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Development of a local three-dimensional numerical simulation model for the laser forming process of aluminium components

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ABSTRACT

The laser beam forming (LBF) process uses the energy of relatively high-powered lasers to cause permanent deformations of components, through the local introduction of thermal stresses. LBF of aluminium material is a process, complex and sensitive, due to the complicated physical phenomena taking place during laser processing. Therefore, definition of optimal process parameters, such as laser power and processing velocity, which will result to desired bending patterns, as well as investigation of forming limits of various components require significant experimental effort. Herein, numerical simulation of LBF process is used to provide partial solution to the problem, by developing a local Finite Element simulation model, capable to predict temperature fields and deformation shapes of laser beam-treated aluminium specimens. The numerical algorithm is based on a non-linear three-dimensional transient thermal–structural analysis, temperature-dependent thermal and mechanical material properties and a laser beam heat flux model. The developed model is validated through the comparison of numerically predicted distribution of temperatures and bending angles to corresponding experimental data of single and multiple laser beam passes. The validated model is then used to define optimal process parameters for the laser forming process of aluminium panels.

1. Introduction

Laser forming recently emerged as a new shaping technique that offers excellent reproducibility, low manufacturing time and cost, as well as, relatively low thermal influence on the material mechanical properties. For those reasons, laser forming is a promising technique with several potential applications in the automobile, shipbuilding and in particular aerospace industry, where the demand to form integrally stiffened structures is high. In comparison to conventional forming technologies, LBF provides the potential for many technological advantages, especially in cases of forming complex or semi-assembled structures of various thicknesses and material types, as well as in rapid prototyping applications.

Although the traditional application of laser forming has been to various steel materials, laser forming process of certain types of aluminium alloys has been recently the object of considerable attention in the aerospace industry. However, the low thickness of formed parts, the elevated laser beam light reflection and the high heat conduction of aluminium alloys are some of the main reasons, which make the use of laser

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forming process more difficult and complex, as compared to its application to steel forming.

During laser forming, the irradiated material is formed under the action of local plastic strains induced by laser heating of the material, instead of the action of mechanical forces and moments applied by the common sheet bending techniques. The local nature of laser irradiation yields high temperature gradients between the irradiated surface and the neighboring material. The high temperature gradients, force the material to expand non-uniformly, which results in irregular thermal expansion between the target and lower surface. As a result the specimen initially bends negatively, as viewed from the laser beam. The non-uniform expansion of the material leads to non-uniform thermal stresses, which result to plastic deformation at locations where thermal stresses exceed the material's yield point. During cooling, the upper material layers shrink more than the bottom, resulting in permanent specimen bending towards the laser beam.

From the above short description, it is obvious that the laser forming process comprises many simultaneous physical mechanisms and is affected by several process and material parameters. The most important parameters are the laser scanning path, the heating conditions including laser power and type, the scanning velocity, the material thermal parameters emissivity and conductivity, as well as, the material coefficient of thermal expansion.

The laser forming technique has been extensively investigated during the recent years. Numerical and experimental investigations have been carried out to better comprehend the mechanisms and the effects of the control parameters on, for example, bending angle and mechanical behaviour. Most of the investigations are mainly limited to steel applications, e.g. Thomson and Pridham (1998), Kyrsanidi et al. (2000), Hennige (2000), Cheng and Lin (2001), Hu et al. (2002), Shichun and Zhong (2002), Zhang et al. (2004), Zhang and Michaleris (2004), Chen et al. (2004) and Hsieh and Lin (2004). More specifically in Thomson and Pridham (1998), Hennige (2000) and Chen et al. (2004) deal with process development, process parametric investigations and optimization, in Kyrsanidi et al. (2000) and Cheng and Lin (2001) refer to simplified analytical solutions, while Zhang and Michaleris (2004) focuses to the comparison of Eulerian and Lagrangian approaches to LBF problem. In Hu et al. (2002), Shichun and Zhong (2002), Zhang et al. (2004) and Hsieh and Lin (2004) different thermo-mechanical simulations are presented, which have some similarities to the presently developed model. However apart from the difference in investigated target material, which is steel in Hu et al. (2002), Shichun and Zhong (2002), Zhang et al. (2004) and Hsieh and Lin (2004), other key differences also exist; in Hu et al. (2002) the investigated sheet forming mechanism is buckling and not bending; in Shichun and Zhong (2002) mechanical results are presented, based on a handling technique for the transitional zone lying between the elastic and plastic material regions; in Zhang et al. (2004) the focus is placed on the definition of minimum discretization requirements of LBF Finite Element models; in Hsieh and Lin (2004) the laser source comprises a single pulse and not a continuous heat source scanning the metal sheet.

Existing investigations referring to aluminium alloys are still small in number (i.e., Chan and Liang, 2000; Merklein et al., 2001; Hu et al., 2001; Geiger et al., 2004; Welsink, 2005). In Chan and Liang (2000), Merklein et al. (2001) and Welsink (2005), experimental investigations concerning bending angle as a function of the laser parameters, as well as, effects on material microstructure are presented. In Hu et al. (2001) experimental investigation and limited Finite Element simulations concerning temperature distribution and bending angle during laser beam forming process of steels and a non-specified aluminium alloy were presented. In Geiger et al. (2004) only thermal FE simulations are performed for investigation of the temperature distribution through the thickness of aluminium alloy sheets for automotive applications.

In the present investigation a local three-dimensional Finite Element model for simulation of the laser forming process of aluminium parts is developed. Non-linear thermal and mechanical analyses are consequently performed, using temperature-dependent thermal and mechanical material properties. The laser beam is modelled as a step-wise moving heat source with Gaussian distribution of heat flux, as proposed in Hu et al. (2002). The simulation model predictions for different laser beam forming conditions (power and speed), material types, specimen thickness and number of passes (multiple passes) are compared to the corresponding experimental results of Welsink (2005). Both results correlate well, indicating the capability of the developed model in the successful prediction of the transient temperature distribution and the resulting bending angle. Consequently, the model applicability is demonstrated through the prediction of the optimal forming parameters, i.e. laser power and speed for two types of aluminium material panels and three different thicknesses.

2. Description of the numerical simulation model development

2.1. *Overview of the simulation approach*

The experimental set-up of a typical laser forming process is presented in Fig. 1. Fixation plates are used to prevent twisting of the specimen during the forming process. The specimen is placed directly on ceramic strokes to prevent the warmth

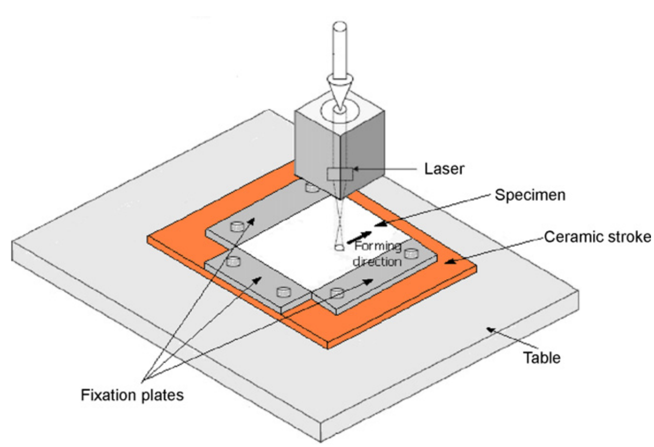

Fig. 1 – Overview of Laser Beam Forming experimental set-up.