\frac{r}{R_k}\right)^2} \left(1 - \frac{z_b}{H_k}\right) \tag{6}$$

2.2. Finite Element Analysis

The use of free triangular elements and refined mesh at the welding area allows for the extraction of more accurate results along with less element number, thus reducing the analysis time. Eight nodded elements having a single degree of freedom (temperature) were used for the meshing. The model created for this simulation was a rectangular thin sheet 40x60mm. An optimized mesh was developed to provide results of a significant accuracy near the laser spot, where the welding occurs.

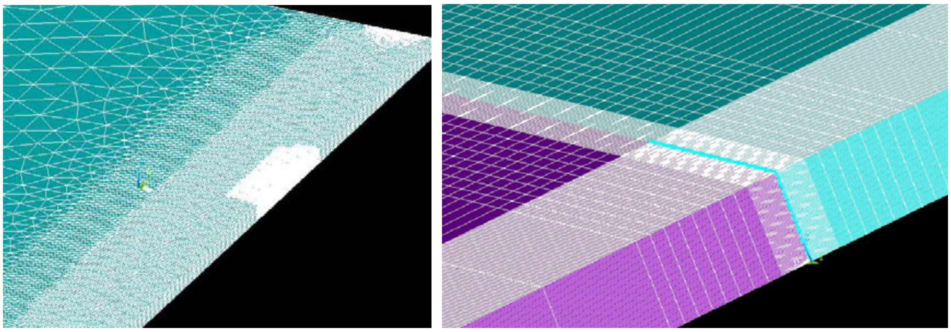

Fig. 3. Finite element model for the monolithic welding (a) 1.2 mm thickness and (b) 3.0 mm thickness

2.3. Theoretical results and experimental verification

For the verification of the aforementioned model, it was solved for the case of a Stainless Steel AISI 304 sheet of 1.2 mm thickness. Mechanical and thermal properties are shown in table 2 and Figure 4.

Table 2. Material properties for AISI 304 and laser constants

Property	Symbol	Value	Unit
Laser Beam radius	r	$4.00\ 10^{-04}$	m
Melting Temperature	T_v	2740	K
Absorption factor	A	30	(%)
Welding Speed	u	0.01	m/s
Air Thermal expansion coefficient	β_{air}	$3.43\ 10^{-03}$	1/K
Air density	ρ_{air}	1.205	Kg/m^3
Air specific heat	Cp_{air}	1.005	Kj/KgK
Air kinematic visvosity	v_{air}	$1.51\ 10^{-05}$	m^2/s
Air thermal conductivity	k_{air}	0.0257	W/Mk
Acceleration due to gravity	g	10	m/s^2
Prandtl Number	Pr	0.715	-

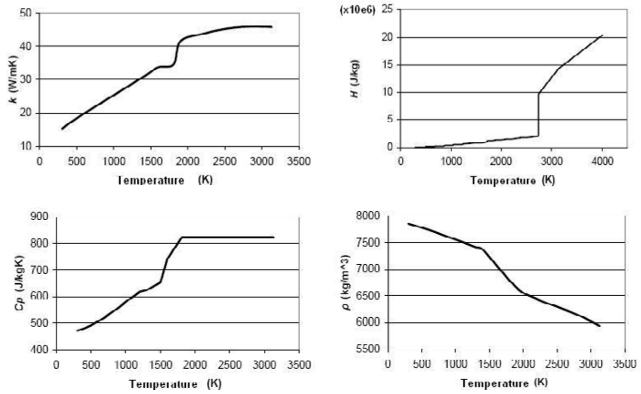

Fig. 4. AISI 304 properties as a function of temperature

The model was solved for the case of butt welding with a laser power of 2000W, welding speed of 100 mm/sec and a welding width of 1 mm. Following the analysis presented in section 2.1, for these specific process parameters, the keyhole radius was estimated to be 0.377 mm, the keyhole depth 0.876 mm and the Peclet number 3.129. The resulting temperature field in the welded specimens is shown in Fig. 5.a. In order for the model to be verified and tuned, the case of butt welding of stainless steel sheets of 3mm thickness was simulated and compared with experimental results (fig. 5b). Experimental data, from a previous study [6], were used for the verification of the proposed analysis.

