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FE modeling and simulation framework for the forming of hybrid metal-composites clinching joints

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ABSTRACT

A 3D elasto-plastic numerical modeling and simulation framework is proposed for the forming of hybrid metal-composites clinching processes. The framework is employed in the commercial finite element software ABAQUS. The proposed FE procedures are presented and discussed in detail. Then, an experimental-numerical validation example of a metal-composites hybrid clinching process is presented. The material pairing of PA6GF30 and EN AW 5754 is chosen for this purpose. Accordingly, a user-defined constitutive model is employed for the PA6GF30 sheet to represent the sophisticated constitutive behavior of composites in more realistic manner. A brief description of the model and the parameter identification is provided. For the EN AW 5754 material, the standard von Mises model is used. The simulation results presented show the applicability and accuracy of the modeling framework, which can serve as a tool to investigate and to improve the mechanical behavior of hybrid clinching joints.

1. General introduction

Recent demands in achieving highly optimized structural components are gaining a significant relevance in different engineering applications [1], especially in high-tech sectors such as the automotive, aerospace, and marine industries, among others. Within the specific case of the automotive industry, the advent of composites materials is promoting the replacement of traditionally employed metals with the aim of manufacturing highly optimized structural parts. Particularly, in terms of structural weight reduction, composites materials help to scale back carbon dioxide emissions and fuel consumption. This is the current trend in the conception of new car body constructions, where multi-material (hybrid) components are being gradually employed, see [1,2]. In this context, fiber reinforced polymer (FRP) composites and light metallic alloys represent an appealing class of work-piece materials for hybrid constructions. For example, in the Audi A6 space frame, components of aluminum and FRP are combined together, see [3]. However, to produce such hybrid constructions, the utilization of appropriate joining techniques represents a major challenge.

There exist various joining techniques in literature for hybrid joints between metal and composites workpieces. These techniques can be divided into three main groups: adhesive bonding, mechanical fastening, and welding [4]. Adhesive bonding employs the use of a chemical agent between the workpieces. Therefore, it relies on the formation of intermolecular forces between the workpieces and the agent adhesive itself for joint formation, see [4,5] and the references therein. In the last decade, the use of adhesive joining techniques has grown substantially due to the development of high-strength and tough adhesives [5]. However, adhesive joints are prone to environmental degradation from multiple factors such as temperature, moisture, and humidity [6]. Furthermore, disassembling of the bonded joints is always accompanied by damage. The high energy inputs of conventional welding techniques (e.g. shielded metal arc welding, gas tungsten arc welding, gas metal arc welding, etc.) result in material metallurgical mismatch [7]. Accordingly, it limits their use in hybrid joints, see [8]. However, new emerging joining techniques have been developed to overcome the problems and limitations related to the traditional existing joining techniques. Examples of these emerging techniques include friction lap welding [9], friction spot joining [10,11], ultrasonic welding [12], laser-assisted direct joining [13], infrared stacking [14], friction riveting [15], and injection joining [16], see [8,17,18] for further discussions. In mechanical joining techniques, the materials are bonded by using some physical methods [19]. In literature, there have been introduced different mechanical joining techniques such as mechanical fasteners (screws, bolts, and rivets, etc.), self-piercing riveting technique, forming based technique, thread-cutting screws, etc., see [19]. Originally, mechanical fastening was used to join metallic materials. However, now it can be employed successfully in the joining of

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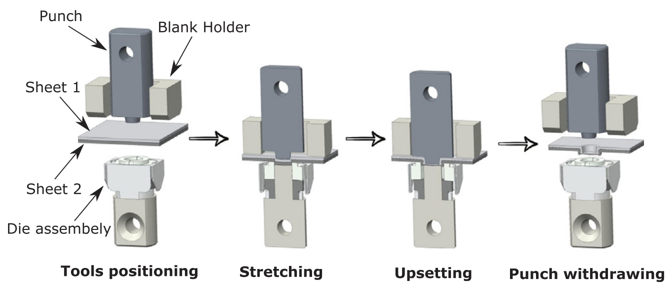

Fig. 1. Schematic description of clinching systems and process (after [40]).

metal-composites workpieces, see the reference therein.

In different innovative markets, the importance of forming-based mechanical joining processes is gaining a significant relevance. This is due to their low cost and ease of automation as compared to other joining techniques where pre-punching, surface treatment, drilling, or additional elements are required, see [21–24]. In lightweight constructions where a high production rate is required, clinching joining technology has demonstrated a promising future as a viable method to join hybrid metal-composites parts. Clinching, also known as press joining, is a high-speed, localized, mechanical fastening procedure of joining two or more sheet components by plastic deformation. The joining process system consists of a punch, a blank holder, and an especial die assembly. To form a clinching joint, the punch presses the forming sheets that are initially clamped between the blank holder and the die assembly to generate an interlocking friction between the sheet components, see Fig. 1.

