Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 207 (2017) 819–824

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on the Technology of Plasticity, ICTP 2017, 17-22 September 2017, Cambridge, United Kingdom

Incremental Sheet Forming of a Composite Made of Thermoplastic Matrix and Glass-Fiber Reinforcement

Romina Conte[a]*, Giuseppina Ambrogio[a], Diego Pulice[a], Francesco Gagliardi[a], Luigino Filice[a]

[a]*University of Calabria – Department of Mechanical, Energy and Management Engineering (DIMEG), via P. Bucci, 45/C, Rende (CS) 87036, Italy*

Abstract

Incremental Sheet Forming (ISF) has been widely investigated in the last twenty years, highlighting advantages as low-cost, higher formability and greater process flexibility if compared to traditional processes. Recent works have proven the ISF feasibility for polymer processing whereas limited investigations exist on composite materials. In the proposed study, an experimental research was carried out with the aim to investigate the influence of process factors on the workability of composite parts. The attention was focused on extruded Reinforced Polyamide-6 sheets. The material is made of thermoplastic matrix and 15% of glass fibers as reinforcement. The processed material is characterized by a glass temperature higher than 50°C and, therefore, ISF was performed with the addition of an external heating source. More in detail, the experiments were carried out on a three axis CNC milling machine equipped with an additional chamber designed for the material heating. In this paper, the influence of the main process factors (i.e. wall slope angle, step depth and process temperature) on the manufactured parts and on the process feasibility was investigated.

Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.

Keywords: Incremental Sheet Formig (ISF); Composite; Glass-fiber reinforcement

---

* Romina Conte. Tel.: +39 0984 494147.
E-mail address: romina.conte@unical.it

1877-7058 © 2017 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.
10.1016/j.proeng.2017.10.835

1. Introduction

Incremental Sheet Forming (ISF) is a process suitable when small batches or single products are required by industry, mainly due to low costs of set-up and equipment [1,2]. One of the main ISF advantages is, in fact, the high level of flexibility mainly due to absence of die or specific tools in the forming of the parts. Against, its working time is consistent making the process slower than the conventional ones, such as stamping and, currently, not competitive for mass production.

ISF has been widely investigated for the production of metal components [3,4] while, more recently, some works have been focused on the performance of the process on polymeric materials [5,6]. Researches have aimed at understanding the influence of the working variables on the outcomes [7,8], analyzing for instance the workability, the quality surface and the microstructure [9].

Limited researches have been carried out to evaluate the possibility of producing composite components by ISF [10-11]. The properties of composites depend on some factors, for instance, on the orientation and distribution of fibers within the matrix or on the proportion of phase and matrix [12]. The usage of composite materials has increased during the last years. Various products have been manufactured for several sectors, mainly where high-performances are required [13,14]. In fact, these innovative materials show a high potential for the aerospace and automotive industries (i.e. structural applications and components of aircraft and spacecraft such as wings, fuselage and empennage components, body and chassis components of automobiles) where the weight reduction of components and the fuel efficiency are the major priorities. The specific stiffness and strength and the energy efficiency, which represent the main advantages of composites, allow the achievement of those objectives [12,15]. High costs and the presence of defect at the interface are two aspects that can limit their usage, if compared with conventional materials [12].

Tape winding, injection molding, compression molding, resin transfer molding, autoclave/prepreg lay-up process, pultrusion are the techniques mainly involved in the manufacturing of composites components [11,13]. Nevertheless, downstream processes allow to further process composite laminates to give them specific shapes [16,17]. ISF can be included in this latter category of processes, even if its feasibility has to be demonstrated yet.

The purpose of this study is to fulfil this gap and to highlight the workability of a thermoplastic material reinforced with short glass fibers by ISF. In detail, a composite, mainly used for automotive components such as housings in HVAC applications, fenders, side linings of trucks and other machinery, bezels, was investigated. Some preliminary results in terms of relation between the process conditions and the outcome will be provided. To investigate the material behaviour, an experimental plan has been designed. Its performing highlights how changes occur in the material formability when it is subjected to the variable setting of specific factors.

The main results, in terms of workability and accuracy, are presented in this work.

2. Material and Method

2.1. Material

Experiments were performed using a composite made of Polyamide-6 (PA 6) and short glass fibers, characterized by a crystalline grain melting range of about 220°C and a short term service temperature of 180°C. The material has a thickness and a fiber volume fraction of 1.1 mm and 15%, respectively.

Laminates are vacuum formable and downstream work techniques, such as machining and laser cutting, allow the production of further semifinished products [18]. The investigated material is widely used to produce components for the aeronautical ad automotive sectors and it is also required in the mechanical engineering field.