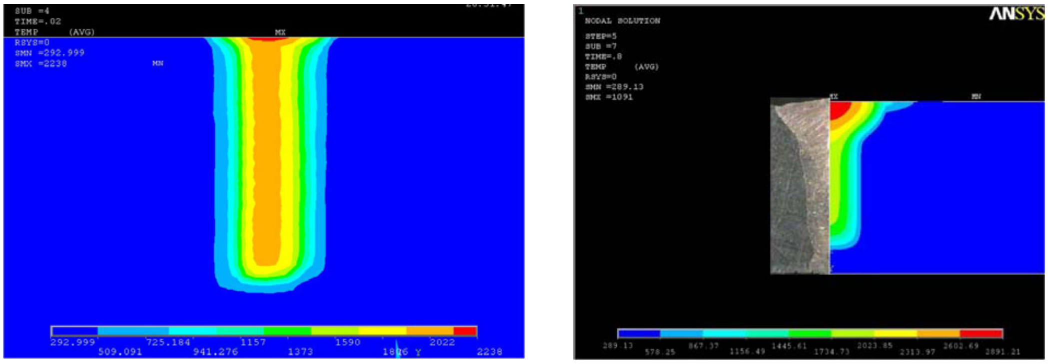

Fig. 5. Laser welding of stainless steel 304 sheet with (a) 1.2mm thickness at P=2000W,uW=10mm/s, (b) 3.0mm thickness at P=5500W,uW=32.9mm/s

3. Theoretical Analysis of laser welding of sandwich materials

3.1. Laser welding of sandwich materials: limitations and proposed approach

Laser welding of sandwich materials with a viscoelastic core is mainly limited because of the heat sensitive core. The core's optimum operation ranges from 318 to 373 K and its melting point is approximately from 600 to 800K. Therefore, laser welding should occur in a way that would not affect the viscoelastic core. Overheating the core or reaching melting temperatures could mean the deterioration of the damping and acoustical properties of the material.

Another aspect of laser welding of such materials is that of the properties at the welding area. There is a very low possibility for the viscoelastic core from the one side of a butt-weld, to merge with the one from the other side, even if the steel sheets are welded together. Then, a perfect welding with the unified material is practically impossible.

Two different butt welding approaches are investigated in the present paper. The conventional approach is to attempt to weld the sandwich material from one side, although this will most certainly result in the evaporation of the viscoelastic core. The alternative approach is that the depth of the welding be controlled through the process parameters in order for the steel sheets to be welded however, without having the temperature of the core raised above its melting temperature.

For the modeling of the former approach, the loading conditions from the calculations used for the laser welding of pure stainless steel are applied to the full depth of the sandwich material. This would certainly affect the core, at the laser welded area, deteriorating the materials properties; although the welding would be probably achieved.

For the alternative, two side approach, the model was solved so as to calculate the process parameters that result in the temperature distribution affecting mainly the upper metal sheet of the material and not its core. Using the proper energy and laser beam depth it was possible to achieve a weld of the upper sheets without causing any harm to the material's viscoelastic core. This way, since the material is symmetrical, laser welding would be possible for both the upper and bottom surfaces of the materials without causing an irreparable damage to the core.

Fig. 6. Laser welding of sandwich materials (a) two side approach, (b) one side approach

3.2. Finite element analysis

In order to simulate the laser welding process to Sandwich materials, the ANSYS program was used. Since the purpose of this paper is to investigate the heat affected zone of the laser welding process on sandwich materials, two different material models were used; one simulating the metallic top and bottom layer and another simulating the viscoelastic core sandwich between them. A contact-target parameter was set between the core and the metal for both sides of the viscoelastic core thus, simulating the penetration of the heat through the top sheet of steel to the core and through it, to the bottom metal sheet. For the simulation of metal and core materials, elements with eight nodes having a single degree of freedom (temperature) were used. The element chosen can also compensate for mass transport heat flow from a constant velocity field. The model was meshed with the use of a mapped mesh with quadrilaterals 8-node elements. Mapping at the welding area was optimized in order for more accurate results to be produced capable of demonstrating, the best possible way, the heat affected zones of the laser welding process.

