ADVANCES IN MATERIALS SCIENCE, Vol. 23, No. 4 (78), December 2023

DOI: 10.2478/adms-2023-0021

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NUMERICAL AND EXPERIMENTAL ANALYSIS OF THE FORGING OF A BIMETALLIC CROSSHEAD

ABSTRACT

The automobile sector has been making increasing efforts to reduce the weight of automobiles, aiming at mitigating pollutant gas emissions. The use of innovative concepts, such as bimetallic components, has become attractive because it makes it possible to increase the strength-to-weight ratio of the components. In this study, the hot forging of a bimetallic crosshead is investigated. In the process, a billet with a cylindrical core of the magnesium alloy AZ61 is enclosed with a hollow cylinder of the aluminum alloy AA 6351 and forged at 400°C. The objective is to reconcile the low density of Mg alloys with the high corrosion resistance of Al alloys. In parallel, a finite element analysis of the process was carried out.

Keywords: *finite element analysis; bimetallic; crosshead*

INTRODUCTION

The automotive industry has been making increasing efforts to mitigate the emissions of pollutant gases. Developments have focused particularly on reducing the weight of vehicles while maintaining other properties. In this context, the use of lightweight alloy components emerges as an advantageous alternative.

Magnesium alloys are strong candidates for achieving the goal of vehicle mass reduction. Magnesium is 36% lighter than aluminum and 78% lighter than iron [1]. However, the lower mechanical strength and low corrosion resistance of magnesium alloys compared to aluminum alloys limit their use [2].

The potential weight reduction can be optimized through the use of innovative concepts, such as composite materials that combine two or more materials. This results in customized characteristics, accentuating the positive properties of the materials and mitigating the negative ones [3]. Through this approach, the low density of magnesium can be reconciled with the high corrosion resistance of aluminum alloys.

Several authors have investigated the manufacturing of different material combinations [4-8]. WANG et al. (2022) studied hot forging of bimetallic gears using aluminum (AA6082) and steel (E355). They found that achieving optimized interface strength for bonding

Received 14 August 2023; Received in revised form 14 October 2023; Accepted 20 October 2023

technology involves balancing interdiffusion and oxide fracture [9]. POLITIS et al. (2012) examined forging to produce a straight bimetallic gear of steel and aluminum. They revealed that the geometries of the two metals used impact the quality of forged bimetallic gears [10].

For forming processes, bimetallic materials composed of Magnesium and Aluminum (Mg-Al) have exhibited potential applications due to their good formability compared to other material combinations [11]. MONDAL et al. (2021) employed friction-assisted forging to shape a bimetallic ring. The study utilized a cylindrical core of magnesium AZ31 covered with an aluminum 6061-T6 tube. In this proposed process, forging is conducted by a rotating tool. Friction-generated heat produces a solid-state bond between materials, eliminating the need for additional external heating [12]. SZOTAO et al. (2019) used numerical modeling to develop a novel bimetallic forging method for door handle components, featuring an AZ31 core coated with grade 1050A aluminum. The authors reported that coating integrity relies on die geometry and forging parameters [13]. FEUERHACK (2013) investigated closed-die forging of Al-Mg core bosses. It was demonstrated that the interface remains intact under predominant compressive stresses, while interface fracture is linked to shear stresses in the region [14].

To ensure good formability, processing must be performed at elevated temperatures since the hexagonal close-packed crystal structure of Magnesium restricts the movement of dislocations, limiting cold forming [15]. In addition to enhancing formability, heating also promotes diffusion, resulting in the formation of intermetallic compounds that ensure the bonding between materials. Consequently, the microstructure and properties of these compounds depend on processing conditions [16-18].

Research related to bimetallic forging has primarily focused on closed-die forging [3] with relatively simple geometries [19] and axisymmetric parts [14,20]. Shaping complex forms in processes with complex material flow is still a gap in the available literature. Therefore, this study aims to investigate the process of isothermal radial extrusion of a Mg/Al bimetallic crosshead. The Finite Element Method is employed to establish kinematic relationships between the materials comprising the bimetallic crosshead. Experimental forging of the bimetallic crosshead is used to validate the numerical results and assess the FEM as a tool for bimetallic design optimization.

