OPTIMIZATION OF LASER WELDING PROCESS FOR THERMOPLASTIC COMPOSITE MATERIALS WITH REGARD TO QUALITY AND COST

Ch.V.Katsiropoulos, G.A.Moraitis, G.N.Labeas and Sp.G.Pantelakis

Laboratory of Technology & Strength of Materials, Department of Mechanical Engineering & Aeronautics, University of Patras, Panepistimioupolis Rion, 26500 Patras, Greece

ABSTRACT

In the present work, the Laser Transmission Welding (LTW) process is optimized with regard to quality and cost for welding thermoplastic stiffeners on aircraft's fuselage skin. A generic optimization concept developed in a previous author's work is used for this study. In this frame, Quality and Cost sensitivity analyses have been performed aiming to derive material dependent Quality Function (QF) and process dependent Cost Estimation Relationships (CERs). QFs and CERs are exploited to derive iteratively the optimal welding parameters. To compute heating and cooling parameters, the process thermal cycle is numerically simulated by means of finite element method. In order to optimize the LTW process with respect to quality and cost, a software tool, namely the LTSM-OPT tool, is extended to the LTW process. The optimal process parameters of the LTW system along with the optimal heating cycle for welding thermoplastic lap-joints are obtained, in the form of a reference welding temperature along with an allowable window which meets the minimum quality requirements. The results of the study were successfully exploited by an aeronautic industry to weld stiffeners on aircraft's fuselage panel.

1. INTRODUCTION

The progress accumulated over several decades on the fiber reinforced polymer technologies led to a dramatic increase in the use of composites in modern civil aircraft primary structures. Despite the development of a series of semi-crystalline high-performance thermoplastic composites offering excellent technological properties, most of the composite materials used on aircraft are still of thermosetting type. The key factor for achieving the breakthrough for a wide spread use of thermoplastic composites in aircraft structures, anticipated already since the early 80s, is to improve the cost efficiency of thermoplastic structures as compared to the cost efficiency of their thermosetting and metallic counterparts.

The low cost efficiency of thermoplastic composite components reflects the costs of raw materials and, primarily, the high costs of the processes involved to manufacture thermoplastic composite aircraft structures. To overcome the above drawbacks has been the subject of several investigations. The straightforward way to reduce raw materials costs has been to replace high-performance semi-crystalline thermoplastics, such as the high price Polyetheretherketone (PEEK), by lower performance/low cost semi-crystalline thermoplastics such as Polyamide (PA) or amorphous thermoplastics such as Polyetherimide (PEI) making thus the compromise of lower performance for lower product cost. The recognition of the decisive contribution of the long process cycles of thermoplastics at elevated temperatures to the final cost of a component [e.g.1, 2] led to the development of material solutions balancing an acceptable reduction of performance by an appreciable decrease of the processing temperature of the materials, e.g carbon fiber reinforced PolyphenyleneSulfide (PPS/C). The same basic ideas, namely to reduce the component's cost by reducing the processing temperature of the thermoplastic matrix along with using a cheaper but still high performance raw material, lie behind the recent trend of developing thermoplastic blends [e.g. 3].

On the other hand, a number of investigations focused on developing concepts for the optimization of the manufacturing processes so as to minimize the manufacturing costs were carried out [4-7]. In parallel to these efforts, to face the problem of the labor cost intensive processes used for the manufacture of thermoplastic composite aircraft components and their strong influence to the component's final cost [e.g. 8] a series of investigations aiming to develop alternative cost effective manufacturing processes involving short process cycles and/or high degree of automation were made, [1, 4, 9].

Moreover, in order to produce integral structures and thus make the final composite part more cost effective, the exploitation of the metallic parts Laser Beam Welding process in the case of composite components joining is currently under investigation [10, 11]. Specifically, thermoplastic polymers have long molecular chains held together by secondary chemical bonds, which allows them to be heated and re-melted; by activating this physicochemical mechanism, thermoplastics can be joined using a wide variety of fusion and interlayer bonding processes [10], thus providing welding potential. However, the application of Laser Welding (LW) to thermoplastic components has been studied only partially; the studies are limited mainly in material types, such as polyamide – PA [11]. However, thermoplastic types which are commonly used in the aeronautical industry (the so called 'high performance thermoplastics), e.g. polyetheretherketone - PEEK, polyetherimide - PEI and polyphenylene sulphide – PPS, have not been investigated so far with respect to their laser welding capability. As a result, the reliable application of LW technology for joining thermoplastic aeronautic parts still requires significant development and investigation.