In order to simulate the heat from the metal sheet to the core, a contact target pair was set, using CONTA 173 and TARGE170 elements. CONTA173 is used to representing contact and sliding between 3-D "target" surfaces and a deformable surface, defined by this element. The element is applicable to 3-D structural and coupled field contact analyses. The contact elements themselves overlay the solid elements, describing the boundary of a deformable body and are potentially in contact with the target surface, defined by TARGE170. This target surface is discretized by a set of target segment elements (TARGE170) and is paired with its associated contact surface via a shared real constant set. Contact occurs when the element surface penetrates one of the target segment elements on a specified target surface. In the present paper, a contact surface is the bottom surface of the upper metal sheet of the sandwich material, whereas a target surface is the upper surface of the material's core.

In order for analysis time to be reduced and more accurate results to be achieved, only half of the model used had its symmetry exploited. Using the calculations made for the laser welding finite element analysis of the stainless steel materials, loading and boundary conditions were applied. The upper and lower layers were considered being

AISI 304 with 0.5 mm thickness, whereas the core material was considered as typical viscoelastic with 0.15 mm thickness (mechanical and thermal properties are indicated in Table 3).

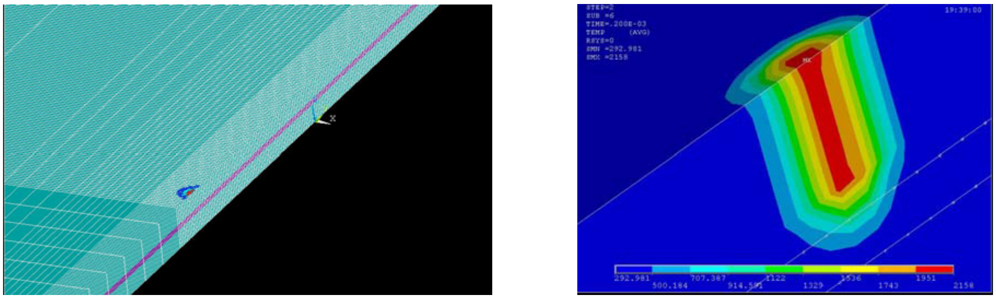

Fig. 7. (a) Finite element model meshing and loading for the case of laser welding butt welding, (b) FEA results for P=2000W and u_W=100 mm/sec

Table 3. Core material properties

Property	Symbol	Value	Unit
Density	*P*	1320	kg/m^3
Specific heat	c_p	2300	J/kg.K
Enthalpy	H	50	J/kg
Thermal Conductivity	K	0.5	W/m.K
Film Coefficient		50	W/m^{2}K
Expansion Coefficient		1.5x10^9	K^{-1}
Viscosity	*M*	9x10^9	Ns/m^2

4. Theoretical Results

The finite element model was worked out for both welding solutions (one side and two side approach). In fig. 7(b), indicative results of the laser welding of the sandwich material are shown.

4.1. Two side approach

As indicated in section 3.1, damaging the core viscoelastic material should be avoided; therefore, it is important that the core group material not be exposed in temperatures above its melting point. On the other hand, the upper and bottom layers have to be welded to at least 70% of their total thickness in order for their welding to be considered safe. For this reason, the investigation has been focused on these aspects. In fig 8(a), the temperature distribution during the laser welding of the sandwich material is simulated for the case of 1,200 W power at a welding speed of 10 mm/s. Figure 8(b) presents the temperature at the interface between the upper steel layer and the core material for a 1,000 W power as a function of the welding speed. As expected, the temperature at the interface is reduced as the welding speed is being increased. This figure indicates that for the core material not be damaged, the welding speed should exceed 10 mm/s, however this does not give any information as to the depth of the welding achieved.

In fig. 9, the welding depth achieved is shown as a function of the welding speed. In order to reach the goal of welding at least the 70% of the total upper layer thickness, the welding speed has to be kept relatively low for the test power of 1,000 W. However, as it can be seen in fig. 8(b), keeping the welding speed low results in an interface temperature that is higher than that of the core's melting point. This implies, that a proportion of the core material will be damaged (burned). The extent of core material damage can be also seen in fig. 9 as a function of welding speed. For a welding depth complying with the 70% criterion (0.35 mm welding depth at the thickness of 0.5 mm), 10% of the core material (0.015 – 0.020 mm) is burned.