MATERIALS AND METHODS

In this study, a bimetallic crosshead is produced using the isothermal radial extrusion process. The process principle and geometric parameters employed in this work are depicted in Figure 1. The billet is forced downwards by the punch against the stationary lower die and counterpunch, thereby radially extruding it into the die cavity. Figure 1 illustrates the initial (left side) and final (right side) position of the punch in the process, while the material flow direction is perpendicular to the punch movement.

The bimetallic crosshead comprises a core of AZ 61 magnesium alloy coated with a shell of AA 6351 aluminum alloy (Figure 2). The core and shell were assembled with an interference fit of 0.1mm using a manual hydraulic press. In the proposed radial extrusion, no flash formation occurs to achieve a near-net shape part. Hence, the dimensions of the bimetallic billet as shown in Figure 2, as well as the die design, are crucial to avoid overloads and tooling damage.

The chemical compositions of the materials were determined by spark emission optical spectrometry and are presented in Table 1. Both compositions fall within the specified nominal range in the literature.

Table 1. *Chemical composition of the crosshead materials (in weight %)*

Material	Al	Mg	Si	Mn	Ti	Zn	Cu	Fe
AA 6351	97.05	0.42	1.12	0.46	0.039	0.01	0.07	0.31
AZ 61	6.21	92.62	0.02	0.16	-	0.76	-	-

The bimetallic billet is assembled with forced adjustment in a manual hydraulic press with a capacity of 10t. After assembly, the crosshead is positioned in the tooling and both are heated in a Sanchis resistive furnace until complete temperature homogenization of the assembly at 400°C. Then, the assembly is quickly transferred to an EKA hydraulic press with a speed of 15mm/s and a capacity of 40t. Finally, the machine is activated, and the isothermal extrusion of the piece takes place, as the volume of the tools prevents heat transfer from the crosshead to the environment, maintaining a constant temperature throughout the process. Lubrication was performed by applying graphite-based lubricant to the surfaces of the dies.

The proposed process was numerically investigated using finite element analysis in the FORGE 3.0 software. Figure 3 depicts the three-dimensional model used in the simulation. Considering the rotational symmetry of the process components, only a portion of the geometry volumes was utilized in the modeling, reducing the number of generated elements and computational effort.