In the present work, the Laser Transmission Welding (LTW) process, one of the variations of LW technologies, is optimized with regard to quality and cost for welding thermoplastic stiffeners on aircraft's fuselage skin. A generic optimization concept developed in a previous author's work [7] is used for this study. In this frame, Quality and Cost sensitivity analyses were performed to derive material dependent Quality Function (QFs) and process dependent Cost Estimation Relationships (CERs). QFs and CERs are exploited to derive iteratively the optimal welding parameters. In the derivation of CERs for the LTW process, the temperature distribution with respect to the process parameters is required. Due to the fact that LTW of thermoplastic parts is quite a new application, experimental temperature measurements were not available. Therefore, the processes thermal cycle is numerically simulated to compute the necessary temperature data. In order to optimize the LTW process with respect to quality and cost, a newly developed software tool, namely the LTSM-OPT tool [7], is extended to the currently investigated LTW process. The optimal process parameters of the LTW system along with the optimal heating cycle for welding thermoplastic lap-joints are obtained, in the form of a reference welding temperature along with an allowable window which meets the minimum quality requirements. The results of the study were successfully exploited by an aeronautic industry in order to define process parameters for welding stiffeners on aircraft's fuselage panel.

2. OPTIMIZATION OF LASER TRANMSISSION WELDING (LTW) PROCESS

2.1 OVERVIEW OF LTW PROCESS

The Laser Transmission Welding (LTW) has been selected as the most suitable technique for joining thick thermoplastic components, which are typically used in the Aeronautic sector. Moreover, size, geometrical requirements and specifications of aeronautical parts can be more easily fulfilled by applying LTW technique rather than alternative technologies [11]. LTW allows the joining of thermoplastics provided that one of the materials (top material) is transparent to laser radiation and the other (bottom material) is absorbent enough for the welding to take place. Parts to be joined are brought into direct contact prior to welding. The laser beam is transmitted through the first material and is totally absorbed within the surface of absorbing material. Direct contact between both parts ensures heating of the transparent part by heat conduction from the absorbing part, *Figure 1*. Welding occurs upon melting and fusion of both thermoplastic materials at the interface. The LTW technology offers the possibility to join separate parts ensuring full continuity of the resin system without the addition of an adhesive system and avoiding also rivet installation, leading to a number of substantial advantages, such as cost savings, weight reduction and manufacturing cycle time reduction.

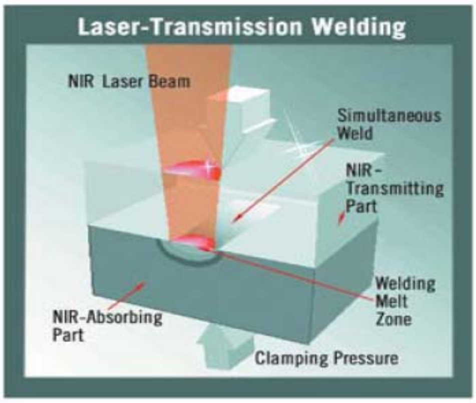


Figure 1: Laser Transmission Welding (LTW) technique [4]

2.2 QUALITY SENSITIVITY ANALYSIS FOR THE PPS/C MATERIAL

It is known that the mechanical properties of a thermoplastic composite component depend on the heating process parameters involved to manufacture the component [e.g. 12]. These dependencies along with the design allowables of the component concerning mechanical properties set a process parameters “window” which ensures components of acceptable quality. It is worth mentioning that in the present work the material investigated was PPS/carbon, as well as that the derived Quality Function depends on the material itself and not on the specific process used for the welding. The most critical mechanical property for the investigated type of structure is the single-lap shear strength. Hence, the mechanical property considered as quality feature for the present application was the single-lap shear strength which is experimentally derived for different welding parameters cases· they are given in Table 1. In this frame, 18 single-lap shear tests were performed according to the AITM 1-0019 specification [13]. As an example, in Figure 2 in a 3 dimensional plot are displayed the derived single-lap shear strength combined with the laser power *P* and the laser speed *LS*.

