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Application of laser peen forming to bend fibre metal laminates by high dynamic loading

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ABSTRACT

Forming parts from the flat fibre-metal laminates (FMLs) is very attractive to reduce the process cycle and labor cost. In this study, laser peen forming with the adaptability to produce large complex shapes is proposed to forming FMLs. Strip samples of glass laminate aluminum reinforced epoxy with different fibre orientations are prepared for experiments. The experimental results provide that the convex bending can be produced by the scanned high dynamic loading from laser irradiations. The bending is favorable to generate in the direction perpendicular to the unidirectional orientated fibres. Increasing the scanning times of arrayed laser shocks can increase the bending deformation to reach a very small saturated radius of curvature. But the risk of delamination failure is observed at the metal/fibre interface. By employing the chemical etching, the plastic deformation in the samples is found to generate in the top and bottom aluminum layers and the upper fibre layer. The study has demonstrated that the high dynamic loading of laser peen forming is a practical pathway to produce bending deformation with the sharp radius of curvature, which would be very attractive to various industrial applications.

1. Introduction

Fibre–metal laminates (FMLs) are new kind of composite materials for advanced aerospace. They consist of alternating layers of fibre reinforced polymers and thin metallic sheets adhesively bonded together. One of the most important objects of their production is to combine the good impact resistance of metals with the better light weight characteristic of fibres (Khan et al., 2009). Because of their excellent fatigue and impact properties, FMLs have been demonstrated success primarily as a substitute to high strength aluminum alloys to reduce the weight of aircraft structures (Vlot et al., 1999).

Manufacturing of FMLs parts is challenging because of the mechanical properties of different constituents contained. Traditionally, autoclave forming is the standard manufacturing process for large complex structures. It is conducted by the lay-up of individual layers on a large mould. And then an autoclave is used to bond metal sheets and fibre reinforced prepreg layers together into their final shape (Sinke, 2003). The disadvantage of autoclave forming is the long processing cycle and labor-intensive costs of whole production (Sinmazçelik et al., 2011). Russig et al. pointed out that a more economical approach would be to form parts from the flat FMLs because the production of the flat FMLs could be largely automated without the requirement of excessive manual interaction (Russig et al., 2013). Since a significant part of FMLs consists of metal sheets, FMLs can be plastically deformed like common metal alloys. Therefore, several conventional processes of sheet metal forming can provide easy and cheap manufacturing approaches to manufacture FMLs parts from the flat laminates. Sinke proposed the roll bending as an appropriate option to form the singly curved shapes. But the significant springback in the circumferential fibre direction would pose a problem. And it is also not applicable to form the doubly curved shapes (Sinke, 2003). Stretch forming, commonly used to form the doubly curved shapes, is another potential process to form the large contoured FMLs. However, considering the small failure strain of fibres about a few percent, only very shallow doubly curvatures are available (Sinke, 2003). Stamp forming, extensively employed because of its ability to mass produce metal parts, was also investigated to validate its formability of FMLs. Mosse et al. observed that the delamination in the glass-reinforced composite FMLs was predominantly within the interface after cold stamp

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forming (Mosse et al., 2005). Furthermore, the effect of preheating on the formability of glass-reinforced composite FMLs was investigated to improve the delamination and shape error significantly but to increase the severity of wrinkling in the outer flange and sidewall (Gresham et al., 2006). Besides the limitation of formability and several kinds of failure, stamp forming is restricted by the size of die press to form FMLs structures. Although conventional forming processes for metal alloys have potential abilities over autoclave forming to improve the productivity and decrease the labor cost, there are still some difficulties in the formability, multiple failure modes and adaptability to form large complex shapes.

Novel forming approaches are expected to fabricate FMLs parts with the advantages of geometry flexibility, low labor-cost and high productivity. Laser forming, one kind of special applications of laser technology without material removal, has been proposed as a flexible and low-volume manufacturing process to form complex shapes of metal parts. Compared with conventional forming process, laser forming of sheet metal requires no mechanical contact of hard tooling. Production of complex shapes can be achieved through the specified scanning strategy of laser spots. Therefore, this approach has many technological advantages including design flexibility, producing complex shapes, and reducing the cost of forming process when low-to medium-volume production or prototyping is concerned in industry (Liu et al., 2004; Vollertsen, 1994). Laser forming, usually indicating laser thermal forming, utilizes a defocus laser source to bend sheet metal parts by introducing thermal stresses across the thickness. Edwardson et al. presented that this process also allowed to form FMLs with sharp radii by introducing the thermal stress in the cover metal layer (Carey et al., 2010). However, under the high thermal exposure and forced cooling, the unintended delamination and material failure of burning and fibre cracking make it hard to maintain material properties of shaped parts. Despite of laser thermal forming, laser peen forming (LPF), a newly derivative of laser peening, is another novel process utilizing laser technology to form complex shapes of metal sheets. It is a purely mechanical process to achieve through the laser-induced high dynamic loading to modify the target curvature. Besides the advantages of non-contact, tool-free, high efficiency, its pure cold-work process makes it possible to generate compressive stresses over both sides of metals, which is very desirable for the shaped parts to resist cracks from corrosion and fatigue. LPF process has attracted much concern in the past several years. Hackle et al. suggested that it could contour thick plate over its large area (Hackel and Harris, 2002). Ocana et al. demonstrated its suitability to bend thin metal strips with different shock positions and pulse energies (Ocaña et al., 2007). Hu et al. experimentally observed that the sheet metal can be made with different bending directions, which continuously and smoothly varies from the concave curvature to the convex by increasing sheet thickness or decreasing laser intensity (Hu et al., 2010). Regarding the thin metal layers included by FMLs, LPF will be a promising high-flexible forming process with the ability to form FMLs parts avoiding the risks of excessive thermal input. However, few studies have been reported about its feasibility to form FMLs material.

