Experimental Investigation of the Impact of Deposition Temperature on the Fracture of PLA-Printed CT Specimens

Étude expérimentale de l'impact de la température de dépôt sur la rupture d'éprouvettes de CT imprimées en PLA

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ABSTRACT. The additive manufacturing process known as Fused Deposition Modeling (FDM) is distinguished by numerous parameters to be set. These parameters determine the mechanical properties and the overall quality of the printed parts. Among these parameters, we are interested in the filament deposition temperature. Indeed, during the systematic printing of each layer, the filaments that compose it undergo fusion, both inside the layer itself and between successive layers. The quality of this welding process significantly influences the resistance to crack propagation, between filaments of the same layer and/or between superimposed layers. This article focuses on the study of the impact of deposition temperature on the resistance to crack propagation in structures created by FDM. An analysis based on the J-Integral approach is developed.

RÉSUMÉ. Le processus de fabrication additive connu sous le nom de Fused Deposition Modeling (FDM) se distingue par de nombreux paramètres à régler. Ces paramètres déterminent les propriétés mécaniques et la qualité globale des pièces imprimées. Parmi ces paramètres, nous nous intéressons à la température de dépôt du filament. En effet, lors de l'impression systématique de chaque couche, les filaments qui la composent subissent une fusion, tant à l'intérieur de la couche elle-même qu'entre les couches successives. La qualité de cette soudure influence significativement la résistance à la propagation des fissures, entre filaments d'une même couche et/ou entre couches superposées. Cet article porte sur l'étude de l'impact de la température de dépôt sur la résistance à la propagation des fissures dans les structures créées par FDM. Une analyse basée sur l'approche J-Integral est développée.

KEYWORDS. FDM, Deposition Temperature, PLA, Resistance Curves, Integral J, J_{IC}.

MOTS-CLÉS. FDM, température de dépôt, PLA, courbes de résistance, J intégrale, J_{IC}.

1. Introduction

While considerable progress has been made in understanding the mechanical performance of 3D-printed parts, a critical knowledge gap persists, specifically regarding the resistance to crack propagation within these structures. This challenge is exacerbated by the intricate microstructures of FDM-printed parts, intricately connected to various printing parameters [AOU 23]. The exploration of damage mechanisms, particularly the separation of contact surfaces between filaments is of particular interest. The quality of filament welding at these contact points is pivotal in determining the resistance to crack propagation within filaments and between layers [VIC 20].

We have developed an experimental approach to investigate the influence of contact surfaces between filaments (cohesion between surfaces) on the resistance to crack propagation in 3D-printed structures using FDM. This approach consists of experimentally determining the resistance to interfacial rupture between (PLA) filaments. To do this, we carried out rupture tests on CT (Compact Tension) specimens printed in PLA. To highlight the effect of the deposition temperature on this resistance, three cases of deposition temperature were considered (T=210°C, T=220°C and T=230°C). The resulting strength curves for each case are determined using the J-integral concept in fracture mechanics.

2. Materials and methods

To analyze the fracture behavior of a structure, one must take into account its level of ductility. Indeed, concerning the ductility of our structure, we must choose one of the two concepts developed to study rupture. The first is Linear Elastic Fracture Mechanics (LEFM) based on the Stress Intensity Factor K and applies only to material with elastic behavior. On the other hand, for a viscoelastic material like polymers where the various forms of plastic deformation appear, before and during the rupture, one considers a second concept based on the elastoplastic mechanics of the rupture (Post Yield Fracture Mechanics PYFM).

This second concept is based on the formulation of the J-integral which is the most appropriate for describing ductile failure in a ductile material. Originally, this integral J was expressed from the following relation [RICE 03]:

$$J = \oint_{\Gamma} \left(w\,dy - T_i \frac{\partial u_i}{\partial x}\,ds \right) \qquad \text{[AOU 23]}$$

Or Γ is an arbitrary contour surrounding the crack tip, w the strain energy density, Ti stress vector components, ui displacement vector components, ds the length increment along the contour, and x and y are the Cartesian coordinates concerning at a chosen landmark.

It is from this integral J that we will analyze the resistance to cracking in our CT specimens printed in (PLA). To do this, we consider the curve ((J = f(Δa), which takes into account the effect of the advance of the crack (Δa) as well as nonlinear behavior. This curve, known as the Resistance curve, describes the energy conditions for crack extension after initiation.

