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ScienceDirect

Procedia Engineering 81 (2014) 1608 – 1613

Procedia Engineering

www.elsevier.com/locate/procedia

11th International Conference on Technology of Plasticity, ICTP 2014, 19-24 October 2014, Nagoya Congress Center, Nagoya, Japan

Forming sheets of metal and fibre-reinforced plastics to hybrid parts in one deep drawing process

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Abstract

Each material has its own advantages and disadvantages in terms of its mechanical, chemical and physical properties. Metallic materials are comparatively ductile and easy to process. Fibre reinforced plastics are very stiff and endure high tensile stresses based on their weight. By intelligent combination of these materials into one overall-part light but strong components may be established. However, the conventional production of a separate fibre reinforced plastic (FRP)-component and a metal component and a subsequent joining is time- and labour-intensive and therefore not economical in mass-production. Thus in this paper a new fabrication technology is presented.

Selection and peer-review under responsibility of the Department of Materials Science and Engineering, Nagoya University

Keywords: Sheet metal forming; Deep drawing; Hybrid parts

1. Introduction

Lightweight construction is an everlasting matter in the aviation and automotive industries. Efficient lightweight construction can be achieved by using appropriate materials with their particular merits each in parts with locally varying mechanical requirements. Therefore, an increasing use of material mix constructions is to be expected in the future for example by Hufenbach et al. (2013). Metallic materials are already widely used and established in most producing industries, among these especially steel and aluminium. They are distinguished for their favourable all-round characteristics and comparatively low costs. Another type of material lately becoming established in the

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1877-7058
Selection and peer-review under responsibility of the Department of Materials Science and Engineering, Nagoya University
doi:10.1016/j.proeng.2014.10.198

market are fibre-reinforced plastics. They are characterised by high strength and stiffness in fibre direction, but only permit low tensile stress crosswise and are difficult to join. Above all, the high costs of such parts due to time and manpower intensive production methods limitate their wide spreading use.

The combination of metallic components, which are reasonably reinforced in highly stressed areas by fibre-reinforced plastics, suggests itself. However, the separate manufacturing of metallic components and a subsequent reinforcing of often complex components with fibre-reinforced plastics would not be affordable. Therefore, a procedure was developed, in which simple semi-finished products made of metal and fibre-reinforced thermoplastics are formed in one shared step to a multi material part. The semi-finished products are placed in the temperature-controlled deep drawing tools and are formed together to one joined part. The challenge in this process consists mainly in the different forming characteristics of the components. The thermoplastic in the FRP must be formed in a warm state. But partially or fully melted it is very soft in comparison to aluminium or even steel and its forming behaviour is sensitive to temperature deviations. Therefore, the different forming properties of the materials must be mastered and a good temperature control in the forming process is required.

2. Deep drawing fibre reinforced plastics

Similar to the deep drawing of metal components, a method is used which allows to draw thermoplastic semi-finished parts to three-dimensional hollow bodies. This process is referred to as thermoforming. For example described by Engelmann et al. (2012), or Schwarzmann and Illig (2001), in this case the ability of the thermoplastic materials to be soft and formable at higher temperatures and to solidify during subsequent cooling again is used. For the forming of pure thermoplastic semi-finished, this process is widespread, especially in the packaging industry. However, when reinforcing the plastic with fibres it cannot be formed easily. The forming of pure thermoplastic is based on the high stretch ability of the plastic. The fibres introduced cannot be stretched with the plastic; therefor other forming mechanisms must take place. Friedrich et al. (1997) describes five mechanisms: resin percolation, transverse flow of laminate layers, inter-ply slip, intra-ply shear and inter-laminar rotation.

3. Forming hybrid-parts of metal and fibre reinforced plastics

There are many different possibilities of combining metals and FRP from metallic components locally reinforced with FRP up to FRP-components with metallic inserts. Fig. 1 shows some of these possible combination principles with each different lightweight construction potential. The optimal combination differs for different applications.

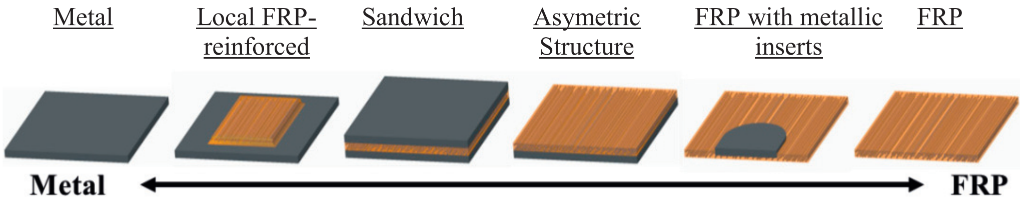

Fig. 1. Schematic illustration of the spectrum of FRP and metal combinations.