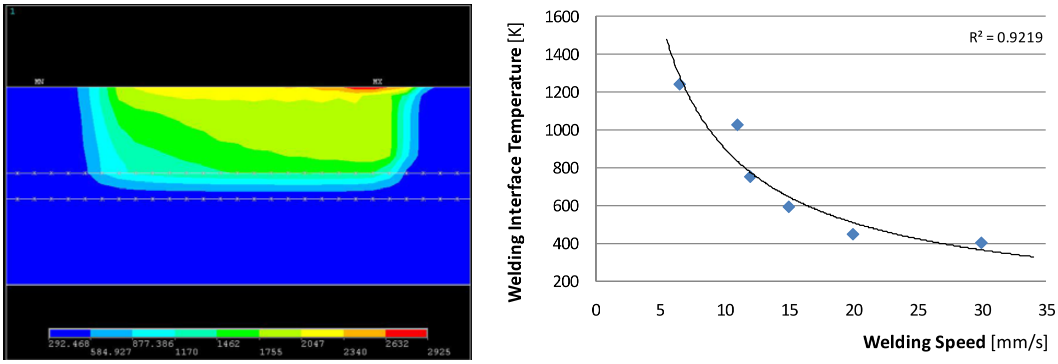

Fig. 8. (a) Laser welding sandwich material at time t=0.3s. P=1200W, u_W =10mm/s, (b) welding interface temperature as a function of welding speed for P=1000W

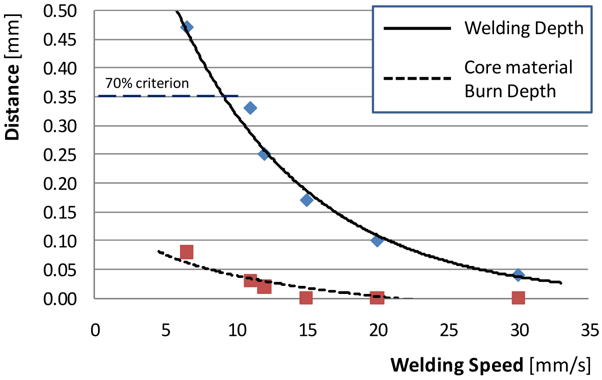

Fig. 9. Welding depth and depth of core material damage as a function of welding speed for P=1,000W

4.2. One side approach

The simulation of the one side approach can be seen in fig. 10. It is obvious from the results that the temperature at the material's core is elevated to a level above its evaporation temperature. This would result in the creation of a void between the two sheets besides harming the properties of the core that exists in the area of the laser welding. From the application's point of view, the overheating of the core will result in the deterioration of the material's damping and acoustical properties. Although, it is possible for both the upper and the lower sheets of the sandwich material to be welded using the one side approach, the resulting void between these two sheets in the area of the welding line will limit the applicability of these sandwich sheets.

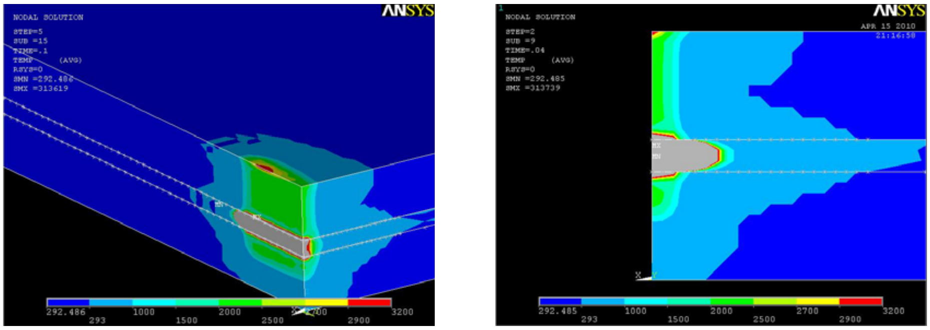

Fig. 10. FEA results for one side approach with P=2000W and u_W=10 mm/sec at (a) 0.1 sec and (b) 0.04 sec. Areas in grey are damaged

5. Conclusions

A finite element model has been proposed for the simulation of the laser welding of sandwich materials. The model was initially checked and verified for the case of a monolithic material and afterwards, it was used for describing the process of sandwich materials. Two different approaches were investigated; the first one having to do with welding the sandwich material in two sides, in a controlled way, so as to avoid overheating the viscoelastic core. The second one having to do with trying to simply apply the conventional one side welding to join the two sandwich sheets. The former approach was found to be feasible for such joining and revealed that the upper and lower steel sheets could be welded up to 70% with causing less than 10% damage to the core material. The one side approach however, was found ineffective to weld the sheets together and prevent any damage from being caused to the core material in the vicinity of the weld.

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