CONTINUOUS FIBRE REINFORCED THERMOPLASTIC JOINING, A LASER-WELDED SEAM MULTI-AXIAL MECHANICAL CHARACTERIZATION AND MODELLING

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Abstract

In recent years, the use of continuous fiber thermoplastic composites has been growing steadily, especially in the transportation industry. The purpose of the work reported here consists in developing an experimental and numerical approach to bring help in the design of laser welded TP reinforced composites. The current paper proposes a test procedure for a multi-axial mechanical characterization of the laser welded seam using the ARCAN-MINES device. This set up allows varying the loading direction while controlling the state of stress inside the joint. On the basis of experimental observations, a non-linear phenomenological material model based on a generalized Drucker-Prager criterion is used. An estimation of strains and stress inside the laser-welded seam could be computed and related to failure observations.

1 Introduction

Aerospace and automotive industries contribute today to a growing use of continuous fibers thermoplastic composites. Indeed, using thermoplastic as a matrix in a fiber reinforced material offers recyclability and productivity advantages over its conventional thermoset counterpart. However, these new structural parts need to be co-developed with efficient joining techniques. Thermoplastics can be joined successfully in a number of different ways, including mechanical fastenings, heat welding or adhesive bonding. Adhesively bonded joints offer an efficient joining method for composites and multi-material parts since it provide a more uniform stress distribution than riveted or bolted joints. In the same way, the recent developments in laser welding technology demonstrate the flexibility of this process for the manufacture of complex thermoplastic reinforced structural parts. This innovative technique [1] shows excellent mechanical performances and aesthetic appearance compared to other traditional assembling methods. Laser-welding industrial expansion is nevertheless hindered by several limitations such as the characterization and modeling of its mechanical properties or failure mechanisms.

2 A brief description of the material

2.1 The welded technique

The material of the study is a unidirectional composite polyamide matrix reinforced by continuous glass fibers. The work was carried out on plates of a thickness of 2.4mm obtained by compressing several UD sheets. The laser joining technique requiring specific optical properties, two types of matrix were used: one transparent and the other absorbent respect to the wavelength of the laser beam. These two polymers are chemically and mechanically equivalent. The absorbent property is obtained by adding a black carbon pigment. During the laser welding, the beam is transmitted through the transparent plate to enable to transform the beam energy into heat at the interface of the two plates (Figure 1). By heat conduction, polymer is sealed and then consolidated (cooled) under pressure.