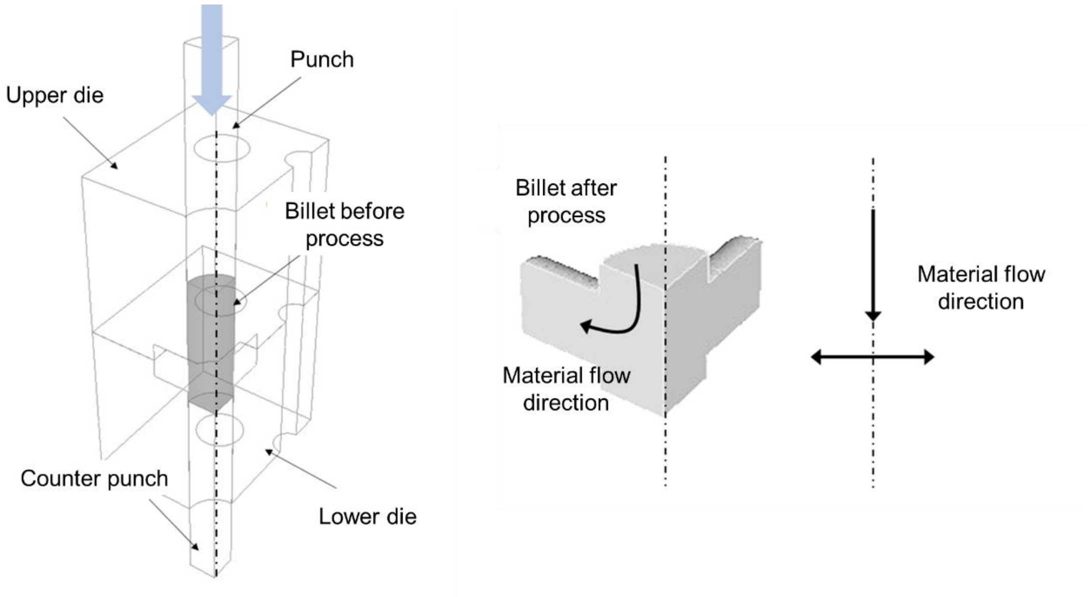

Fig. 1. Schematic drawing of the radial extrusion process of a crosshead

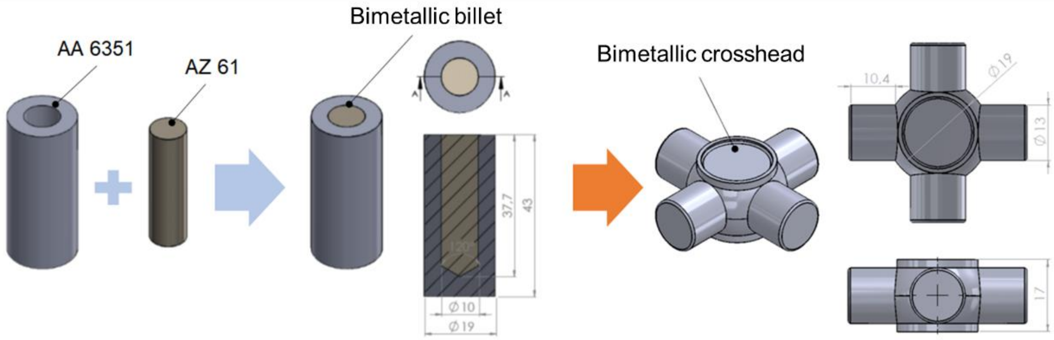

Fig. 2. Detailing of the generatrix and the final piece

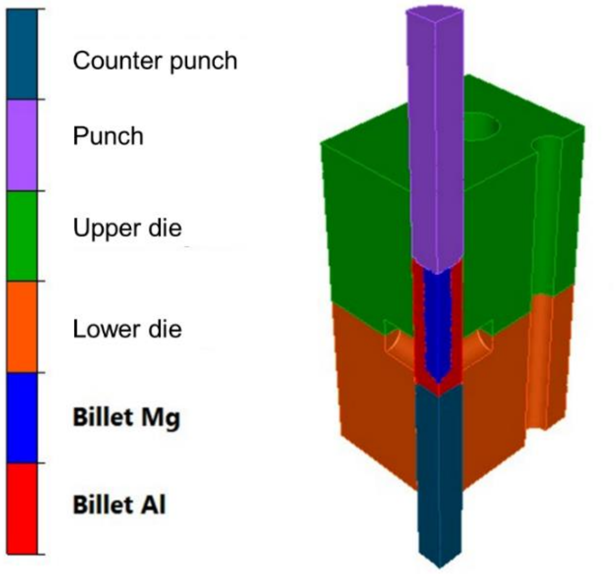

Fig. 3. Three-dimensional model of the radial extrusion process

In order to reduce computation time, elastoplastic material behavior was assigned only to the bimetallic blank, while the tools were considered rigid (non-deformable). The Hensel-Spittel model was employed to describe the mechanical behavior of the working materials. This model enables the calculation of the yield stress (k_f) based on the current strain (φ), strain rate ($\dot{\varphi}$), and forming temperature (ϑ). The model parameters for both materials of the blank (Table 2) were integrated into the software's library. Machine kinematic data were input into the model, and the maximum stroke was set at 10.1 mm. As the volume of the work material is equal to the volume of the tool cavity, the stroke value was defined using the law of constancy of volumes. The punch moves as necessary to completely fill the cavities and obtain the final geometry. Table 3 outlines the thermal, mechanical, and operational parameters utilized in the numerical simulation. Considering the complexity of the material flow and the small thickness of the Al coating, a preliminary study was carried out to define the best mesh configuration. First, a mesh size range capable of avoiding failures during simulation processing was defined. Next, mesh convergence was performed to refine the selection of mesh parameters.

