FAILURE ASSESSMENT OF TRANSMISSION DIODE LASER WELDED POLYPROPYLENE

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Abstract: The aim of present work is to predict using finite element analysis the failure of polypropylene welded samples using the Laser Diode Transmission technique. The studied material is a commercial polypropylene (PP). The mechanical behaviour of the welded samples is modelled using elastic purely plastic law with a von Mises yield criterion. Both the thermal degradation and the heterogeneity of the weld zone were taken into account in the modelling, to approach the welding conditions and the geometry of the weld. The linear mechanic’s fracture was adopted to assess the failure of the welded samples. The assumption of the plane deformations is chosen to calculate the integral of contour of Rice “J” and to characterize the singularity of the stress field surrounding the weld zone. Good agreement is. The good agreement observed between the predicted and this experimentally obtained load failure suggests that our approach can be used as a tool for the prediction of failure of laser diode welded specimens.

Key words: polypropylene, diode laser welding, failure assessment.

1. INTRODUCTION

Polypropylene (PP) is one of the most widely used polymers. The combination of low density, chemical resistance, low cost and a balance of stiffness and toughness allow thermoplastics to play a leading role and replace other materials in many important applications.

Two general forms of laser welding of plastics exist: direct laser welding and transmission laser welding. Direct laser welding usually uses CO2 laser radiation, which is readily absorbed by plastics, allowing quick joints to be made, but limiting the depth of penetration of the beam and restricting the technique to film applications. The shorter wavelength radiation produced by Nd:YAG, fibre and diode lasers is less readily absorbed by plastics, but these lasers are suitable for performing transmission laser welding. In this operation, it is necessary for one of the plastics to be transmissive to laser light and the other to absorb the laser energy, to ensure that the heating is concentrated at the joint region. Alternatively, an opaque surface coating may be applied at the joint, to weld two transmissive plastics. Transmission laser welding is capable of welding thicker parts than direct welding, and since the heat affected zone is confined to the joint region no marking of the outer surfaces occurs.

Among the properties of thermoplastics, deformation and ultimate tensile strength have revealed as a topical preoccupation in order to utilize them effectively in service applications, since almost every application, even the most trivial, involves some load bearing capability.

Therefore the increase in using polymer welds for several industrial applications leads to a strong need of developments of constitutive models. These models are based on either phenomenological or microscopic aspects. The purpose of this paper is to assess the influence of microstructure heterogeneity on the mechanical behaviour of polypropylene (PP) thermoplastics welded by diode laser.

The mechanical behaviour of flat samples under uniaxial load was studied by numerical and experimental approaches. The ultimate strength of a thermoplastic is naturally important in the matching of a material to an application, as with deformational properties. Some preliminary trials brought the authors to adopt the mechanics of fragile rupture as the most suitable law to predict ultimate tensile strength.

2. PROPERTIES OF PROPYLENE AND ITS WELD

Both pure polypropylene and 2% carbon black filled polypropylene were used in this investigation. The most important material properties related to these materials are summarized in Table 1.

Table 1: The most important material properties related to the welding behaviour of polypropylene. Obtained by DSC at 20°C/mn (Tg : vitreous transition, Tf : fusion et Tc : cristallinization).

materials	T_g (°C)	T_f (°C)	T_c (°C)	X_c (%)
PP	-18	170	110	31
PP (2%C)	-16	173	112	33

The laser beam is totally absorbed within the surface (interfacial) of carbon black filled propylene. Direct contact between the parts ensures heating of polypropylene at the joint interface. Welding occurs upon melting and fusion of both materials at the interface. The heating and melting of the polymer is started from absorbed energy black part.

50mmx50mmx3mm narrow plaques were used as sample geometry. Figure 1 shows the welding setup.