In the target process the semi-finished products, consisting of the metallic component and the fibre-reinforced plastic, are formed together. In this way, the separate manufacturing of the individual components and subsequently joining is avoided. The desired process route is shown in Fig. 2. At the beginning the preparation of semi-finished products and a subsequent joining take place. Afterwards the part is heated. The joining can be achieved in various ways. On one hand, the adhesive properties of the melted thermoplastic material may be employed. Thus, a separate joining operation can be saved. In this case, the sheets are inserted together into the die and bonded during the forming process. For this, however, the matrix must be at least partially melted, causing a greatly reduced flow resistance (Pohl, 2000; Palkowski et al., 2006). Alternatively, an adhesive between components may increase the bonding strength.

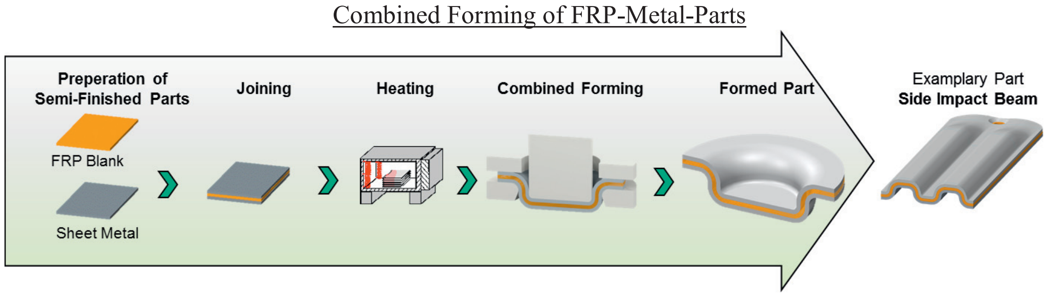

Fig. 2. Illustration of the combined forming process rout of FRP-metal-parts.

Before forming metallic and reinforced thermoplastics in one drawing process, some characteristic properties of the components must be considered. The metal forming processing properties of fibre-reinforced plastics differ significantly from the properties of metals. There are some special characteristics of FRPs. The big difference in the processing properties becomes especially noticeable when forming the components together. Forming of the thermoplastic material is only possible at elevated temperatures. Depending on the thermoplastic this can be up to 300 °C. A defined temperature balance is a precondition for a successful forming operation. At low temperatures the thermoplastic will not be formed successfully. If the temperature is too high, however, the thermoplastic will be decomposed and thus be destroyed.

For the forming of the metallic component comparatively high forces are required. However, only limited forces can be transmitted by the FRP, as this would lead to manufacturing failures. The FRP can be sheared off at the edges, or wrinkles of the sheet metal can be pressed into the soft FRP matrix. These difficulties can be resolved or weakened by means of suitable tools and temperature management. Another challenge in forming unidirectional fibre-reinforced plastics is a strongly anisotropic forming behaviour. The fibre layers cannot be stretched in the direction of the fibres. In contrast, perpendicular to the fibre direction the FRP can be formed comparatively easy due to inter-ply slip.

If conventional forming technologies and machines are already used in a factory, the combination of metal-FRP-metal sandwiches are the first choice for an easy change to working with FRP-metal-compounds. Here, only the metallic components are in contact with the forming tools. Since the FRP is located between the metal components, it cannot be sheared-off in the forming process. Instead relative movement between sheet and tool can take place as in conventional deep drawing. Furthermore, no adhesion between the plastic and the die occurs and the metallic sheets build a protective shell. This shell prevents the molten plastic from displacement due to the high forces necessary to form the metallic component. Therefore, in the following the forming of sandwich composites was investigated.

4. Experimental Setup

4.1. Combined Forming

When deep drawing cups different stress states and thus resulting elongation take place. The investigation of the formability of different materials can be performed by means of deep drawing of round cups reasonably. As described, unidirectional reinforced FRP's show a strong direction dependence of the formability. Since round cups are rotationally symmetric, the forming properties can be compared in all directions directly with each other within one part. Therefore, first cups were made from an aluminium-FRP-aluminium-sandwich at the Institute of Forming Technology and Machines.

The aluminium alloy AW-5754 with a sheet thickness of 1 mm was used. The FRP component was made of unidirectional glass-fibre-reinforced PA6 (GRP) with a fibre volume content of about 40 %. FRPs with a thickness of 1.2 mm and 2.5 mm were employed. As shown in Fig. 3, the semi-finished products were joined without an adhesion promoter during the forming process, using the adhesive properties of the thermoplastic only and formed in one step. The surface temperature of the tool components (punch, die, down holder) was set to 270 °C. To ensure the joining of the half-finished products, a die with a bottom was used. By this, the sheets were compressed in the lower point and thus can form a compound. In order to avoid excessive squeezing-out of the thermoplastics in the flange, the down holder device was detached. The chosen distance was 0.5 mm less than the overall height of the sandwich. In the side wall area, a free deformation zone was implemented in order to consider the forming behaviour without constrain. For this, a punch diameter of 100 mm and a drawing die diameter of 120 mm were used. The targeted drawing depth was 35 mm. In the lowest process point the forming process was stopped and the part was removed after cooling.