LPF process is characterized by the dynamic loading as high as several GPa with the duration of tens of nanoseconds. The key issue concerned is about its feasibility to bend FMLs by introducing plastic deformation in the laminates without any delamination failure. In recent years, a number of studies were performed to investigate the impact resistance of FMLs under different loading conditions. Mugica et al. analyzed the impact induced penetration and perforation behaviors of a 2024-T3 aluminum-based fibre metal laminate under low-velocity impact tests (Múgica et al., 2014). Sitnikova et al. investigated the perforation failure of FMLs panels subjected to the localized high intensity blast loading (Sitnikova et al., 2014). Different from previous studies, the impact effect induced by LPF is a non-contact process generated by pulsed-laser induced shock pressure to bend the FMLs materials without expecting any failures.

The objective of this work is to address the applicability of LPF process to forming FMLs through its high dynamic loading. Strip samples with different fibre orientations were prepared for experiments. Different laser irradiations by alternating scanning times of arrayed laser shocks were used to investigate the forming limit of bending deformation and the potential delamination failure. The plastic deformation generated in the laminates was analyzed with the residual bending profiles after removing the top and bottom aluminum layer by chemical etching.

2. Physical process

Laser peening process originates from the ability to drive high amplitude shock waves into a material surface with a short-pulsed laser of high power density (several GW/cm^2, 1–50 ns). This process is usually carried out under a confined regime configuration as shown in Fig. 1(a). The metallic surface is first locally coated with an opaque absorbent layer and then is covered by a transparent overlay of water. The absorbent layer acts as a sacrificial material to prevent the thermal effect from heating the surface by laser irradiation, and a thin layer of it vaporizes upon the absorption of laser energy to generate plasma. The transparent overlay of water confines the thermally expanding vapor and plasma against the target surface to generate a high-amplitude transient pressure loading exceeding the yield strength of material. The high shock loading causes the target to undergo high strain-rate plastic deformation up to 10^6 s^{-1} (Montross et al., 2002).

With the plastic deformation generated in the metal part as shown in Fig. 1(b), the local plastic deformation induced about the shocked region makes the material flow to bend towards or away from the laser beam with concave or convex curvatures, depending on the plastically deformed layer under different laser power density and the specimen thickness (Hu et al., 2010). Large or complex curvatures can be generated by controlling the distribution of laser shocks.

3. Experiments

3.1. Material preparation

FMLs are a family of laminates by alternating layers of thin metal sheets and thin composite layers. Glass laminate aluminum reinforced epoxy (GLARE), the best-known member of these laminates, consists of glass fibre reinforced pregregs and high strength aluminum alloy sheets. GLARE laminates have been commercialized to be used in the main fuselage skin and the leading edges of the horizontal and vertical tail planes of new, high capacity Airbus A380 (Sinmazçelik et al., 2011).

GLARE laminates with different prepreg orientations are prepared with the standard bonding technology for LPF experiments. They are consisted of three aluminum alloy 2024-T3 layers with the nominal thickness of each layer about 0.30 mm and two intermediate layers of the glass fibre prepreg with the thickness of each layer about 0.30 mm. As shown in Fig. 2(a), the composite laminate of GLARE 2 has the unidirectional fibres aligned with the rolling direction of aluminum alloy, while GLARE 3 as shown in Fig. 2(b), has a cross-ply fibre layer stacked to the nearest outer aluminum layer, in relation to the rolling direction of the aluminum. Mechanical properties for two composite laminates under quasi-static conditions are list in Table 1.

In order to investigate the effect of fibre orientations on the development of bending deformation, strip samples with dimensions of 70 mm × 15 mm were machined from the prepared GLARE