Table 2. *Hensel-Spittel parameters for AZ 61 and AA 6351 alloys*

Parameter	AZ 61 [21]	AA 6351 [22]
A	88899.384	953.65542
m_1	0.002638	-0.00524
m_2	0.505723	-0.01407
m_3	-0.072545	0.10998
m_4	-0.000138	-0.00913
m_5	0.027881	0
m_6	0	0
m_7	4.382078	0
m_8	0.000596	0
m_9	-0.988923	0

Table 3. *Thermal, mechanical, and operational parameters used in the numerical simulation of the isothermal radial extrusion process*

Mesh Type	Triangular
Mesh Size	0.5 mm
Workpiece Material	AZ 61 AA 6351
Initial Workpiece Temperature	400°C
Initial Tool Temperature	400°C
Friction Coefficient	0.3
Tool Velocity	15 mm/s

RESULTS AND DISCUSSION

Figure 4 illustrates the forged piece during the extraction of the lower die and after extraction. The experiments demonstrate the suitability of the Al-Mg composite for radial extrusion under the analyzed condition. Macro and microscopic analyzes demonstrated that the final pieces did not present cracks or specific surface damage. This outcome aligns with those of FEUERHACK et al. (2013), who investigated the axial and radial strain of Al-Mg bimetallic core bosses [23].

The forming parameters did not lead to a metallurgical bond between the metals composing the bimetallic crosshead. However, the forged component exhibits rotational and axial interlocking due to metal flow. This interlocking results from the plastic strain of materials within the crosshead geometry.

The combination of the two materials employed in the forging process enabled a weight reduction of 15% compared to pieces exclusively forged from AA 6351 aluminum alloy. The bimetallic approach facilitated a lighter production while preserving the excellent corrosion protection properties of the aluminum alloy.

The comparison between experiments and simulations revealed a good correspondence of material flow. Figure 5 illustrates the comparison between the formed piece and the simulation result.

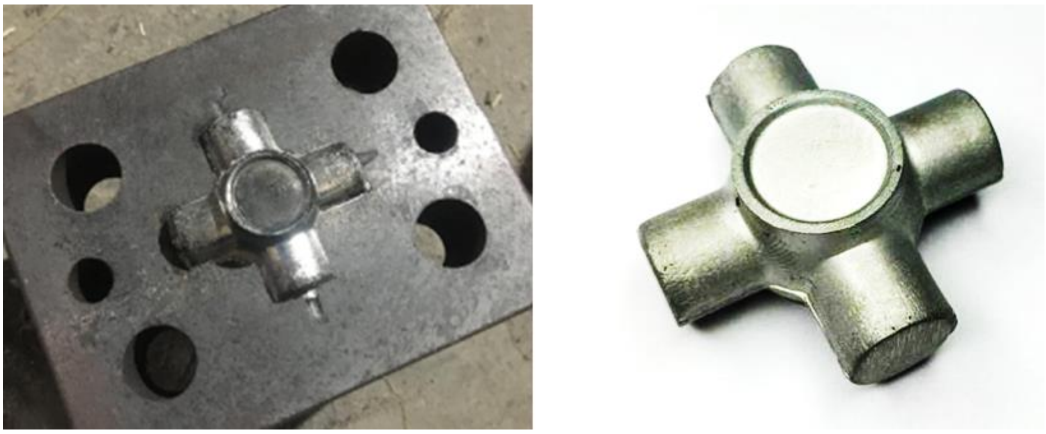

Fig. 4. Forged crosshead

Figure 6 illustrates various stages of the component during the forging process, from the initial undeformed geometry to the final piece (100% completion). During the action of the punch, the compression of the core material occurs, forcing the material to flow radially into the tool cavities. Initially, the thickness of the AA 6351 layer remains relatively uniform. After a punch advancement of 40%, the layer thickness varies significantly along the arms of the crosshead. During the formation of the arms, radial extrusion is restricted at the interface between the core and the lower die due to friction effects. This effect is exacerbated by the high contact stress generated by the unidirectional process. On the other hand, at the upper core-upper die interface, the contact stress is reduced, leading to a lesser friction effect.

