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Characterization of strain rate effects in sheet laser forming

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ABSTRACT

This work presents numerical simulations and experimental validation of sheet laser forming processes using a single-step straight path with different laser beam powers (four levels ranging from 30 W to 120 W) and scanning speeds (four levels ranging from 5 mm/s to 20 mm/s) in graphite-coated AISI 304 stainless steel 0.6-mm-thick sheets. The numerical simulations of these cases are performed via a coupled thermomechanical finite element formulation accounting for large strains, temperature-dependent material properties and convection–radiation phenomena. Firstly, a rate-independent plastic model is used. Although this model adequately predicts the final bending angle for the cases achieving relatively low maximum temperatures, i.e. cases with low laser beam powers and high scanning speeds, it fails in describing the deformation pattern for the cases with higher maximum temperatures, i.e. cases with high laser beam powers and low scanning speeds. Secondly, in order to overcome this drawback, a rate-dependent viscoplastic model including a stress-dependent viscosity law is proposed to simulate the same cases. The final bending angles provided by this model are found to be in good agreement with the experimental measurements for the whole ranges of laser beam power and scanning speed studied in this work. Therefore, the use of this viscoplastic model in the simulation of sheet laser forming allows us to conclude that the strain rate effects, which mainly play a relevant role at high temperatures, can be adequately characterized.

1. Introduction

Laser forming is a flexible and particularly suitable manufacturing technique for low-volume production and/or rapid prototyping of sheet metal components in which either forming tools or external forces are not needed [1–5]. This process allows the bending of the work piece through the development of thermomechanical strains generated by the heating of a laser beam with a given power and scanning speed. The formation of a high thermal gradient along the plate thickness is the most appropriate condition to achieve controllable bending angles. This is the so-called thermal gradient mechanism that typically occurs where the ratio between the diameter of the laser beam and the plate thickness is relatively small [6–8]. In the heating phase, once the stress exceeds the material yield strength, plastic deformations occur under a compressive

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stress field due to the fact that the heated region is restricted to expand by the surrounding material that is at a lower temperature. In the cooling stage, the work piece shrinks on the heated surface under tensile stresses which make the plate bend toward the laser beam. In this way, the sheet laser forming method allows flexibility, that conventional methods cannot in general achieve, combined with a good dimensional accuracy level, thus attracting interest in sectors such as the aeronautics, nanotechnology and automotive industry [9–11]. Nevertheless, a strict control of all the operating variables, e.g., laser beam diameter, power and scanning speed, is needed in order to obtain the desired final shape.

Despite all the advances in the field, the accurate description of the thermomechanical material response during laser forming is a complex task that led in recent years to the use of finite element simulations focused on different aspects of the process: effects of operating variables on the deformation field [12–26], use of non-standard forming materials [27,28], influence of edge effects [29–33], multi-scan forming [34–38], and production of complex shapes using general heating paths [39–48]. In all these works, the rate-independent plasticity theory adopted to model the material behavior provided numerical results that reasonably fit the corresponding experimental measurements. Nevertheless, it has been recognized that this approach cannot accomplish a realistic prediction of the final bending angle when the peak temperature is high compared to the melting temperature of the forming material such as those measured in cases with high-laser-beam powers and low scanning speeds [48,49] or, more precisely, in cases with high values of line energy (LE) [6–8], defined as the ratio between the laser beam power P and the scanning speed V. In this situation, the strain rate effects on the flow stress and thus deformation become quite significant, even with moderate strain rate levels [49]. Within the context of plasticity, such effects were considered via an empirical-based flow stress relationship defined in terms of the equivalent strain rate and temperature with parameters determined through uniaxial tension and/or compression tests at certain temperatures [49]. Although the computed results with this last approach were consistent with the experimental observations, a more exhaustive assessment of strain rate effects for a wide range of operating variables is still needed.

This work presents an experimental and numerical analysis of a single-pass laser-forming process applied to graphite-coated thin 0.6-mm-thick AISI 304 stainless steel sheets aimed at characterizing strain rate effects when specific combinations of laser power and scanning speeds on a linear path are used. To this end, the proposed methodology described in Section 2 consists in two stages, respectively devoted to the realization of laser bending tests and the numerical simulation of this process carried out with a coupled thermomechanical finite element formulation accounting for large strains, temperature-dependent material properties and convection–radiation phenomena. In order to assess the influence of the strain rate on the thermomechanical material response, the numerical analysis is performed via two different models: firstly, a rate-independent plastic model and, secondly, a rate-dependent viscoplastic model including a stress-dependent viscosity law specifically defined in this study. The numerical results obtained with these two models are compared and discussed in Section 3. The viscoplastic simulations are found to provide a satisfactory experimental validation of the final bending angle for the whole ranges of laser beam power and scanning speed considered in this study. Finally, the concluding remarks are presented in Section 4.

2. Methods

2.1. Experimental procedure

Set-up

In the experimental forming tests, an optical Yb-doped fiber laser with maximum nominal power of 200 W was used. The laser wavelength has a spectral range near the infrared (1060–1080 nm). This equipment has its own digital system, where the needed operating parameters of the laser beam, such as the power energy and the power delivery option (i.e. continuous, discrete or by pulses), can be determined. It is composed of the laser equipment, the optical fiber, and the collimator from where the radiation comes out. To focus the laser beam, two biconvex lenses were mounted to obtain the desired beam diameter, which in this work was adopted as 1.2 mm. In this experimental configuration, the laser system was maintained fixed, while the different plates to be formed were mounted on a CNC table, as shown in Fig. 1a (see [48] for more details).

It is important to estimate the set-up energy losses in order to calculate the real power that enters the plate. The power loss in one lens was measured with a powermeter, resulting in an average of 9.92% for a wide range of different output powers. Thus, the total power loss was considered as approximately 20% for the present device.

Material

The material used corresponds to AISI 304 stainless steel plates, with a thickness of 0.6 mm and a chemical composition shown in Table 1. The temperature-dependent thermomechanical properties of this material are plotted in Fig. 2.

Studied cases

All the experimental forming tests were performed with rectangular samples of 75 mm in length and 60 mm in width, firmly clamped in one end in order to avoid warping of the sheet; see Fig. 1b. In order to increase the amount of laser energy absorbed by the sheet, all samples were coated with a graphite layer [50]. Four levels of both laser beam power (including the energy loss) and scanning speed were considered in the tests, resulting in a total of 16 different cases obtained by a combination of power and scanning speed values labeled as: $P_1 = 30$ W, $P_2 = 60$ W, $P_3 = 90$ W, $P_4 = 120$ W,

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