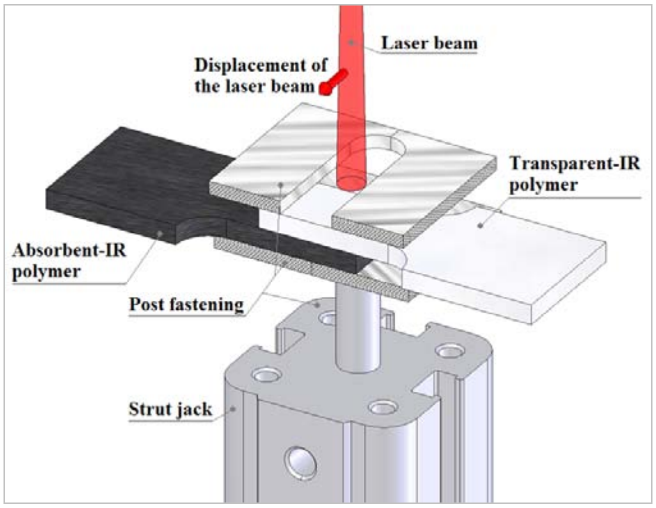


Figure 1. Welding setup.

Effects of the influence of laser power density and irradiation time (welding speed) on the weld structure was investigated as well as the material parameters (black content) on weld soundness and heat affected zone and bead shape were performed [1]. From microscopic observations it appears that the cross section of the joining area has an elliptic geometry. The centre of the ellipse is located at the interface of both polymers. The increase of the laser power leads to a larger volume of the welding zone with a more important depth penetration. The increase of velocity conducts to a decrease in the volume of the welding zone that geometry remains elliptic

IR results as well as microscopic observations showed the thermal gradients produces an evolution of the cristallinity fraction along the cross section of the welding joint, a change on the morphology of the spherulites and the occurrence of a void due to the thermal decomposition and the vaporization of the polypropylene related to the presence of high temperature gradients in the seam. Hence, schematically, different zones in the welded part can be distinguished. In each zone, crystalline morphology is related to specific thermal cycle. The aim of this investigation is to study the influence of the microstructure and cristallinity rate on the failure of the welded samples loaded under uniaxial tensile conditions.

Several models can be used for the prediction of polypropylene weld failure: damage models, fracture mechanics, non-linear mechanics.

Uniaxial tensile tests were conducted on welded samples. The obtained results show that the behaviour of the specimens is linear until the fracture which was initiated in the proximity of the weld bead and developed into the black part (Figure 2).

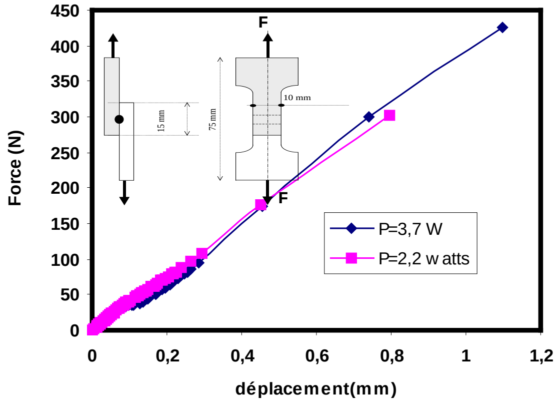


Figure 2. Tensile test curve for a polypropylene weld obtained with 1,5 mm/s welding speed.

3. MECAHNICAL MODEL OF THE WELD

Several works have dealt with the mechanical behavior of polypropylene. Uniaxial tensile tests show that the behavior is not linear at room temperature. The brittle-to-ductile temperature increases with increased cristallinity, which also increases the yield stress. Mechanical properties strongly depend on the cristallinity rate (X_c), the spherolite size (ϕ) and the molar mass (MW) [2, 3, 4]. Table 2 shows the quasi-linear relation between the cristallinity rate and the mechanical properties. More authors investigated the relation between the cristallinity rate and the PP rupture. [5, 6]. Plastic yielding and fracture influence the entropy change in polypropylene through a significant change in the dissipation factor. An increase in crystallinity results in an increase in the entropy [7].

In this paper it was conceived that the mechanical behavior of the both transparent and pigmented layers can be described using an elastic perfectly plastic law with a Von Mises criterion (Eq. N°1). Material properties of each layer depend essentially on the crystallinity ratio X_c (table 2).

Table : PP properties against the rate of cristallinity [VAN 98 I et II]..