2.2. Method

ISF process consists of a local and progressive deformation of a sheet blank using a CNC machine, which controls a forming tool. It is considered a low cost process since conventional punches and dies are avoided, therefore the flexibility is one of its main advantages and makes it an attractive alternative for small batches or prototypes [19]. However, previous preliminary research carried out by some of the authors have highlighted that the composite manufacturing can not be obtained if ISF is applied in the conventional way and without any support material [20]. On the contrary, better results can be found by introducing the assistance of an additional low-cost-high-formable material blank that facilitates the process and drives the composite manufacturing.

In other words, experiments were carried out superimposing an Aluminum AA1050 sheet (150mm×150mm×1mm) on the composite one and manufacturing both simultaneously. The Aluminum sheet works like a "flexible die" which sustains the composite deformation that conversely should not maintain the imposed shape.

For the purpose of this study, a Mazak Nexus 410A work-centre machine was used for the ISF running. A designed fixture, additional equipped with a thermal isolated chamber, was mounted on the CNC milling machine (Fig. 1). A square composite sheet (150mm×150mm×1.1mm), together with the Aluminum, was placed and fixed on the frame in order to be clamped during the deformation. A cone-shaped part, with the outer diameter of 130 mm and a final depth of 30mm was selected to test the formability. A punch with a 10 mm diameter hemispherical head was chosen to locally form both the sheets and a lubricant emulsion was supplied on the Aluminum sheet during the process to reduce friction. Additionally, taking into account the glass transition temperature of the composite material, the initial working temperature was set accordingly. A control unit was added to the equipment for this purpose and the temperature was carefully monitored through a thermocouple before the process starting. A hole on the metal sheet allowed the measurement on the upper surface of the composite.

Fig. 1. ISF equipment and parts at the end of the process.

3. Experimental plan

Taking into account both the well assessed base of knowledge on conventional materials manufactured by ISF [21] and the preliminary investigation carried out by the authors [9, 20], in this study the attention was directly focalised on the main parameters which strongly affect the ISF feasibility and the quality of the outcomes. Three process variables were evaluated: the wall angle (α), the step depth (p) and the imposed temperature (T). Each of them was varied on two levels in a predefined range, fixed by a preliminary set of screening tests. A full orthogonal experimental plane was performed and three replications were executed for each test configuration to prove the repeatability. Details of fixed and variable values are listed in Table 1 and Table 2.

Table 1. Fixed process parameters details

Fixed Parameters		
Sheet thickness (PA GF15%)	1,1	mm
Sheet thickness (AA5754)	1	mm
Punch Diameter	10	mm
Spindle speed	100	RPM
Forming velocity	5000	mm/min

Table 2. Variable process parameters details

Variable Parameters			
Wall angle (α)	30	40	°
Step depth (p)	1	2	mm
Temperature (T)	150	200	°C

4. Analysis of the results

The material formability, the thickness distribution and the part accuracy were the main objectives of the analysis. These outcomes were referred directly to the average values of each test configuration, because of the good repetitions of the experiments as well as the standard deviation close to zero. At the same time, due to the limited number of investigated configurations, the direct observation of the phenomena is justified without the application of statistical approach.

Concerning the material formability, all the test configurations gave back sound components (Fig. 2.a) with exception of the experiment carried out with α=40°, p=1mm and T=150°C. In this case, a fracture on the specimen occurred abruptly due to the combined effect of lower values of step depth and process temperature (Fig. 2.b).

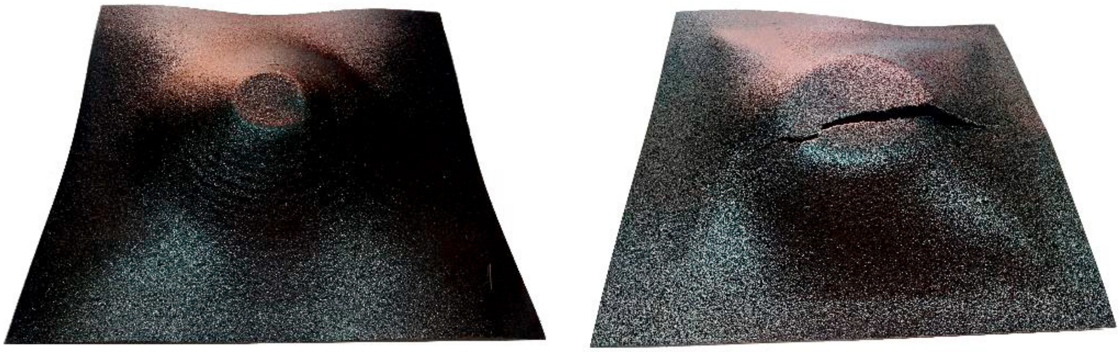
(a) (b)

Fig. 2. (a) Sound and (b) broken parts.