Welding parameters cases	Welding parameters			Single-lap shear strength SLS	
	Laser Power P [W]	Laser speed LS [mm/min]	Welding Temperature T_{ap} [°C]	Derived value [MPa]	Number of tests
C-1	165	1000	340	47	*5*
C-2	220	1000	385	78	*5*
C-3	330	1200	320	61	*3*
C-4	385	1200	395	77	*5*

Table 1: Different welding parameters cases and the respective derived SLS strength

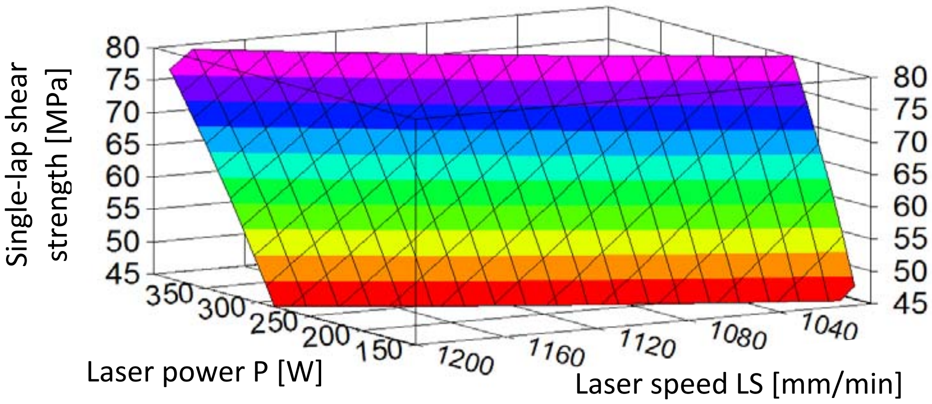


Figure 2: 3-dimensional plot combining the derived single-lap shear strength with the laser power P and the laser speed LS

The above results were exploited to derive the Quality Function (QF) which is an equation that relates the investigated important quality parameter to the LTW parameters, namely the laser power *P*, the laser speed *LS* and the applied temperature during the welding T_{ap}. The derived QF along with the fitting coefficients are given in Table 2.

Important Quality parameter	Quality Function - QF	Fitting coefficients
Single-lap shear strength SLS	$\boldsymbol{SLS = Q_1 \cdot P - Q_2 \cdot LS + Q_3 \cdot T_{ap}}$	$Q_1=11{,}6\cdot10^{-2}$ MPa · $[W]^{-1}$ $Q_2=5{,}3\cdot10^{-2}$ MPa · $[mm]^{-1}$ [min] $Q_3=25{,}5$ MPa · $[^oC]^{-1}$

Table 2: Quality Function for the PPS/C material

2.3 THERMO-MECHANICAL SIMULATION OF THE LTW PROCESS

To reduce the required experimental effort in deriving the required temperature data, simulation of the thermal cycle of the LTW process has been performed using finite element (FE) method. The numerical simulation is based on the virtual application of the laser radiation on the material and provides accurate temperature data, relating the process parameters (i.e. laser power, distance from the plate, welding speed) to the welding temperature. In this frame, a thermo-mechanical analysis of the heating-welding stage is performed using the commercial FE code ANSYS; the finite element model created is shown in Figure 3. Thermal Elements Solid 70 are used to model the laser beam as well as the heat conduction within the thermoplastic plate.