X_C (%)	E (MPa)	σ_s (MPa)	ε_s (%)
31	601	19.5	17.0
38	962	25.4	11.0
43	1228	31.9	8.8
53	1650	41.0	4.0

$$\begin{cases} f = \sigma_{eq} - \sigma_s \prec 0 \Rightarrow \underline{\underline{\varepsilon}} = \underline{\underline{\varepsilon}}_e = \dfrac{1+\nu}{E}\underline{\underline{\sigma}} - \dfrac{\nu}{E} Tr\left(\underline{\underline{\sigma}}\right)\underline{\underline{I}} \\ f = 0 \ \text{ et } \ \dfrac{\partial f}{\partial \underline{\underline{\sigma}}} : \dot{\underline{\underline{\sigma}}} \Rightarrow \underline{\underline{\varepsilon}} = \underline{\underline{\varepsilon}}_e + \underline{\underline{\varepsilon}}_p \ \text{ avec } \ d\underline{\underline{\varepsilon}}_p = \lambda \dfrac{\partial f}{\partial \underline{\underline{\sigma}}} \end{cases}$$

For transparent PP X_c=31% whereas different situations are considered for the weld: the weld bead is assumed as a homogeneous and isotropic medium with X_c=37% and the weld bead is a heterogeneous medium decomposed on three homogeneous domains. Each domain is characterized by its own crystallinity ratio. The plane deformation condition was given to the weld in the proximity of weld bead, which tackled the singularity due to the domain change due to the different material properties. Rice integral was calculated at the point of singularity (J). In case of straight fissure and fragile crack « G » and « J » are connected by the following equation Ed. 2:

$$G = J = \frac{1-\nu^2}{E}\left(K_I^2 + K_{II}^2\right) + \frac{K_{III}^2}{2\mu}$$

The tensile test was performed on a weld manufactured with P_{laser}=40 W et V_{laser}= 3mm/s. The heat affected zone was given an elliptic shape. The mesh was made up of 2° degree triangular elements. At the proximity of the weld bead the elements of the mesh were square.

The weld heterogeneity was modeled by means of three wrapping ellipsis. Each of three ellipses had different mechanical properties, as showed in figure 3.

Figure 4 shows the geometrical model of weld. A displacement along the x direction of 1mm during 10 seconds is imposed.

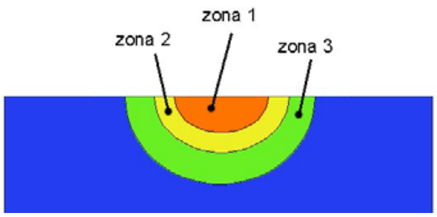
zone 3: E_1= 650 Mpa, ν=0.35, σ_s=21 Mpa; zone 2 E_2= 750MPa; ν=0.35; σ_s=23 Mpa; zone 1: E_1= 850 Mpa, ν=0.35, σ_s=25 MPa.	

Figure 3. Ellipsis with different mechanical properties.

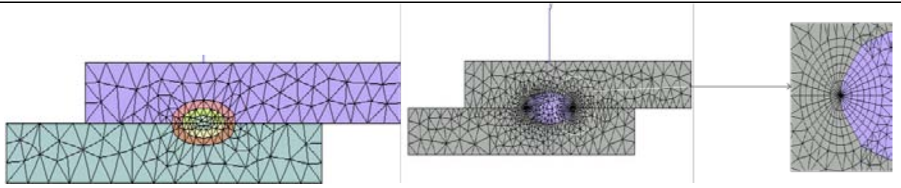


Figure 4. Geometrical model of weld.

4. NUMERICAL RESULTS

Figure 5 shows the force (N) against the displacement (mm) during the simulation of the tensile test for two different set of the mechanical properties of the weld. It appears clearly that the microstructure inside the beam does not influence the response of the loaded welded samples.

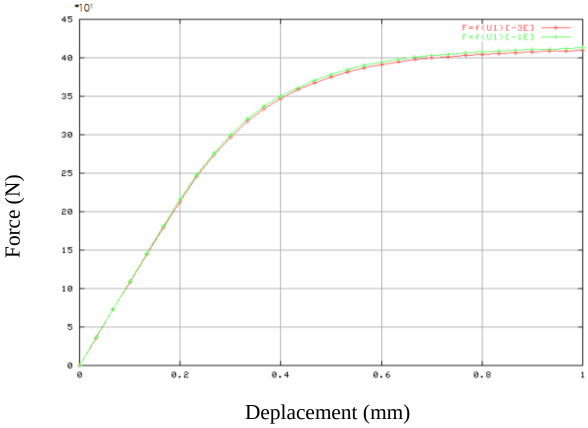


Figure 5. Numerical simulation of the tensile test.