Fig. 3. Schematic illustration of the deep drawing process using non-joined metal-FRP-sandwiches.

4.2. Initial state of the semi-finished glass fibre reinforced plastics

Before forming and analysing the formed FRP, the initial state of the layers and fibres must be investigated. For this purpose, 2.5 mm thick FRP plates were embedded in an epoxy resin and micrographic pictures were taken. The images are shown in Fig. 4. The dark grey areas of the samples represent the thermoplastic PA6, while the glass fibres are shown in white. The unidirectional configuration of the FRP plates can be seen clearly in these images again. Especially axially to the fibre direction, the individual fibre layers are clearly visible. In the manufacturing process of the FRP blanks PA6 films and glass fibre sheets were stacked and bonded under pressure and heat. By this, the heated thermoplastic penetrates the fibre layers. The layers generated within this process cannot be annulled completely. In the lower image in Fig. 4 a photograph perpendicular to the fibre direction is shown. Due to minimal variations of the photographing plane to the fibre direction, the fibres appear as lines as the section is at a shallow angle to the viewing photographing plane.

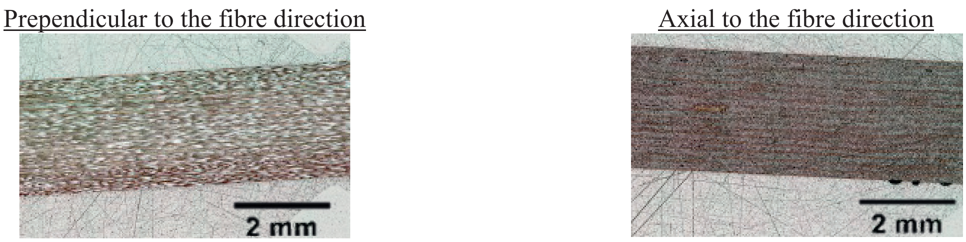

Fig. 4. Micrographs of the initial state of the GRP axial and perpendicular to the fibre direction.

5. Results

Cups could be produced successfully of both material combinations. The left picture of Fig. 5 shows a cup with 1.2 mm thick GRP and on the right side a cup with a 2.5 mm thick GRP. In the forming process the squeezing-out of the matrix could not be prevented completely. Especially perpendicular to the fibre direction the GRP emerged between the cover plates. In these directions the layers offer a comparatively good interlaminar slip and accordingly the GRP easily emerges. In fibre direction, however, only a slight or no squeeze-out at all of thermoplastic was observed. The fibres cannot be extended; accordingly an extension of the GRP in this direction can only occur when either the fibres or fibre layers slide on each other or the thermoplastic is forced out between the fibres. The large surface area and associated friction between thermoplastics and fibres is obviously sufficient to prevent excessive squeezing-out of the GRP in this direction.

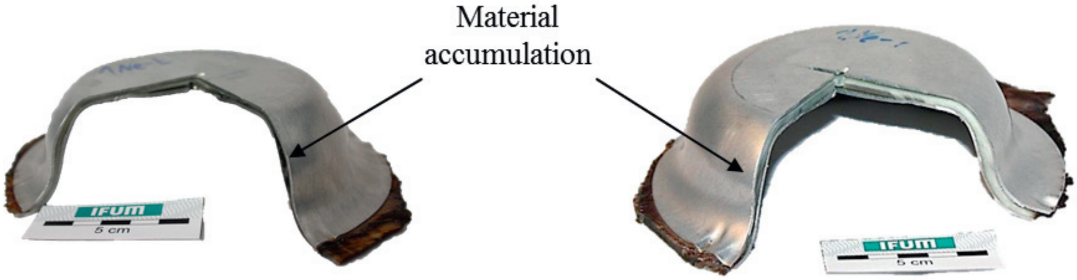

Fig. 5. Pictures of deep drawn sandwich cups. Left: 1.2 mm thick GRP. Right: 2.5 mm thick GRP.

The squeezed-out thermoplastic material in the flange area has changed its colour from white to brown. The discoloration occurred only in the flange area, where direct contact of GRP to tool took place. Maybe the aluminium cover sheets could transfer the introduced temperature quickly enough to cooler areas, so that the GRP between the cover sheets did not suffer that high temperatures. The thermoplastic on the other hand which was forced out, comes into direct contact with the tool and thus suffers higher temperatures. In the production of real parts, a trimming of the flange is carried out, which would eliminate these discoloured areas. The optical and mechanical impairment of the GRP in this area would therefore not affect the part quality.

