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Material-based design of the extrusion of bimetallic tubes

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ABSTRACT

Using finite element and polycrystalline plasticity modeling, we explore the influence of die design and material behavior on the extrusion of bimetallic tubes. Three distinctly different extrusion designs are introduced and evaluated based on a range of macroscopic and microstructural criteria: die and punch stress, interface roughness, peak forming loads, and strain and crystallographic texture heterogeneities across the tube thickness. We find that an extrusion die design proposed here that differs from the conventional one is better for reduction of peak forming load satisfying objectives of the traditional design. However, when the design is more constrained and considerations of strain and microstructural heterogeneities and gradients are made part of the design criteria, we show that one die design promotes such gradients while the other minimizes them. In all three designs, large disparities in flow stress and hardening rate (>3 times) lead to larger interfacial strain gradients. These findings provide basic die designs that can be used to evaluate the degree and locations of strain and texture gradients across the tube thickness.

1. Introduction

Bimetallic tubes have proven to be an economical solution for achieving combinations of desirable mechanical properties, such as high strength and elongation, physical properties such as electrical conductivity and corrosion resistance, while at the same time reducing weight [1–3]. Examples of successfully tailored bimetal tubes include high strength and high electrical conductivity for use in heat exchangers and high strength and high corrosion resistance for mass transport [4]. Specifically, rather than replacing the entire tube material with a corrosion resistant material, which often is more expensive, the core tube material is kept and the protective material is bonded onto the outside and/or inside surfaces. In one example, composite aluminum-clad/copper (Al-clad/Cu) tubes offer 50% reduction in weight and increased corrosion resistance as compared to monolithic Cu tubes. In another example, for an equivalent electrical conductivity, the Al/Cu-clad tubes offer reduction in weight and 30–40% reduction in cost compared to Cu [5].

To form a bimetal tube, two initially separated metals must be bonded, either by diffusion or deformation. Rotary piercing [6], tube rolling [7], forward, backward and radial extrusions [8] are commonly used deformation techniques for manufacturing tubes. For large-scale production of bimetallic tubes in ambient conditions, deformation bonding via extrusion is the more attractive method among these techniques. In this case, tube shaping and bimetallic bonding can occur within the same extrusion step, provided that a sufficient amount of strain is imposed. Bimetal bonding via deformation techniques has been proven viable for not only fabricating bimetallic tubes of Cu and Al [9] but also for bimetallic wires [10], rods [5,11] and sheets [12,13] with substantial improvements in material properties that cannot be achieved from a single material.

In this work, we focus on optimizing the extrusion process for a bimetallic tube comprised of two concentric dissimilar metals. The standard die is shown in Fig. 1 [14]. The two metals are placed in the desired order, with the outer *sleeve* metal placed outside of the inner *core* metal. Together, they are pushed over an internal mandrel, so that they form a bimetal tube with a final inner diameter ID_f and final outer diameter OD_f and a single internal bimetal interface. The final thickness t_f is smaller than the initial t_i. The reduction in area r is determined by the starting ID_i and OD_i and die angle θ. As mentioned, the strains imparted by the extrusion need to be sufficiently high such that the sleeve and core metals bond by deformation.

To optimize the extrusion process, analytical and numerical models have proven instrumental [15,16]. The number of extrusion

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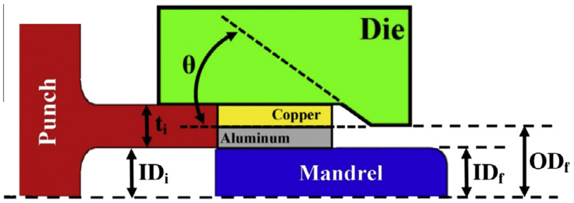

Fig. 1. Schematic of a typical bimetal tube extrusion setup (axisymmetric).

design variables is typically large, ranging from geometric features of the die, such as the reduction ratio r, die angle θ, and die channel profile, to material strength and hardening characteristics, and to the processing parameters, such as ram speed and friction. These effects are highly coupled with each other. For example, the material flow characteristics, final stress and strain distributions, and response of the die and punch during the extrusion are sensitive to the profile of the die channel [17–19]. Attempts have been made to optimize die profiles by evaluating conical, flat, streamlined, hyperbolic, or cosine profiles, and the hyperbolic profile was found to require minimum energy for extruding an alloy [19,20]. Subsequent to modeling, small-scale laboratory dies can be built for validation and testing. As an example, Fig. 2 shows a 3D schematic of the die targeted for construction at the University of New Hampshire (UNH). The main constraints for this design are a limit load of 250 kN and a strain component perpendicular to the interface of at least 0.6 to assure bonding.