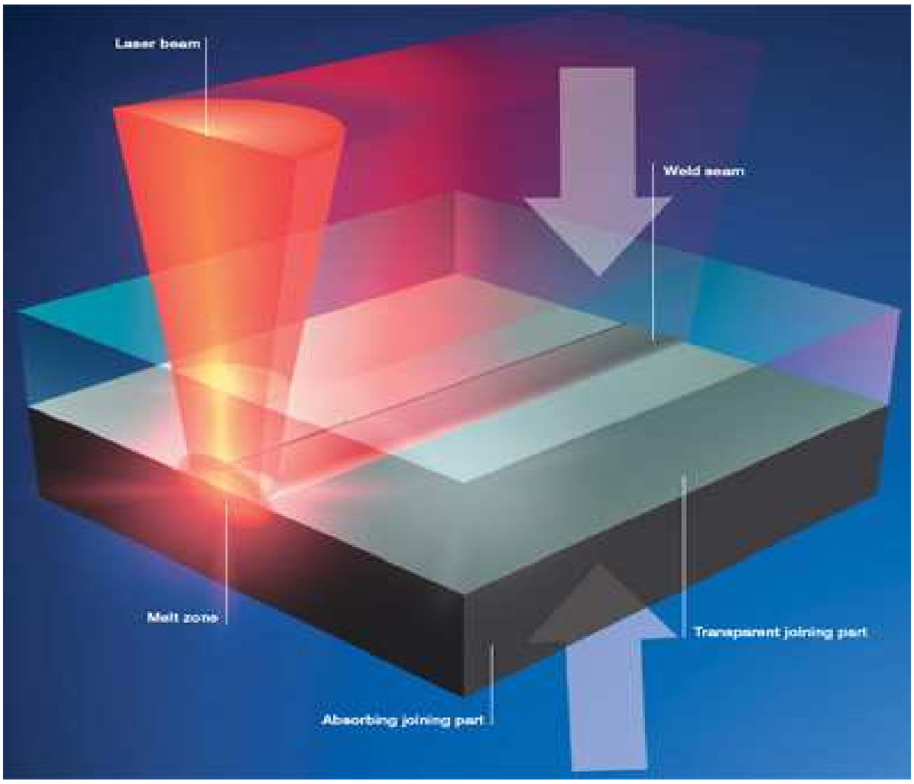


Figure 1. The laser energy is transmitted through the top transparent plate and is absorbed at the interface. Courtesy: Leister Technologies LLC

The joining quality is highly dependent on the thermal conductivity of constituents: fibers and matrix. The glass fibers have conductivity five times greater than that of polyamide and it is necessary to adapt the parameters of the laser beam to heat a fair amount of material.

Because of this thermal conductivity difference, the joining quality will be better in the case of a welding perpendicular to the direction of the fibers [1].

2.1 Microstructure analysis

The observation of the microstructure of the assembly by scanning electron microscopy does not reveal correctly the geometry of the welded zone. We can only see that fibres are distributed uniformly and continuously in the welding area. Microtome sections and optical observations show a seam thickness of about 500µm microns with about 60% on the side of the absorber plate (Figure 2).

Figure 2. The laser weld seam geometry obtain after microtome cuts [8].

3 Mechanical characterization of the welded part

On many joined structures the lap shear test is commonly used to assess the behavior and the mechanical strength of the junction. However, this test is very complex to analyze in order to establish a model. Indeed, the rotation of the substrates introduces a tension-shear coupling difficult to investigate.

To overcome this difficulty, we have used a specific setup to characterize the intrinsic behavior of the welded seam. This device called ARCAN-MINES (Figure 3) is described in the following paragraphs and allows controlling the stress state and thus facilitating the identification step of the model. The lap shear tests are nevertheless used for the validation step.

3.1 Experimental setup

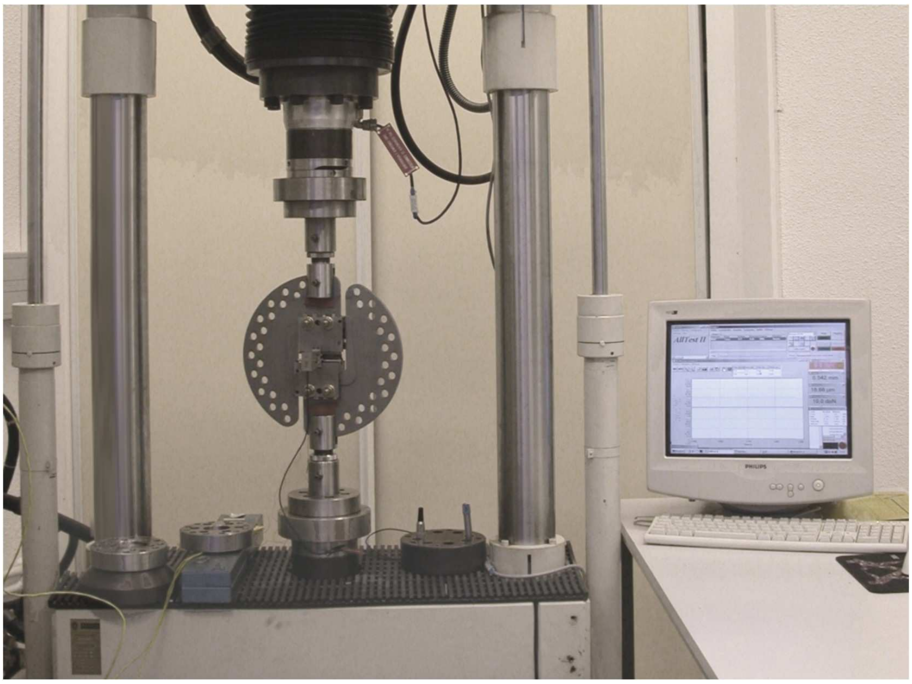


Figure 3. ARCAN-MINES experimental set-up to characterize the welded seam in a multi-axial state.