Beyond the formability, this preliminary investigation highlighted evident distortion out of the forming area, probably due to high residual stresses in the sheet. This effect could be reduced if a proper process optimization was carried out. In detail, the use of a backing plate, taking into account the shape of the part to be formed, and the optimization of the various process parameters should decrease the pointed out shape distortion.

Observations that are more interesting can be derived by the thickness distribution extracted on the truncated cone profile along the two orthogonal planes perpendicular to the clamping zone. For sake of simplicity, only half averaged measures are displayed. In detail, Figure 3 reports the obtained values for the experiments carried out with a wall angle of 40° and changing the other process parameters. Looking at the displayed trends, a reduced sheet thinning can be observed for the lower step depth. This consideration leads to conclude that ISF, performed on composite sheet, maintains the same intrinsic deformation mechanics shown for metallic sheets. The deformation results strongly localised to the contact zone between the punch and the sheet. In fact, lower local deformations allow lower thinning on the whole shape.

Furthermore, comparing the curves with the same wall angle and step depth but changing the process temperature, the overlapping is quite fitting thus suggesting that in the investigated range, the temperature does not influence the thinning phenomenon.

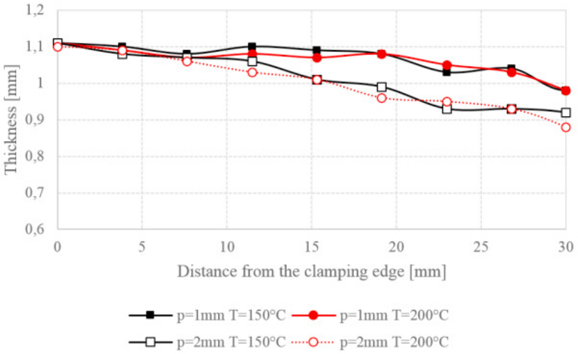

Fig. 3. Thickness distribution measured from the clamping edge for α=40°.

Figure 4 displays additional comparisons between experiments carried out varying the wall angle: as it can be observed, higher is the slope of the cone, more consistent is the thinning.

Finally, at this stage of the research, the part accuracy was evaluated just in terms of springback by comparing the final height reached after the manufacturing step with the targeted height (H_f=30mm). The measured values are reported in Fig. 5. Generally speaking, better performances are obtained working at higher temperature and with higher step depth. However, the overall part inaccuracy represents the main drawback that penalizes the process results. According to that, a robust optimization has to be pursued in future works to get a more accurate shape considering the whole 3D profile (i.e. final height, achieved angle, shape distortion).

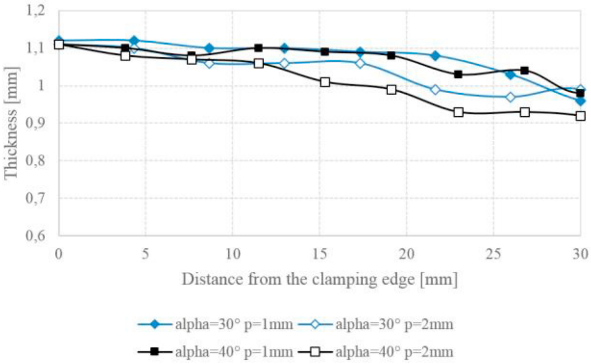

Fig. 4. Thickness distribution measured from the clamping edge for T=150°C.

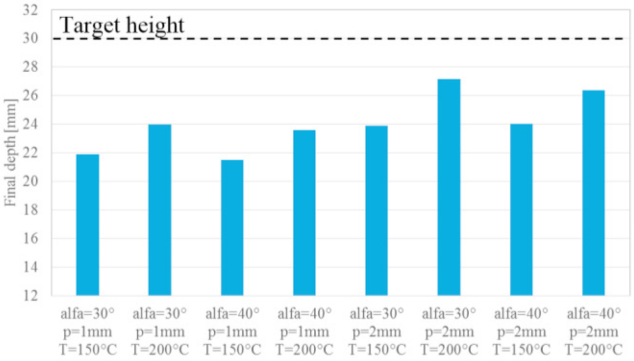

Fig. 5. Final height measured at the end of the manufacturing step.