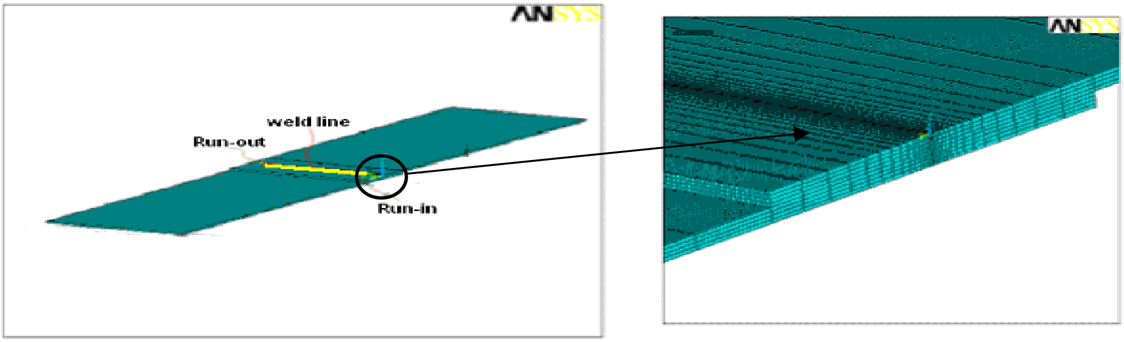
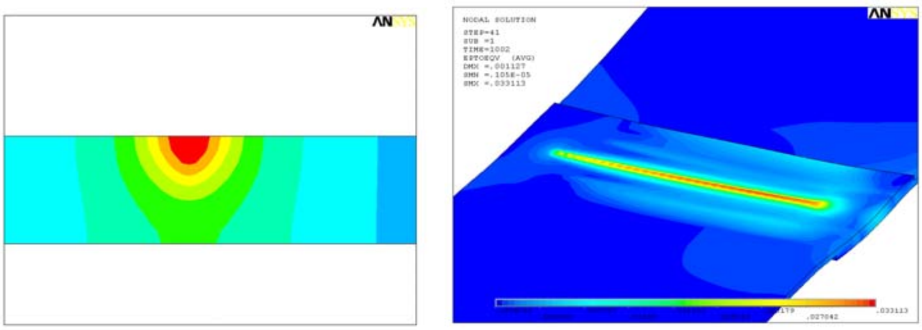


Figure 3: Finite element model created for the simulation of the LTW process

In the first part of the analysis, the effect of the various process parameters such as, distance between the laser source and the material, laser power and laser speed, on the temperature distribution within the material is investigated. Indicative temperature distribution results for the case of P=255W, LS=1000mm/min, d=20mm and t=1mm are presented in Figure 4a. The second part of the simulation analysis involves the calculation of the residual stresses and the respective strains caused by the thermal stresses induced within the material during the welding, as indicatively shown in Figure 4b, for the above mentioned case. Such stresses and strains are critical because the affect the final welded component distortion.



(a) *(b)*

Figure 4: Calculated temperature distribution (a) and residual strains during the LTW process

The welding temperature results, for each combination of the process parameters during the heating stage, obtained by the simulation are used afterwards in the creation of appropriate Cost Estimation Relationships (CERs). Indicatively, some parametric simulation results are displayed in Figure 5, where *t*, *LS* and *d*, stand for thickness of the material, laser speed and distance between material and laser source respectively.

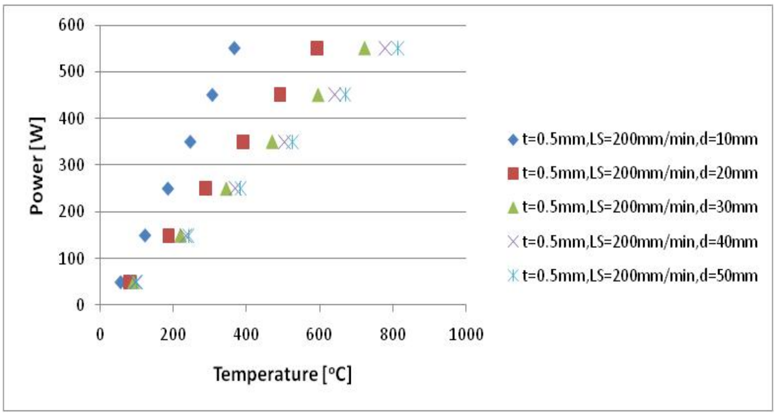


Figure 5: Welding temperature versus the laser power for different distance between the laser source and the material

2.4 LTW PROCESS COST SENSITIVITY ANALYSIS

Apart from the mechanical performance of the welded part, the cost efficiency of LTW technology is studied in the present work by means of a process cost estimation analysis based on the Activity Based Costing (ABC) methodology. To apply the Activity Based Costing method for deriving Cost Estimation Relationships (CERs) the CDF process was divided into the following six sub-processes:

i. *Material supply,* which refers to the purchase of the raw material.
ii. *Preparation of the tool and the material* which means preparing the welding machine to be ready for use and treating the material in order to achieve better optical properties.
iii. *Placing of the material* on the machine table
iv. *Definition of the process parameters* and *calibration*
v. *Welding,* where the laser source travels over the weld line and welds the thermoplastic parts.
vi. *Material post-treatment, NDT inspection and storage.*

The most important 'Cost drivers' determined for each sub-process of the LTW process are given in Table 3. In the Table, a distinction has been made to 'part' related data, 'process' related data and 'material and infrastructure cost' data.