In practice, this energy J can be deduced by experience through the following formula [AST 10]:

$$J = \frac{\eta\, U}{B\,(W\text{-}a_0)} \qquad \text{[VIC 20]}$$

According to ASTM D 6068 [AST 10], the energy required to expand the crack, U, is used to calculate J. The total energy (U_T) is the sum of U and Ui, the indentation energy:

$$J = \frac{\eta (U_T\text{-}\,U_i)}{B\,(W\text{-}a_0)} \qquad \text{[RICE 03]}$$

W is the width of the specimen. η is a geometric dimensionless parameter. Garcia et al [MER 74] claim that to calculate J of polymers, the factor η depends only on the ratio between the length of the crack a0 and the width of the specimen W (a0/W).

Clarke and Landes [CLA 79] succeeded in obtaining an approximation of η for the CT specimen using the following formula:

$$\eta = 2 + 0.522 \left(1\text{-}\ \frac{a_0}{w}\right) \qquad \text{[AST 10]}$$

The approach followed to determine the two energies U_T and Ui is developed in the experimental results section. And it is from their values that we deduce those of J via equation (3).

To produce the CT specimens with notch (Fig. 1) and without notch (same dimensions as the case without notch), a CAD model was produced using the FDM manufacturing method. This digital model was converted into a Stereolithography (STL) file, which was also translated into a machine instruction file (G-code). This file describes the trajectories of the nozzle which deposits the filling material in filament form.

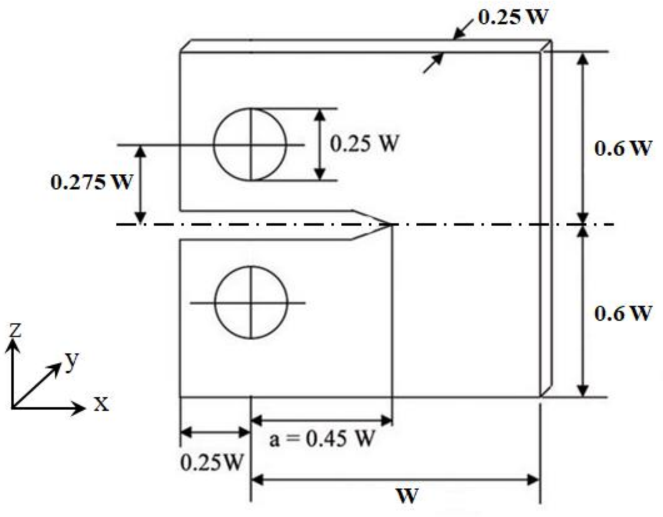


Figure 1. *Dimensions of CT specimen to ASTM D5045 [8].*

Once the file has been obtained, the samples can be produced on a 3D printer. The printing parameters adopted are shown in Table 1.

Print parameters	Value	Unit
Layer thickness	0.2	mm
Raster width	0.56	mm
Fill density	100	%
Number of contours	2	
Platform temperature	60	°C
Extrusion speed	40	mm/s
Construction orientation	XYZ	
Number of contours	2	
Material	PLA Red	

Table 1. *Parameters used for printing*

3. Results and discussion

The The ISO 13586 and ASTM D5045 standards postulate that to evaluate J of a thermoplastic and thermosetting material, the tests must be conducted on CT specimens [RIC 20,VIC 20]. We remind you that this FDM printing technique is a process of building successive layers that allows us to control and produce samples with different deposition temperatures. For our study, we considered three cases of temperature (T=210°C, T=220°C and T=230°C).

In compliance with the ISO 13586 standard, we carried out our tests with a speed of 1 mm/min and in an ambient environment (T=23°). After each test, three types of data were collected:

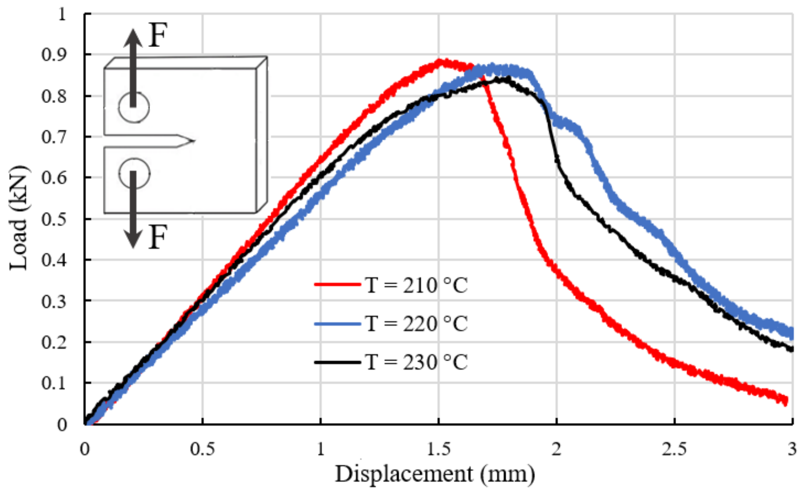
- The load-displacement curves which lead to the calculation of the integral J via the relation (3)