In designing dies for bimetallic extrusion, the aim is typically to minimize peak forming loads and die stresses while ensuring a bond between the two metals. Additional aspects of importance, often not taken into account in modeling, are heterogeneity in stress and strain across the tube thickness, particularly at the die/metal surfaces and at the bimetal interface, and microstructural development of the two metals during the extrusion. The latter, microstructural (grain shape, dislocation density, etc.) and crystallographic texture evolution, controls the ability of the bimetal to plastically deform [9,21–24]. They are also largely a consequence of the details of the extrusion process [25–27]. Many performance metrics for a pressurized tube in service, such as the strength, conductivity, corrosion resistance, strongly depend on its microstructure and texture [28]. Thus employing a material-based design strategies [29–38] for optimizing bimetallic tube extrusions is desirable.

Using a suite of material-based design criteria, we present and numerically examine three distinct die designs for bimetal tube extrusion. Towards this end, we use finite element (FE) based models in order to reveal the effect of die channel shape on heterogeneity in stress, strain, and microstructure across the tube thickness. Specifically to assess the influence on system-level stress and strain distributions that develop during the extrusion, we use a conventional FE model with a J2 plasticity constitutive law coupled to isotropic hardening. We will term this approach FE-PL. However to examine the development of local gradients in texture and plasticity anisotropy, the FE-PL approach cannot be used. Instead, we employ a recently developed finite element visco-plastic self-consistent (FE-VPSC) method [39–42]. FE-VPSC couples the spatially resolved stress and strain fields of FE with the polycrystalline plasticity based constitutive law of VPSC [43] that takes texture as input and captures texture evolution as a

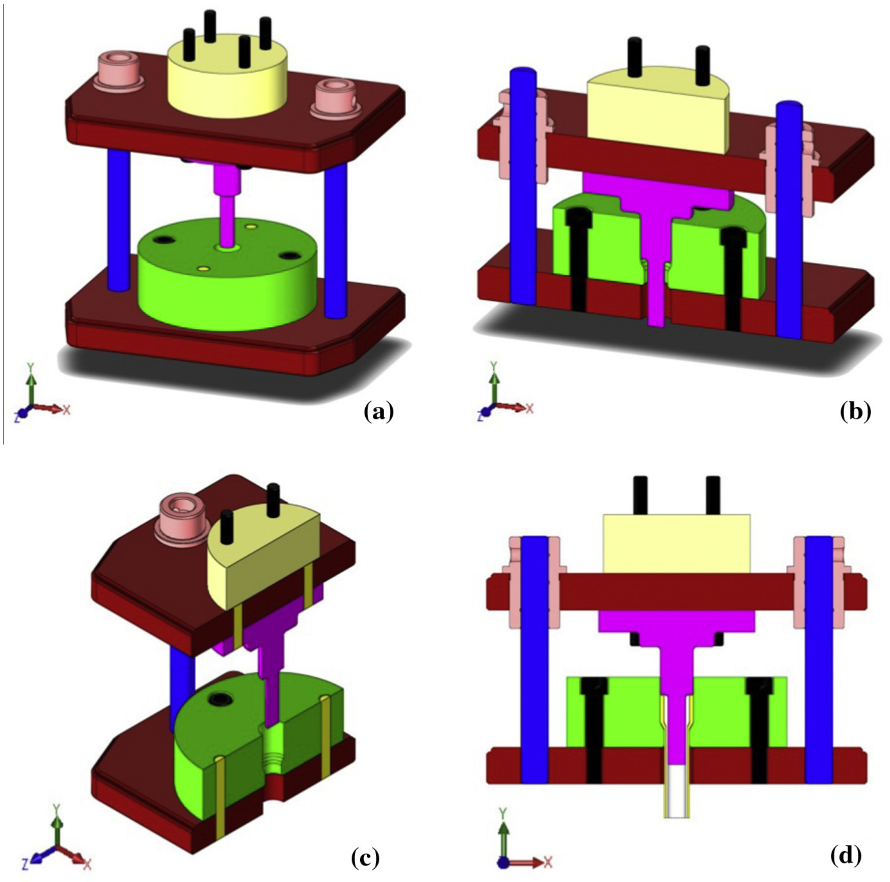

Fig. 2. UNH die design for manufacturing tubes with dissimilar materials (a) trimetric view, (b) trimetric x–y view cut, (c) isometric y–z view cut, and (d) front view cut shoving the bimetallic tube.