The laser-welded seam has been tested by using a specific system able to apply a multi-axial state of stress. Thanks to this set up inspired from Arcan setup [2][3][4], it is possible to characterize the joint either in tensile, compressive and shear loading. This set up is made of two half circular disks which are joined together thanks to the tested specimen (Figure 4). It as already been successfully used for the characterization of adhesive joints [5][6][7].

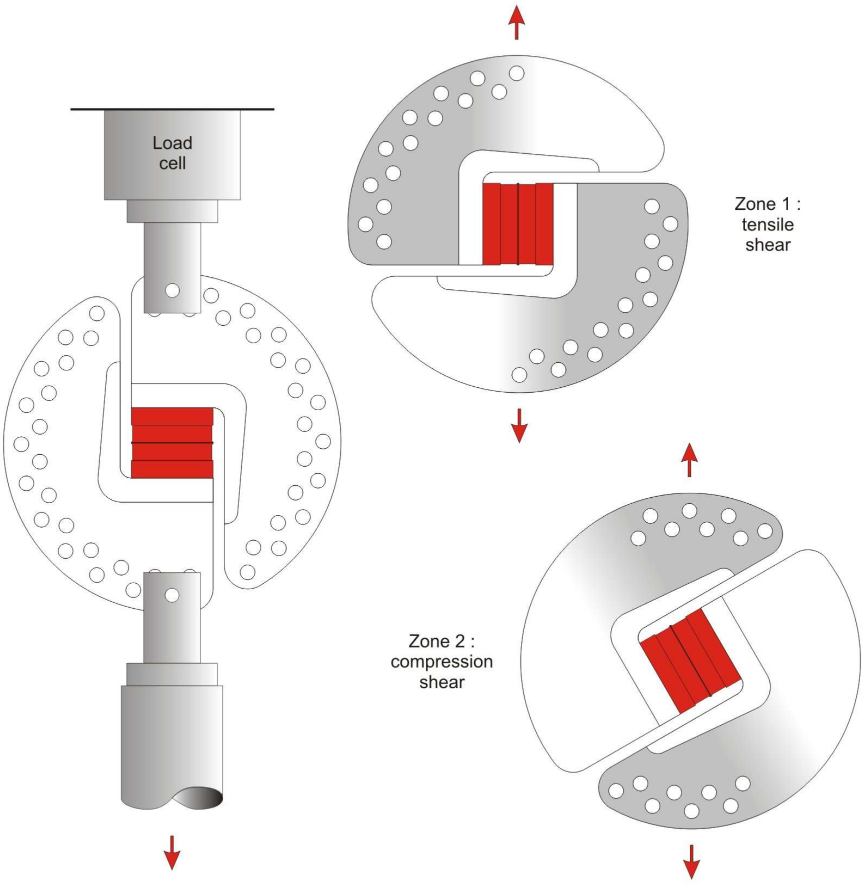


Figure 4. The Specific set up to characterize the weld seam is composed of two half circular disks joined together with the tested specimen. it is possible to characterize the joint either in tensile, compressive and shear loading [5].

3.2 Specimens and experimental investigations

The specimens are stuck on metal part by adhesive bonding. The adhesive covers a surface of 700 mm^2 to be able to test a laser weld seam surface of 50 mm^2. The main difficulty is to evaluate the small displacements across the welded seam. A high resolution extensometer, grip on the metallic part of the specimen, allows to record the variation of length or shear close to the joint itself (measurement base of 10mm). This displacement could be used with the imposed load to obtain the rigidity of the “sandwich” composed by: the upper substrate, the welded composite material and the lower substrate. An estimation of strains inside the joint could be computed by deducting the deformation of the two substrates. This approach is nevertheless based on approximations of elastic properties of substrates and dimensions of the weld seam. The tests have been carried out in quasi-static conditions.