This limitation to material flow at the bottom of the arms results in a reduction in the thickness of the aluminum alloy layer in this region. Conversely, a slight increase in the protective layer thickness is observed at the upper part of the crosshead arms. This asymmetric material flow occurred in all arms of the crosshead. Despite the fluctuation in aluminum shell thickness, it is noteworthy that the layer remained intact throughout the entire geometry, and magnesium is exposed only on the upper part of the piece.

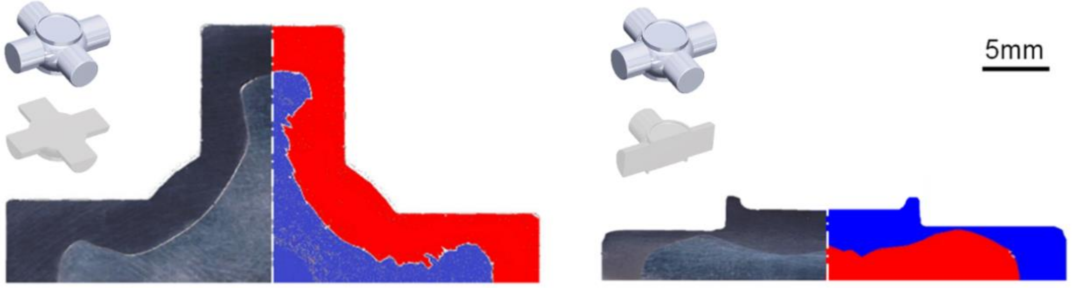

Fig. 5. Comparison between experimental material flow and numerical simulation

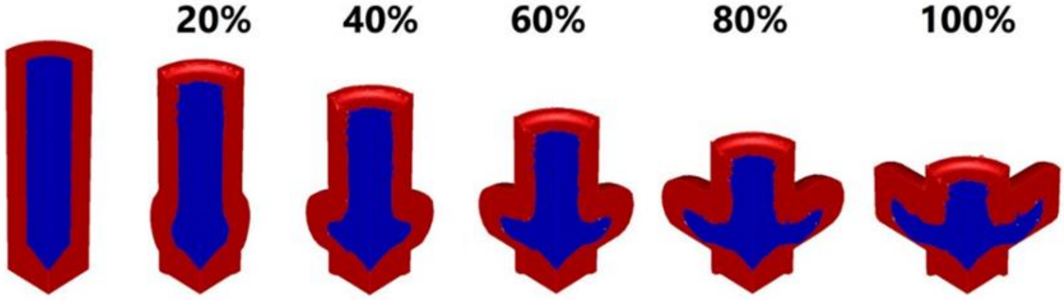

Fig. 6. Material flow during tool closure

In order to investigate the friction effect at the Al-Mg interface on material flow, simulations were conducted with friction coefficients of $\mu = 0.0$, 0.1, 0.2, and 0.3 between the core and cladding materials. The friction coefficients at the interfaces between the core and the tools were kept at 0.3 to eliminate their influence on the material flow, as reported by POLITIS et al. (2014). As emphasized by them, the interfacial friction between the core and the outer layer significantly affects material flow and the tendency for thickness reduction and shell fracture. Significant variations in the aluminum layer thickness were observed with the modification of the friction coefficient. The value of $\mu = 0.3$ yielded numerical results closer to reality in terms of material flow and was used for subsequent analyses.

The variation in shell thickness relative to the core material can serve as a criterion for assessing the quality of a formed bimetallic composite [24,25]. Figures 7 and 8 depict the calculated, experimental, and initial outer layer thickness variation at two points of the piece. Both numerical and experimental results exhibit good agreement, with a maximum deviation of only 13%. The maximum observed reduction in thickness compared to the initial thickness was 92%.