Furthermore, it was not possible to prevent wrinkling of 1st and 2nd order. Since the down holder device was set at a constant distance, wrinkles in the flange could not be suppressed. Instead, wrinkles in the aluminium sheets could press into the softened GRP. The wrinkles of 2nd order occurred almost exclusively in the inner cover plate of the component. In Fig. 5 the GRP accumulations due to wrinkling of the inner sheet in the side wall can be seen. This uneven wrinkling of the aluminium sheets led to local material displacements and accumulations of GRP in the side wall. In this case, different forming mechanisms depending on the fibre direction took place.

With the help of microscopic investigations of these areas, the major forming mechanisms can be deduced. If an area is investigated, in which the drawing direction is perpendicular to the fibre direction (resp. axial to viewing direction), and an accumulations of material appeared, an altered layer structure is evident (Fig. 6 left). From this point of view, the individual layers can be easily identified. It is found that the GRP filled the cavities using overlapping fibre layers. A similar behaviour in the bottom of a part has also been reported by Breuer (1997) when producing components made of fibre reinforced thermoplastics.

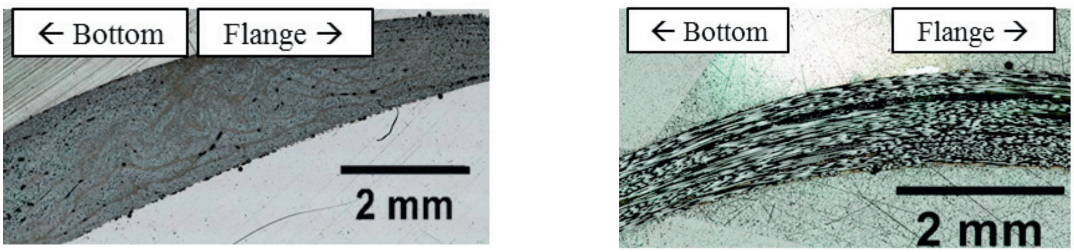

Fig. 6. Micrographs of GRP in the side wall axial (left) and at the punch edge perpendicular (right) to the fibre direction.

In the area of the punch edge, a interlaminar rotation of the layers can be observed. In Fig. 6 right a micrograph is shown, where the fibre direction is perpendicular. As already described, minimal deviations between the angle of the viewing plane to the fibre direction means that the fibres are shown as elongated white structure, since the fibres were cut at a shallow angle. The longer the fibres appear in the image, the more parallel the cutting plane is to the fibre level. In the shown micrographs, significant variations in the parallelism of the fibres to the cutting plane can be recognized. Specifically on the inside of the punch edge, the fibre direction deviates significantly from the direction of the surrounding regions. This effect was able to be observed both in the forming of GRP blanks of 1.2 and 2.5 mm in thickness.

As the forming behaviours of both materials interact, when forming simultaneous, these differences cannot be neglected simply. At the Institute of Forming Technology and Machines efforts are made to work this process. Besides to the process development, the modelling and interaction of these materials in numerical simulations are seen as important key factors to a successful process. Furthermore, the simulation of the forming process is in particular important for the design of components as the change of orientation and arrangement of the fibres significantly change the strength of the component.

6. Summary and Prospect

A simultaneous forming of aluminium-GRP-aluminium sandwiches could be performed successfully. Using microscopical investigations, new insights in the forming mechanisms of GRP, when forming simultaneously with aluminium cover sheets, were achieved. However, challenges in the combined forming arise. Wrinkling in the flange area is one of the major challenges. In conventional deep drawing the down holder supresses wrinkles in the flange area. But when forming sandwich cups with thick FRP-layers, high down holder forces would extrude the FRP from the flange in areas where the drawing direction is perpendicular to the fibre direction. Furthermore, in the inner cover sheets wrinkling of 2^{nd} order was seen. Following the wrinkling, the GRP was forced to accumulate or thin out in certain areas. It was seen, that in areas, where the fibre direction is perpendicular to the drawing direction, the fibre layers start to overlap in order to fill upcoming cavitation. A tool concept with an all-over tool contact, and thus pressure, is suggested in order to prevent wrinkling in the side wall area. In order to gain further understanding of the forming behaviour and interaction of the components metal, thermoplastic and fibres a thorough investigation and further experimental set-ups are necessary. Especially the effects of the temperature, an appropriate tool concept and simulation models seem to be key factors.

Acknowledgements

The authors would like to thank the German Federation of Industrial Research Associations (AiF), the European Research Association for Sheet Metal Working (EFB) and the Federal Ministry of Economics and Technology (BMWi) for funding this research project AiF 17689BR. Furthermore, the authors would like to thank the companies which participated in this research project.

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