4 Mechanical behavior and validation

A mechanical behavior model attempts to describe, in an exact fashion, the relationship between the measurements and the parameters of interest. Various approaches are used to develop such models and in order to reflect the coupling between mechanical properties and the microstructure we will adopt a phenomenological description. This approach relies on identifying the primary mechanisms responsible for the behavior of the material which have been observed experimentally. Of course, through this approach, the relevance of the model is based on the choice of phenomena which play a significant role. The model is build for a specific application with principles and assumptions that give a general framework.

The phenomenological models based on the thermodynamics of irreversible processes have not evolved in an identical way for all the materials. If the literature relative to metallic materials is very abundant, it is not the same for polymers and even less for such welded structures. Many questions remain as the microstructural mechanisms.

Multiaxial tests (0°, 30°, 60° and 90°) performed on the welded joint can highlight the effect of hydrostatic pressure. Thus we have used a pressure dependent elasto-viscoplasticity model. This model (yield surface (3)) is an extension of the linear Drucker-Prager (DP) model proposed in 1952 which depends on the second deviatoric invariant J_2 (von-Mises Cauchy stress (2)) and the hydrostatic pressure I_1 (1).

$$I_1 = tr\left(\underset{\sim}{\sigma}\right) \tag{1}$$

$$J\left(\underset{\sim}{\sigma}\right) = \sqrt{3J_2\left(\underset{\sim}{\sigma}\right)} \tag{2}$$

$$f(\sigma) = J\left(\underset{\sim}{\sigma}\right) - \beta R_0 + (\beta - 1) I_1\left(\underset{\sim}{\sigma}\right) \quad with \quad \beta \geq 0 \tag{3}$$

For higher hydrostatic sensitivity, we used an exponent form of the DP model allowing elevated exponent values (4). To facilitate the identification, the yield function is homogeneous to a stress in its final form (5). The model implemented on the in-house Z-Set program [5] allows both kinematic and isotropic hardening.

$$f_a\left(\underset{\sim}{\sigma}\right) = J^{\,a}\left(\underset{\sim}{\sigma}\right) - \beta R_0^{\,a} + (\beta - 1) I_1\left(\underset{\sim}{\sigma}\right) R_0^{\,a-1} \; avec \; \beta \geq 0 \; et \; a \geq 1 \tag{4}$$

$$f(f_a) = signe(f_a)\sqrt[a]{|f_a|} \quad avec \;\; a \geq 1 \tag{5}$$

By representing the yield stress in the plane (I_1, J) (Figure 5), we notice that the boundary between the elastic and plastic is characterized by an ellipsoid envelope rather than a horizontal line, as it is the case for isotropic materials which are modeled with the von-Mises criterion. The failure stress could be plotted in the same way with similar comments. The same form of criterion can therefore define the elastic envelope and the ultimate strength in the plane (I_1, J). It is then possible to predict the elastic limit whatever the loading direction. Using statistics, it is also possible to predict this elastic limit and the ultimate strength with a chosen confidence interval. Indeed, it is possible to take into account the fluctuations associated to the welding process and the local heterogeneities of the microstructure.