To meet the current industrial demands, most of the current investigations have focused their interest on metal-metal clinching joining procedures [23]. Accordingly, a great deal of research has been done already on experimental and numerical investigations of this joining procedure, see [23–30] among many others. On the contrary, hybrid clinching procedures have received limited attention until now. The majority of the existing investigations has been devoted to experimental investigations and focused its intention on the joinability and feasibility of hybrid metal-composites sheets via clinching, see [17,31–34] and the references therein. For example, the feasibility of joining aluminum and Carbon Fiber Reinforced Polymer (CFRP) via clinching has been studied in [32]. In [34] a new type of clinching tool called a spring die has been proposed and designed to improve the joinability of CFRP and aluminum. In [33] the effectiveness of two-steps clinching for joining aluminum and CFRP composites has been investigated. Recently, the new friction assisted clinching technique has been performed and studied on aluminum and CFRP laminates, see [17].

In the design of mechanical structures which contain clinching joints, the characteristic information of these joints is very essential [35]. Based on this, in order to achieve a profound understanding of clinching joints, extensive investigations are needed. For example, the influence and effect of tool shape and process parameters on the clinching process for hybrid metal-composites workpieces have been investigated by many authors, see [15,36,37] among many others. However, considering that experimental tests are expensive and time-consuming, advanced and robust numerical modeling and simulation techniques are necessary. Not only to model the forming process but also to subsequently study and investigate the behavior of clinched joints and come up with equivalent simplified modeling techniques to fully exploit the advantages of this technology, see [48–51] among many others.

The rapid growth of the computational capacities motivates the building of sophisticated modeling frameworks which allow the simulation of a wide variety of complex engineering applications. Accordingly, in this paper, a numerical 3D elasto-plastic simulation framework for the forming of hybrid metal-composites clinching joints is presented. The necessity of a 3D framework was elaborated in [38], in consideration of the anisotropy of composites sheets. The hybrid clinching simulation framework is built in the commercial finite element software Abaqus. Accordingly, the proposed FE modeling and simulation procedures are described in detail. For validation purposes, an aluminum alloy sheet (EN AW 5754) and a semi-finished plate of short fiber reinforced polyamide (PA6GF30) are selected. This selection is made due to their common application in industry. Consequently, the geometrically non-linear anisotropic plasticity model developed in [38] and validated in [39] is employed in the co-rotational framework as a user-defined subroutine for PA6GF30. A brief description of the constitutive model and the parameter identification is outlined. The obtained numerical simulation results are discussed and validated against experimental data for clinching. Finally, the main conclusions of the current study along with the prospective future developments are detailed.

For the sake of transparency, this paper focuses on the FE modeling and simulation of the forming step in hybrid metal-composites clinching processes, employing a user-defined anisotropic pressure-dependent plasticity model for the composites sheet. The work conducted in [38,39] was devoted to the constitutive modeling and model validation, respectively. On the other hand, the work carried out in [40,41] discussed the material characterization and the experiential investigation of hybrid clinching processes. In [42], the FE analysis of hybrid clinching processes was presented using LS-DYNA. Therein, an isotropic constitutive model was used for the composites sheet.

2. FE simulation procedures

In this section, the FE modeling and simulation procedures are described in detail. Herein, the ABAQUS platform is used.

For computational simplicity and efficiency, the numerical investigations of metal-metal joining procedures are commonly performed using a 2D axisymmetric modeling technique, see [25–27] to quote few of them. Herein, a 3D FE modeling framework is proposed to account for the anisotropy of composites sheets, hence, the substantial change of preferential material direction (fibers orientation) which takes place throughout metal-composites clinching joining procedures, see [38,40,41]. However, the dimensional reduction of the framework from 3D to 2D can still be accomplished to serve as an approximation under certain circumstances, particularly with regard to the mechanical behavior of the composites sheets. Composites with very mild anisotropy i.e. composites with approximately uniform fiber orientation distribution, are a specific example of this case, see [42,43]. Fig. 2 shows a schematic 3D representation of the system for hybrid metal-composites clinching joints.

The pairing sheets are considered deformable, subsequently, the 8-node linear brick element type C3D8R for finite strains is employed in order to avoid convergence difficulties that may arise due to contact interactions. Reduced numerical integration (with hourglass control) is used to reduce the computational costs, and to prevent the well-known transverse shear locking effects in bending-dominant regions. Each sheets' geometry is discretized by an appropriate number of elements across the thickness. This helps to limit the artificial energy that is

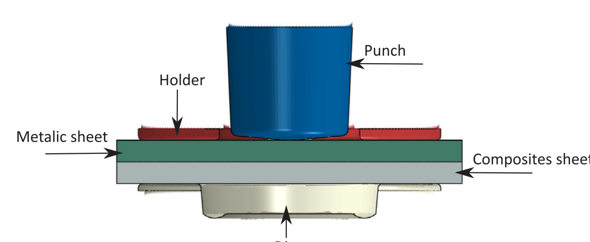

Fig. 2. Schematic 3D representation of the hybrid metal-composites clinching system.