5. Conclusions

The main reason for the lack of the widespread acceptance of composites made of thermoplastic matrix is that they are more difficult to process than thermosets. A number of techniques have been developed for thermoplastic composites processing, but they are limited used. Hence, intensive research and development efforts are underway to develop new techniques for forming amenable thermoplastic composites [12]. The purpose of the study is a preliminary feasibility analysis on forming of thermoplastic composite sheets by ISF. More in particular, the investigated material is a glass fiber reinforced polyamide-6, widely used in automotive applications. Starting from the available base of knowledge on thermoplastic materials and considering the ISF peculiarities, an experimental investigation was planned changing three main process conditions: the wall angle, the step depth and the process temperature. Preliminary results were obtained concerning the process feasibility, which must be improved with additional research. However this first outcome represents an innovation for secondary operations on composites by ISF. The experiments highlighted that properly choosing the tool depth step and the process temperature, firstly, sound parts can be formed with a moderate sheet thinning. Naturally, further experimental investigations are required for a full understanding of the material behaviour and for the shape optimisation. In particular, the microscopic analysis becomes fundamental for the observation of the fiber distribution after the manufacturing step and for the full comprehension of the investigated phenomena. All these activities will be proposed in coming works.

References

[1] J.J. Park, Y.H. Kim, Fundamental studies on the incremental sheet metal forming technique, J. Mater. Process. Technol. 140 (2003) 447–453.
[2] G. Ambrogio, L. De Napoli, L. Filice, F. Gagliardi, M. Muzzupappa, Application of Incremental Forming process for high customised medical prodct manufacturing, Journal of Materials Processing Technology 162 (2005) 156-162.
[3] L. Fratini, G. Ambrogio, R. Di Lorenzo, L. Filice, F. Micari, Influence of mechanical properties of the sheet material on formability in single point incremental forming, CIRP Annals-Manufacturing Technology, 53(1) (2004) 207-210.
[4] L. Filice, L. Fratini, F. Micari, Analysis of material formability in incremental forming, CIRP annals-Manufacturing technology, 51(1) (2002) 199-202.
[5] T.A. Marques, M.B. Silva, P.A.F. Martins, On the potential of single point incremental forming of sheet polymer parts, The International Journal of Advanced Manufacturing Technology, 60(1-4) (2012) 75-86.
[6] I. Bagudanch, M.L. Garcia-Romeu, M. Sabater, Incremental forming of polymers: process parameters selection from the perspective of electric energy consumption and cost, Journal of Cleaner Production 112 (2016) 1013-1024.
[7] P.A.F. Martins, L. Kwiatkowski, V. Franzen, A.E. Tekkaya, M. Kleiner, Single point incremental forming of polymers, CIRP Annals-Manufacturing Technology, 58(1) (2009) 229-232.
[8] V.S. Le, A. Ghiotti, G. Lucchetta, Preliminary studies on single point incremental forming for thermoplastic materials, International Journal of Material Forming, 1(1) (2008) 1179-1182.
[9] R. Conte, F. Gagliardi, G. Ambrogio, F. Filice, P. Russo, Performance analysis of the Incremental Sheet Forming on PMMA using a combined chemical and mechanical approach, submitted at the 20th ESAFORM Conference, April 26th-28th 2017, Dublin (In press)
[10] M. Fiorotto, M. Sorgente, G. Lucchetta, Preliminary studies on single point incremental forming for composite materials, International Journal of Material Forming, 3 (2010) 951-954.
[11] M.E. Tuttle, Structural analysis of polymeric composite materials, CRC Press, 2012.
[12] M. Balasubramanian, Composite materials and processing, CRC press, 2013.
[13] S. Mazumdar, Composites manufacturing: materials, product, and process engineering, CrC press, 2001.
[14] L.P. Durand, Composite materials research progress, Nova Publishers, 2008.
[15] T.G. Donderwinkel, B. Rietman, S.P. Haanappel, R. Akkerman, (2016, October). Stamp forming optimization for formability and crystallinity, in: F. Chinesta, E. Cueto, E. Abisset-Chavanne (Eds.), AIP Conference Proceedings, AIP Publishing, Vol. 1769, No. 1, p. 170029.
[16] T. Jamin, M. Dubé, L. Laberge Lebel, Stamp forming of thermoplastic composites: effect of radius and thickness on part quality, ECCM16 - 16TH European Conference on Composite Materials, Seville, Spain, 22-26 June 2014.
[17] R.M. Stack, F. Lai, Development in thermoforming thermoplastic composites.
[18] N. Hendel, Vacuum formable nylon sheets, IAPD Magazine, (2003) 44-45.
[19] M. Azaouzi, N. Lebaal, Tool path optimization for single point incremental sheet forming using response surface method, Simulation Modelling Practice and Theory 24 (2012) 49-58.
[20] R. Conte, G. Ambrogio, L. Filice, F. Gagliardi, P. Russo, Preliminary experimental analysis on incremental forminf of fiberglass reinforces polyamide 6, submitted at AITEM 2017, September 11th-13th 2017, Pisa (In press)
[21] G. Hirt, J. Ames, M. Bambach, R. Kopp, Forming strategies and process modelling for CNC incremental sheet forming, CIRP Annals-Manufacturing Technology, 53(1) (2004) 203-206.