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Technical Paper

The state of residual stresses in the Cu/Steel bonded laminates after ISF deformation: An experimental analysis

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ABSTRACT

Incremental Sheet Forming (ISF) is a novel sheet forming process. Being characterized by severe deformation, the process is likely to induce high residual stresses in the sheet metal components. These stresses in turn can affect the lifetime and integrity of the components. The present study, therefore, systematically analyzes the state of in-plane residual stresses as the function of technological parameters. The Cu/Steel bonded laminates are deformed and the hole drill tests are performed to determine the residual stresses in the laminates. The results show that the in-plane principal residual stresses are compressive in nature. Further, their magnitude decreases from one end to the other end of thickness section (i.e., from contact surface to non-contact surface). The in-plane maximum residual shear stress is found to be a way smaller than either of the in-plane principal residual stresses. The Analysis of Variance is performed to identify the role of technological parameters on the state of residual stresses. It is found that the tool diameter and wall angle are the most influential parameters while the rotation is the least influential parameter in this regard. The detailed analysis of response surfaces reveal that the combination of low diameter, high angle, middle step size, medium rotation, high feed rate and rolled condition of material (i.e., no annealing) promote the development of higher residual stresses. The relationship between the equivalent residual stress and the post-ISF yield stress shows that the former quantity is generally smaller than the latter one. Finally, empirical models are proposed to predict the state of in-plane principal residual stresses in the Cu/Steel components produced through the ISF process.

1. Introduction

Residual stresses are those that are retained in a structure or a body when external loads are removed. These can be categorized into macro- and micro- stresses. The former kind of residual stresses arise from the misfits in a material/body spanning over macroscopic or long distances [1]. Such residual stresses occur due to non-uniform plastic deformation and thermal gradients. The latter type of residual stresses, such as stresses due to phase transformations, originate when the misfit regions span over microscopic dimensions [1].

The residual stresses, if tensile in nature, combined with the service stresses can cause unexpected failure thus shortening the product life [2–4]. These, on the other hand, improve the fatigue life by lowering the mean stress when their nature is compressive [5,6]. Depending on their nature, the residual stresses can delay or accelerate the onset of plastic deformation [7]. These are also the source of geometrical inaccuracies in the plastically formed components [8]. Therefore, in order to overcome such issues and to benefit from the residual stresses, it is necessary to know their state.

Metal forming processes are known to induce residual stresses in the components. For example, stretching predominantly causes the tensile residual stresses while rolling and forging primarily induce the compressive residual stresses [9]. Incremental Sheet Forming (ISF) is a novel sheet forming process whereby a small-sized tool imposes deformation onto the sheet in a successive manner [10–13]. The deformation is restricted to the vicinity of tool/sheet contact zone. The forming tool, which is usually a round steel bar with spherical end, imposes bending, stretching and shear strains onto the sheet [14–18]. Owing to peculiar deformation characteristics, the ISF process extends the forming limits of sheet metals well beyond the classical forming limits [19]. The process has been reported to produce parts with reasonable accuracy [20]. However, it is economical for the small production runs

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Nomenclature

d	Tool diameter
θ	Wall angle
ω	Tool rotation
f	Feed rate
p	Step size
T	Annealing temperature
σ_1	In-plane principal residual stress in the tool travel direction
σ_2	In-plane principal residual stress in the transverse direction
c	Contact
nc	Non-contact
E	Elastic modulus
Y_s	Pre-ISF yield stress of material
Y'	Post-ISF yield stress of material
UTS	Ultimate tensile strength
K	Strength co-efficient
n	Hardening exponent
ΔL	Tensile elongation

[21]. The sustainability studies have shown that the process has good environmental performance [22]. To date, the ISF process has demonstrated numerous applications for the automobile and bio-medical sectors [23]. Further details and the latest achievements regarding the process have been reported in the review papers [20,24].