As a consequence the heterogeneity of the weld can be neglected. Figure 6 shows the Von Mises equivalent constraint. A bending phenomenon is noted corresponding to experimental observations.

The highest value of von Mises equivalent stress is detected inside the weld with a maximum located at the proximity of the seam leading to the highest equivalent plastic strain (figure 7). These results explain experimental observations during tensile tests consisting in the fact that fracture was initiated in the proximity of the weld bead and developed into the black part.

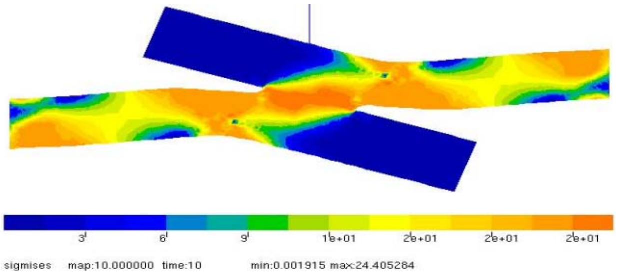


Figure 6. Von Mises equivalent constraint.

Considering that the restitution energy of the pure propylene is about 3 J/m2 [4] and that the black content reduces it, the rupture of the weld can be placed at 0.8 mm displacement, which correspond at a load of about 400N (see figure 8). The failure load obtained from finite element analysis is quite equal to that obtained experimentally.

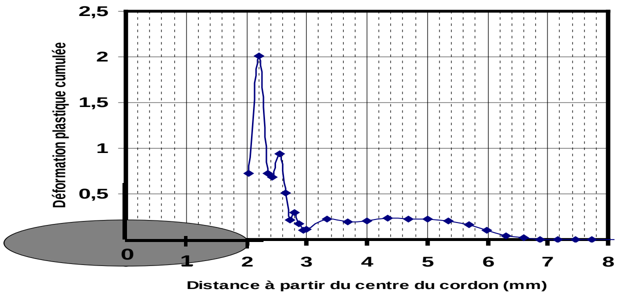


Figure 7. Highest equivalent plastic strain.

5. CONCLUSION

The mechanical behavior of laser joined of polypropylene was investigated by numerical and experimental analysis. The numerical simulation of weld mechanical strength and rupture took into account the material heterogeneity, which depends on weld recristallization and the material degradation during the cooling phase of the thermal cycle, which causes also material lack.

The numerical results gave the idea that that heterogeneity can play a minor role in the mechanical strength and rupture of the weld. The displacement at fracture was calculated by means of the Rice integral.

The obtained results can be used for a deeper understanding of the PP weld mecahnical behaviour when deformation is due to a superimposed displacement.

REFERENCES

[1] Ghorbel, Casalino et Abed R. Characterization of thermal and mechanical effects of diode laser welding of Polypropylene. MATERIALS & DESIGN, Materials and Design 30 (2009) 2745–2751.

[2] Van der Wal A., Mulder J.J., Thijs H.A. et Gaymans R.J. “Fracture of Plypropylene : 1. The effect of molecular weight and temperature at low and high test speed” Polymer vol. 39 No. 22, pp. 5467-5475, 1998.

[3] Van der Wal A., Mulder J.J. et Gaymans R.J. “Fracture of Plypropylene: 2. The effect of crystallinity” Polymer vol. 39 No. 22, pp. 5477-5481, 1998.

[4] Avella, M. Dell’Erba, R., Martuscelli, E. et Ragosta, G. “Influence of molecular mass, thermal treatment and nucleating agent on structure and fracture toughness of isotactic polypropylene”, Polymer, Vol. 34, N° 14, pp. 2951-2960, 1992.

[5] Mareri, P., Bastide, S., Binda, N. et Crespy, A. “Mechanical behaviour pf polypropylene composites containing fine mineral filler: effect of filler surface treatment” Comp. Sci. Tech. 58, 747-752, 1998.

[6] Zebarjad, S. M., Tahani, M. et Sajjadi, S. A., “Influence of fillers particles on deformation and fracture mechanism of isotactic polypropylene”, J. of Mat. Processing Tech., article in press, 2004.

[7] T. Vu-Khanh, M. El Majdoubi. Entropy change with yielding and fracture of polypropylene. Theoretical and Applied Fracture Mechanics 51 (2009) 111–116.