- The load-time curves that allow us to follow the crack

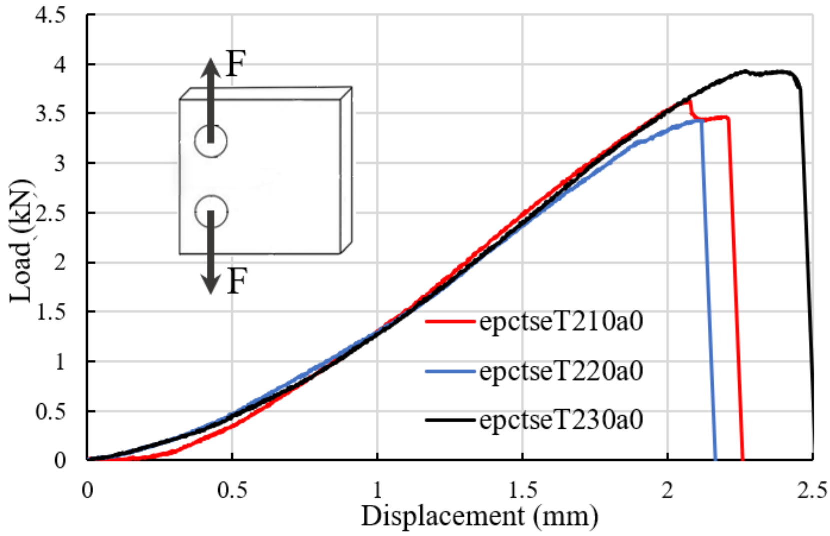
- The follow-up videos of the crack through which we measure its progress Δa as a function of time.

3.1. Resistance Curves

From our tests, we obtained load-displacement curves for two types of specimens. The first type relates to CT specimens with a notch (Fig. 2-a) and the second corresponds to specimens without a notch (Fig. 2-b). From the results of these two types of specimens we are going to deduce values of the integral J [CLA 79].



(a)

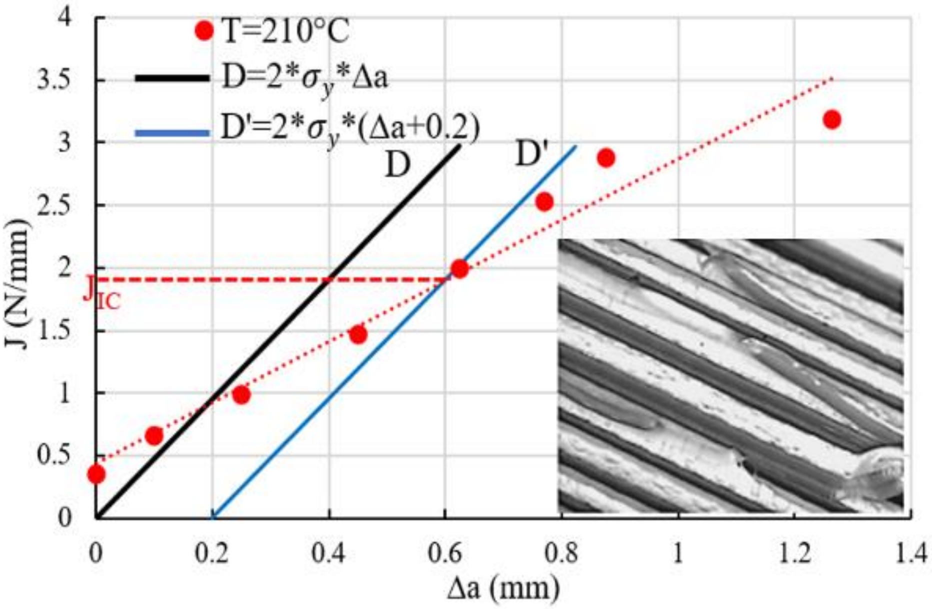


(b)