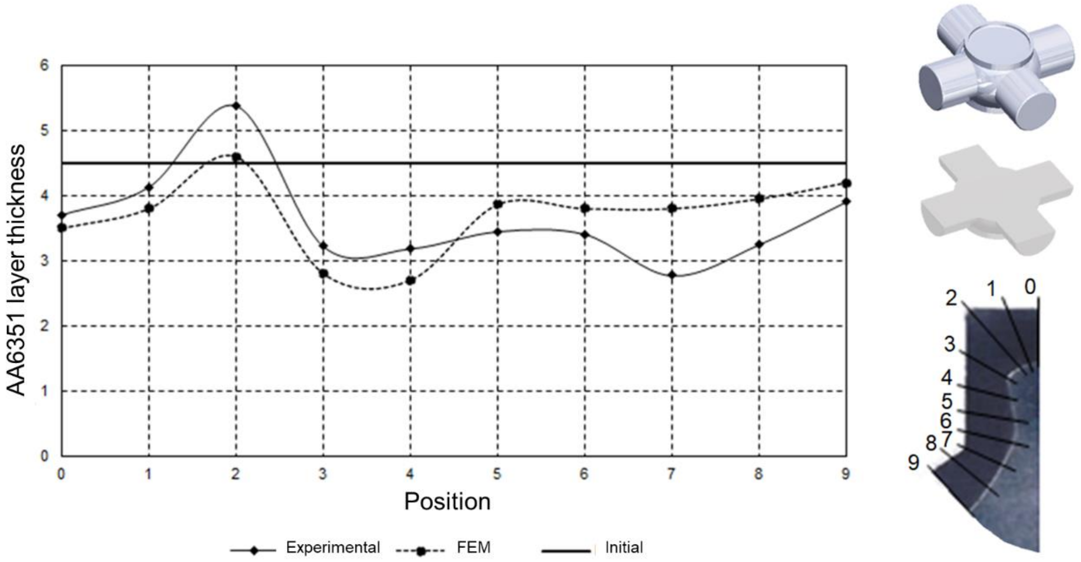

Fig. 7. Comparison of Calculated, Experimental, and Initial Thickness Variation in the XY Plane

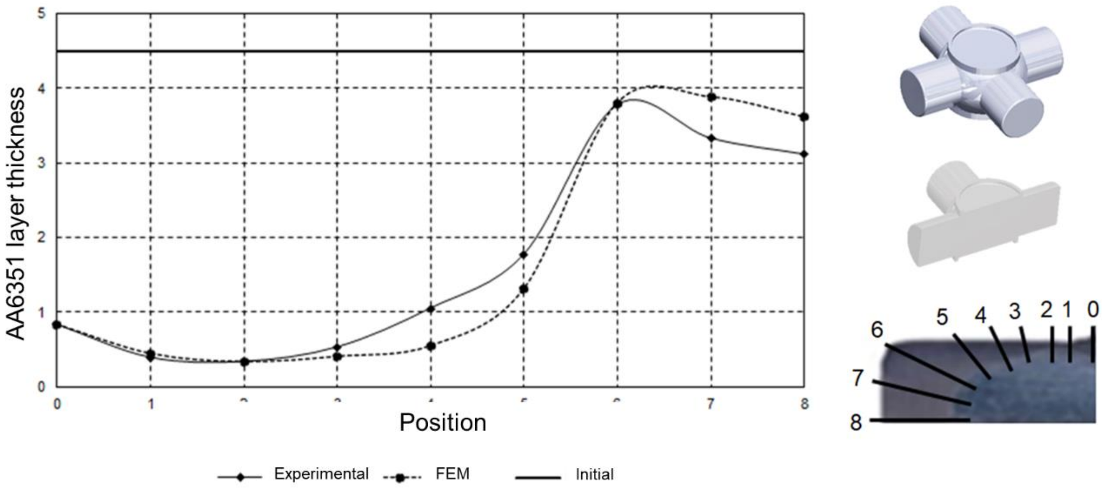

Fig. 8. Comparison of Calculated, Experimental, and Initial Thickness Variation in the XZ Plane

The heterogeneous material flow, which resulted in the alteration of the external aluminum layer thickness, is reflected in the strain distribution across the piece at the end of forming (Figure 9). The maximum strain value, near $\varphi=7$, is observed at the point where the aluminum layer thickness has the most significant reduction. The strain values of the magnesium core increase towards the end of the crosshead arm. This is attributed to the radial extrusion of the material to shape the arms of the piece.