Part data	*PAA* [m^2]	Part area
	WP [kgr]	Weight of the part
	NPL [/]	Number of plies
	PAP [m]	Part perimeter
	THPL [m]	Ply thickness
	APL [m^2]	Ply area
	CMP	Complexity of the part
	WL [m]	Welding length
	ρ [kgr/m^3]	Resin specific mass
	A	Absorptivity
	WA [m^2]	Welding area

Material and infrastructure cost data	k_{pr} (cost unit/kgr)	Material cost
	k_w (cost unit/hour)	Worker cost
	K_{NDT} (cost unit/hour)	NDT equipment cost
	K_{pi} (cost unit/hour)	Pressure equipment cost
	K_{mach} (cost unit/hour)	Laser source cost
	Equipment cost	
	Maintenance cost	

<table>
<tr><td rowspan="6">Process data</td><td>P [W]</td><td>Laser power</td></tr>
<tr><td>D [mm]</td><td>Distance between material and laser source</td></tr>
<tr><td>LS [mm/min]</td><td>Welding speed</td></tr>
<tr><td>Npc [/]</td><td>Volume</td></tr>
<tr><td>Lf [years]</td><td>Estimated life of the equipment</td></tr>
<tr><td>Nm [/]</td><td>Number of maintenances</td></tr>
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Table 3: Cost drivers for the LTW process

After the process's 'cost drivers' have been identified, mathematical functions that express their relation to the consumption of the resources, i.e. the Cost Estimation Relationships (CERs), should be formulated. These functions may be extracted from the analysis of statistical, experimental or empirical data. The total cost of the component is calculated as the sum of costs referring to the various sub-processes. A representative CER example is the total cost of the welding sub-process. It is given by the function:

$$K_5 = (\kappa_{mach} + 2 \cdot \kappa_w) \cdot t_5 = (\kappa_{mach} + 2 \cdot \kappa_w) \cdot 1.1 \cdot A \cdot \frac{NPL \cdot THPL}{T_{ap}} + 0.01 \cdot WL + 0.5 \quad (1)$$

where:

$$T_{ap} = e^{1.41 \cdot 10^{-3} \cdot P - 7.85 \cdot 10^{-4} \cdot LS - 2.89 \cdot 10^{11} \cdot D - 5.78 \cdot 10^{12}} \quad (2)$$

The relation (2) connects the main parameters of the laser source system (i.e. laser power, distance laser source-material, laser speed) with the welding temperature and therefore with the respective cost (1). The relationship between the welding temperature T_{ap} and the cost parameters of the welding sub-process were derived by using the results of the numerical simulation presented in section 2.3. The factors of eq. (2) were obtained by means of performing regression analysis of FE simulation data.

It is worth noticing that, although the main target of the present work is to estimate the recurring costs, the depreciation cost of the machines used, K_{cap}, is taken into account at the final step of the cost estimation by relating the production rate (volume) with the initial investment for the equipment. It has also to be mentioned that no learning curve effects are taken into account since the examined process is under development and thus in a very early stage, for accounting of a learning curve.

Using the above CERs, each parameter's contribution to the total part cost was evaluated. Additionally, the major cost-and time-consuming sub-steps of the LTW process were investigated in order to identify and improve the critical sub-processes and their respective process parameters. Indicatively, for the case of LS=1000mm/min, P=250W and thickness of the material t=1mm, the component's under investigation welding cost is 2188 Euros and as a most cost and time consuming sub-process is identified the '*welding*' and the *placing of the material'*, respectively, as shown in Figure 6.