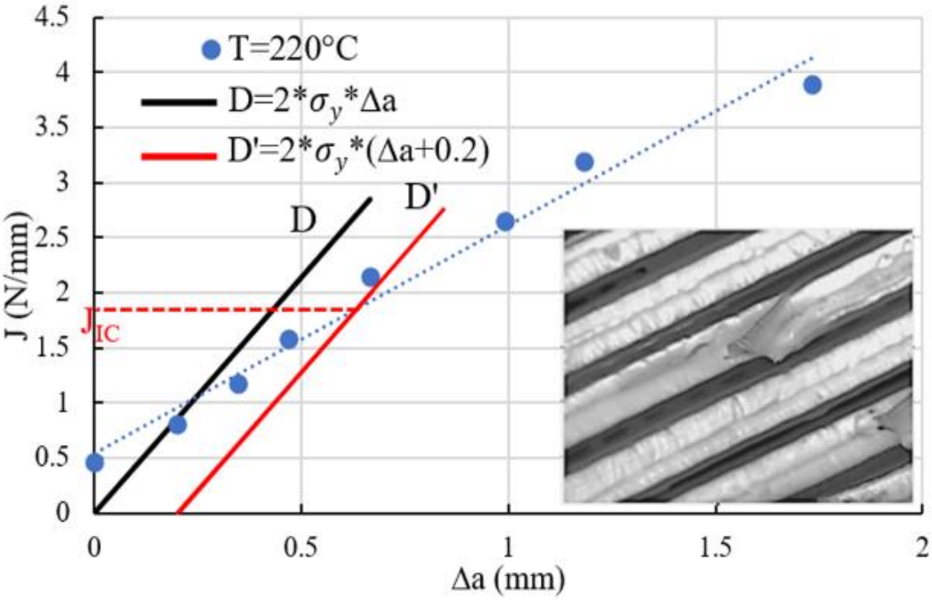
Figure 2. *Load-displacement curves of CT test specimens for T=210°C, T=220°C and T=230°C, for: (a) with notch and (b) without notch.*

To experimentally determine the energies U_T and Ui, for a given deposition temperature, we place ourselves on the curves concerned as shown in the graphs above. From Figure 2-a (Sample with notch), we determine the energy U_T which is the area under the curve from zero to the displacement which corresponds to the maximum force F applied to the notched and pre-cracked specimen. This same force is considered to be determined Ui from Figure 2-b (Sample without notch). Finally, from the determination of the energies U_T and Ui, J can be calculated for each width of the filament by equation (3).

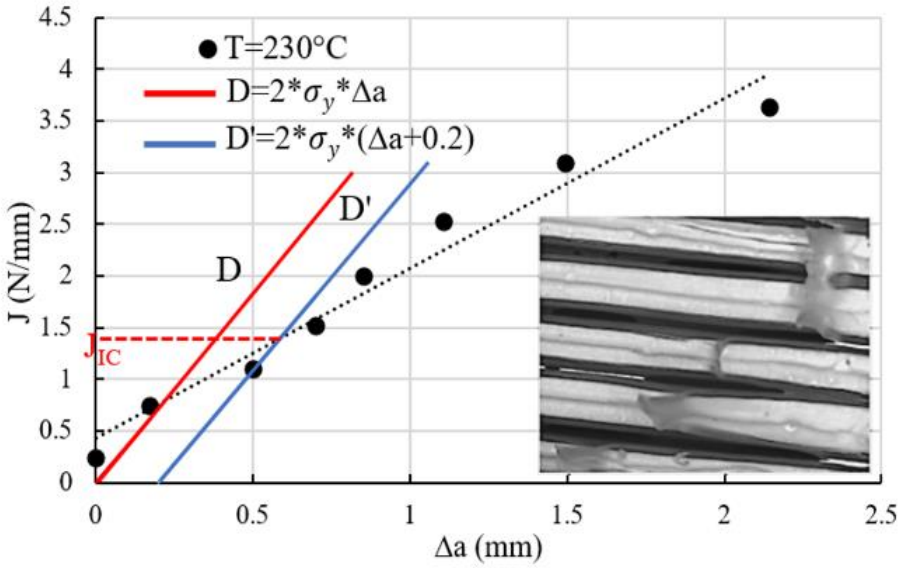
To plot the resistance curve which results in the evolution of J as a function of Δa, it is necessary to determine for each progression Δa, the corresponding energy J. To do this, we used our video recordings of the propagation of the crack during the tensile test on the CT specimens. With these recordings, we have for each time ti, an advancement Δai of the crack. And for each ti corresponds a tensile force Fi which itself corresponds to a displacement di. With this force Fi, the energies U_T^i and U_i^i are determined by standing on the curves (F, d) (see Fig. 2). And it is from these energies U_T^i and U_i^i hat we deduce by formula (3) the value of Ji. Finally, we obtain a series of points (Δa, Ji) from which we can draw the resistance curve as shown in Figure 3. The critical J_{IC} values which make it possible to properly quantify the resistance to crack propagation, correspond to the intersection of the blunt line D' ($J = 2*\sigma y*(\Delta a+0.2)$) and the line (J, Δa). σy being the stress at the tensile yield point of the material.