The heterogeneous distribution of plastic strain is linked to the process kinetics. The movement of the mobile punch in relation to the stationary tools intensifies friction, leading to aluminum coating reduction. An alternative to achieving more uniform material flow could be employing a bidirectional forging process [26]. In this configuration, the counter punch isn't static but penetrates the die. This promotes a more even distribution of strain and velocity [27]. As a result, the tendency for the aluminum layer to remain intact and uniform is greater. Additionally, bidirectional forging also enables a reduction in required force for the process and induced stresses on the tools.

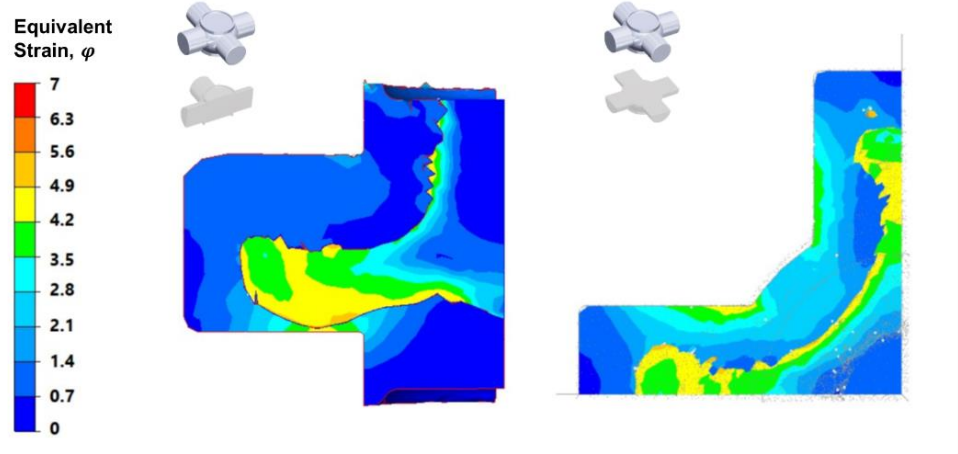

Fig. 9. Distribution of equivalent strain along the piece after forming

Figure 10 depicts the numerical result of temperature distribution in the component at the process's conclusion. Temperature values range between 452 and 455°C. This outcome underscores that the tool structure remained heated throughout forming, preventing heat loss from the core to the environment. The slight temperature increase observed results from the conversion of forming work into heat. During the forging process, a thermal camera mapped tool temperatures. The values observed on the external surfaces of the tools align with numerical results, confirming an isothermal strain process for the component.