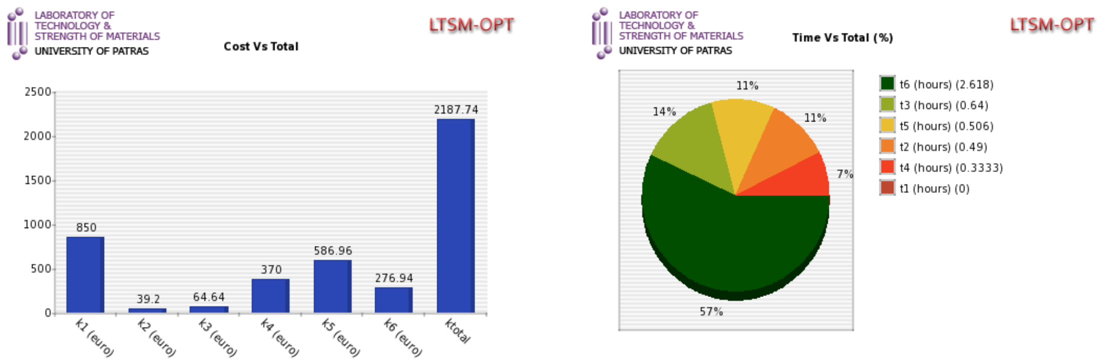

Figure 6: Cost and time of each sub-process for a specific solution

2.5 DERIVATION OF THE OPTIMAL LTW PROCESS FEATURES AND VALIDATION

Input data is given to the appropriately modified LTSM-OPT tool coupled with a range for the variation of the features of the LTW (e.g. laser power between 200 and 400) such as to obtain quality values and respective cost for every possible combination. For the present investigation the quality value target is given in Table 4. The optimal welding parameters as well as the respective laser welding features for realizing the required quality are derived as an output, Table 5. The achieved values of the quality features and the cost for the calculated optimal solution are given in Table 4.

Quality feature	**Target value**	**Achieved value**
SLS [MPa]	60	60.07
Cost	1824 €	

Table 4: Required Quality feature and cost and the respective values achieved for the derived optimal solution

Features of the laser welding unit	Welding speed [mm/min]	1180
	Distance between laser source and material *D* [mm]	20
	Welding temperature T_{ap} [^{o}C]	365±5 ^{o}C
	Laser power *P* [W]	345

Table 5: Optimal features of the laser welding unit

As stated above, the results of the study were successfully exploited by an aeronautic industry for the identification of the optimal solution for welding stiffeners on aircraft's fuselage panel. In this frame a diode laser source unit was used and its features were set according to the calculated optimal solution. The thermoplastic plate was placed and kept under pressure on the table of the device, and three stiffeners, which were already placed using sealant, were welded in 35mm distance each from the other. Figure 7 shows the panel with the laser welded stiffeners (on the right) and another panel with the stiffeners joined conventionally (on the left).

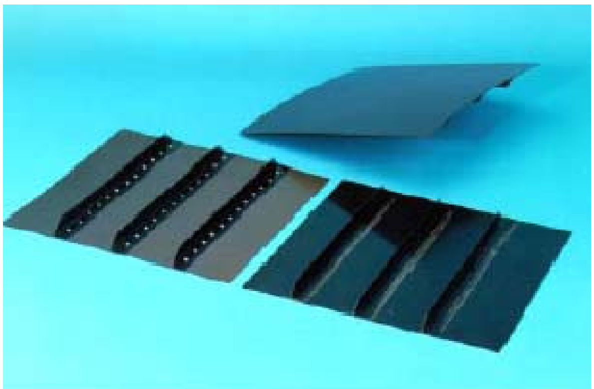

Figure 7: The panels with the riveted (on the left) and the laser welded (on the right) stiffeners

CONCLUSIONS

A generic concept for the optimization of manufacturing processes of composite material components with regard to product's quality and cost is used for the optimization of the welding thermoplastic stiffeners on flat composite panels using Laser Transmission Welding (LTW). The concept involves a quality sensitivity analysis to derive material dependent Quality Functions (QFs) along with the derivation of process dependent Cost Estimation Relationships (CERs) based on the Activity Based Costing methodology. To reduce the required effort in order to derive experimental data, simulation of the thermal cycle of the LTW process has been performed using finite element (FE) method.

For deriving the optimal welding parameters leading to minimum cost for quality which still satisfies the design and quality requirements an iterative optimization procedure was used. Using the LTSM-OPT software tool the features of the LTW system configuration for welding thermoplastic stiffeners on flat composite panels were obtained. The derived solution is optimized with regard to quality and cost.

The results of the study were successfully exploited by an aeronautic industry for implementing the optimal welding solution derived by the current analysis in the welding of stiffeners on aircraft's fuselage panel.

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