Similar to those by the other metal forming processes, the components produced through the ISF process also experience residual stresses. The first piece of work on the measurement of residual stresses in the incrementally formed (i.e., ISFed) parts was carried out by Tanaka et al. [25]. They performed Finite Element Analysis to quantify the effect of process parameters on the residual stresses. Radu et al. [26] later conducted the hole-drill tests to analyze the role of parameters on the development of residual stresses in the Al-1050 sheet. However, discrepancy exists in the findings of the two studies. As an instance, according to Radu et al. [26], the stress magnitude reduces when the tool diameter increases while Tanaka et al. [25] claim the opposite. The nature of residual stresses, however, in both of the studies has been shown to vary between compression and tension across the thickness section of specimen. Radu et al. [27] extended research on the residual stresses by establishing the cause and effect relationship for the dimensional accuracy. It was found that the geometrical error in the ISFed parts generally reduces as the magnitude of surface residual stresses decreases. Singh et al. [28] determined the surface residual stresses in the components produced by deformation machining, the mix of thin wall machining and ISF processes. Overall, the stresses were found to be compressive in nature contrary to the tension-compression in ISF.

The latest study on the residual stresses in ISF was performed by Jiménez et al. [29]. The test geometry with wall angle continuously varying along the depth was employed. The stresses were measured on the inner and outer surfaces through X-ray diffraction method. The results endorsed the previous finding that the stress nature varies from compression to tension due to bending. Moreover, the bending stress was observed to have role on the development of residual stresses and crack appearance on the outer surface of Al-6061 sheet parts. It was also identified that the driving force for grain boundary migration was of the order of magnitude of residual stresses.

The above studies provide the important fundamental knowledge on the state of residual stresses in ISF. However, the ranges of parameters opted were relatively narrow. Furthermore, the combined effects of parameters on the residual stresses were not investigated. The annealing condition of a material affects the flow stress, which in turn can affect the residual stresses during the forming process. Therefore, the role of this parameter on the development of residual stresses also needs to be examined.

Nowadays, the applications of multi-layered sheet metals (called clad sheets or bonded laminates) are increasing as these offer superior combination of properties than the constituting monolithic sheets. These bonded laminates are believed to exhibit complex deformation behavior as compared to their constituents [30,31]. The previous studies on ISF have mainly focused on the residual stresses in the monolithic sheet metals. Therefore, there is a need to explore the state of residual stresses in the bonded laminates taking the aforementioned gaps related points into account.

The objective of the present work is to determine the state of residual stresses in the bonded laminates. Having wide applications in the automobile and nuclear industries [32], the Cu/Steel bonded laminates are employed as the experimental material. The Design of Experiment (DoE) approach is employed to analyze the state of residual stresses in the ISFed laminates. A number of technological parameters (i.e., 6) are varied over wide ranges and parameter-stress correlations are developed.

2. Experiments

The DoE approach was adopted to analyze the effect of ISF processing on the residual stresses in the Cu/Steel bonded laminates. A detailed experimental plan was formulated following the Response Surface Method (RSM) [33]. The RSM is a collection of mathematical and statistical techniques for building empirical model. It explores relationships between several explanatory (input) variables and one or more response variables, through the following generalized mathematical form:

$$Y = f(X_1, X_2, X_3-, X_n) + E \quad (1)$$

where X_i is the input variable (process parameter), E is the error due to noise and Y is the response.

Another objective of RSM is to optimize a response (output variable) being affected by a number of input variables. The RSM offers three main designs including Central Composite Design, Box Behnken Design and D-Optimal Design. The D-Optimal is a computer-generated design built up from a random starting point [33]. This procedure allows the design to be flexible to include additional constraints, be designed for custom models including block effects and afford more control to the number of runs. This design can be built with the continuous, discrete (numeric but limited to specific levels) and categorical factors. Optimal design provides flexibility in selecting the candidate points, and further it varies each input factor over 5 levels [33]. Therefore, this design was opted for the present investigation.

Six technological parameters were chosen as the input variables of D-Optimal Design. The parameters with their respective low/high levels are shown in Table 1. These include tool diameter (d), wall angle (θ), rotation (ω), feed rate (f), annealing temperature (T) and step size (p). The reader is referred to the literature for their definitions [20,24]. As can be seen from Table 1, the parameters in the current study were varied wider ranges as compared to those employed in the previous experimental study on the residual stresses in a monolithic sheet [14]. Moreover, the current list of parameters contains two additional parameters namely wall angle and annealing temperature.

The exercise of developing combinations of runs in the test plan was performed using the commercial package Design Expert DX10. The vertices, center of edges, constraint plane centroids, axial check