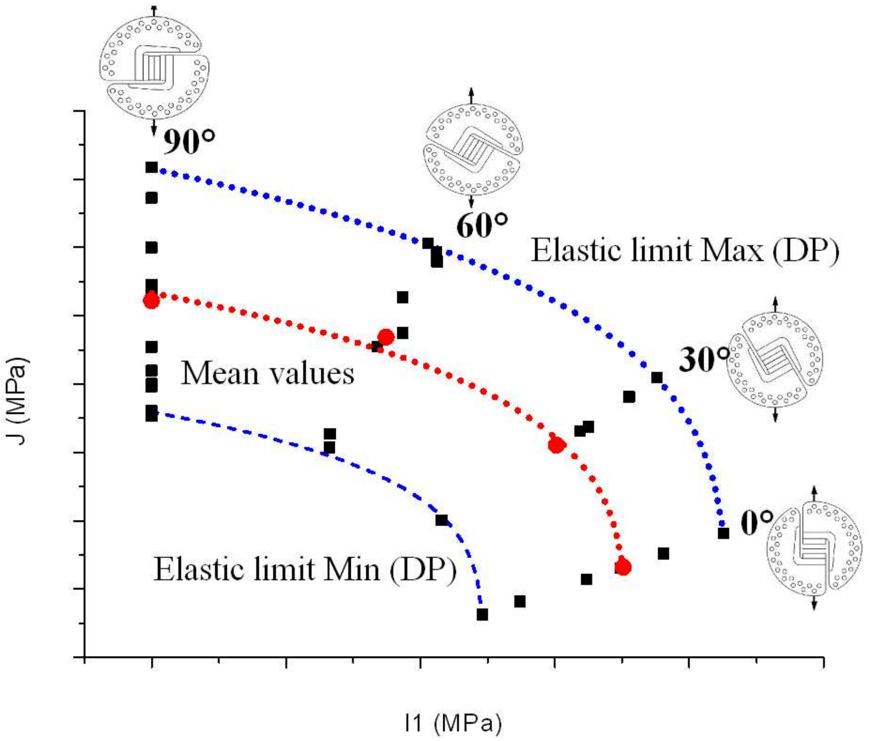


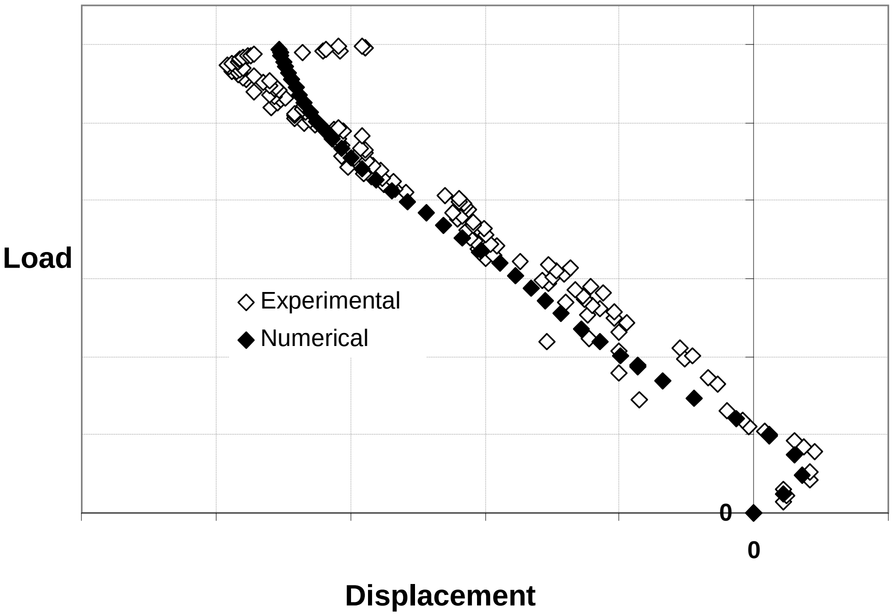
Figure 5. (I_1, J) plane showing the high hydrostatic sensitivity needed in the model to capture the behavior of the weld seam whatever the loading direction.

The evolution of the envelope has been described by a non-linear kinematic hardening using reverse engineering. A finite element model of the ARCAN-MINES test has been used to carry on the identification of the non-linear part of the model not described in this paper but following the reference [5].

The validation of the model has been carried on lap shear results with success and on the stiffener represented on the figure 6.

Figure 6. Stiffener dedicated to the validation step.

During the test, an optical measure of the deformation closed to the weld seam has been computed. It is then possible to compare this measure to the numerical one obtains with artificial sensors on a finite element model of the stiffener. We can see a very good correlation for this comparison thus validating the model identification (figure 7).



Conclusion

Within the study of a laser-weld seam in quasi-static loading, this paper presents the using of a specific setup to determine the evolution of its mechanical behaviour in multi-axial loadings. This ARCAN-MINES setup, previously used for adhesive bonding has been successfully used to characterize this new joined method. Results show the high dependence on the hydrostatic stress requiring the use of an adapted exponent form of the Drucker-Prager model. Finite element method and reverse engineering has been used to identify the non-linear kinematic hardening. A good agreement is obtained with two types of validation tests: single lap shear test and a stiffener representing an industrial structure.

Acknowledgments

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