(a)



(b)



(c)

Figure 3. *J-energy curves as a function of crack advancement Δa for: (a) T=210°C, (b) T=220°C and (c) T=230°C.*

According to these results, the 210°C temperature generates better resistance to crack propagation (J_{IC} = 1.9 N/mm). When the molten filament deposition temperature is increased to 220°C, this resistance decreases significantly (J_{IC} = 1.8 N/mm). On the other hand, when the temperature is increased to 230°C, this resistance drops considerably (J_{IC} = 1.4 N/mm).

Three crucial zones are observed within the intricate structure of the fracture facies (Fig.3). The first is a whitish zone that corresponds to the separation with tearing of material between filaments of the superimposed layers. Concurrently, the second is a contrasting grey zone emerges, marking the precise contact region between adjacent filaments. In the third zone, intricate details come to light as black spots emerge within the grey zone, revealing instances of loss of cohesion.

For the structures obtained at 230°C, this resistance is mainly manifested by the separation of the filaments in different planes (Fracture facies Fig3 c). On the other hand, for the cases of T=210°C and T=220°C (Facies of rupture Fig 3. a and b), the damage occurs partially by the separation of the filaments, but mainly by transverse breaks of the filaments in a very specific direction. For these last two cases (210°C and 220°C), we can therefore qualify the interfaces between filaments as more resistant than in the case (T=230°).

4. Conclusions

In summary, through our study we have highlighted the effect of the deposition temperature on the quality of the resistance to interfacial rupture between filaments of a structure printed by FDM. To do this, we carried out experimental tests on CT specimens printed with different deposition temperatures. From the results obtained and the concept of nonlinear fracture mechanics, we determined the J_{IC} values.

According to the results obtained, we found that with a temperature of 210°C, the specimen presents better resistance to crack propagation (J_{IC} = 1.9 N/mm), while with a temperature of 220°C, this resistance decreased significantly (J_{IC} = 1.8 N/mm). A further increase in temperature up to 230°C resulted in a considerable drop in this strength (J_{IC} = 1.4 N/mm).

For the latter case (T= 230°C), the breakage occurs mainly by separation of the filaments as shown as black spots emerge within the grey zone (Fracture facies Fig 3 c)., while for the cases T=210°C and T=220°C, the damage occurs both by separation of the filaments and by transverse ruptures of the filaments as we can see in (Facies of rupture Fig 3. a and b). Finally, to have a structure printed by FDM with better mechanical resistance at the level of the interfaces between filaments, it is recommended to use slightly low deposition temperatures (between 210°C and 220°).

References

[AOU 23] Aourik, O., Chouaf, A., & Othmani, M., «Analysis of the resistance to crack propagation in SENT test specimens printed in ABS using parallel or crossed filaments between layers ». *Frattura ed Integrità Strutturale*, 17(63), 246-256, 2023.

[AST 99] ASTM D5045, «Standard Test Methods for Plane-Strain Fracture Toughness and Strain Energy Release Rate of Plastic Materials », *ASTM International*, *West Conshohocken*, PA, 1999.

[AST 10] ASTM International. Committee D20 on Plastics, «Standard Test Method for Determining JR Curves of Plastic Materials », *ASTM International*, 2010.

[CLA 79] G. Clarke and J. Landes, «Evaluation of the J Integral for the Compact Specimen » *J. Test. Eval*., 1979.

[ISO 18] ISO 13586, «Plastics - Determination of Fracture Toughness (GIC and KIC) - Linear Elastic Fracture Mechanics (LEFM) Approach », *International Organization for Standardization*, Geneva, Switzerland, 2018.

[MER 74] Merkle JG, Corten HT. «A J integral analysis for the compact specimen considering axial force as well as bending effects ». *J Press Ves Technol*, 96:286–92, 1974.

[RIC 20] Rice JR. «A path independent integral and the approximate analysis of strain concentration by notches and cracks». *J Appl Mech*, 35:379–86, 1968.

[VIC 20] Vicente, C.M.S.; Martins, T.S.; Leite, M.; Ribeiro, A.; Reis, L. «Influence of fused deposition modeling parameters on the mechanical properties of ABS parts ». *Polym. Adv. Technol*, 31, 501–507, 2020.