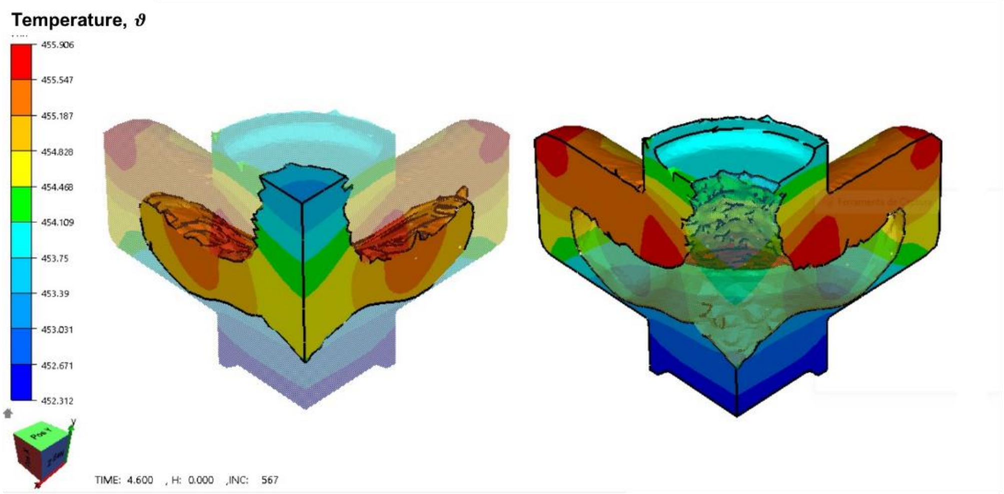

Fig. 10. Temperature distribution along the piece after forming

Figure 11 presents the evolution of the forming force as a function of punch displacement during the forging of the crosshead. At the beginning of the core compression, the force experiences a rapid increase up to approximately 5 kN. During the radial extrusion for the formation of the crosshead arms, the force remains practically unchanged. The force only experiences a drastic increase during the final filling of the piece's details. When the material reaches the die walls, the curve adopts an almost vertical behavior, reaching the maximum value of approximately 15 kN. Figure 11 overlays numerically obtained data via finite element analysis onto the experimental results. The numerical simulation shows high agreement with the experimental results, validating the numerical analyses conducted in this study.

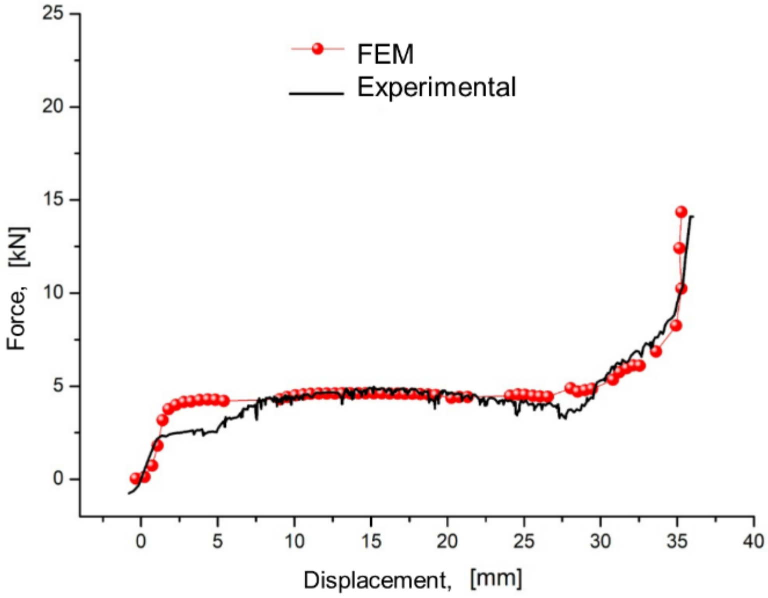

Fig. 11. Evolution of forming force as a function of punch displacement in the forging of a crosshead

CONCLUSIONS

This study aimed to investigate the isothermal forging of a bimetallic crosshead composed of a core made from AZ61 magnesium alloy and an outer layer from AA 6351 aluminum alloy. The numerical and experimental analyses of the process led to the following conclusions:

- Isothermal forging at 400°C ensures forgeability for the materials composing the bimetallic core. The crosshead obtained through radial forging is free from cracks or specific surface and internal damage.
- The friction coefficient between the core and the protective layer of the core during forming is $\mu=0.3$. This value significantly influences material flow during forging.
- The material flow during forging resulted in a substantial variation in shell thickness relative to the core material. The maximum observed reduction in thickness compared to the initial thickness was 92%. The distribution of the protective layer thickness in relation to the core can be used as a criterion to assess the quality of a formed bimetallic composite. Thus, adjustments to the process kinetics are necessary to reduce the observed shell thickness variation.

Overall, this study provides valuable insights into the isothermal forging of bimetallic crossheads, with implications for optimizing the process parameters to achieve desired product quality and material distribution.

ACKNOWLEDGEMENT

The authors thank CNPq, CAPES and FAPERGS for financial support (FAPERGS/CAPES 06/2018, process: 19/2551-0000710-8);(CNPq/ MCTI/FNDCT nº 18/2021, process: 404196/2021- 7);(CNPq research productivity – PQ1-4/2021; PDJ – 25/2021 150252/2022-6; GD – 2019);(CAPES (PROEX-IES-2020); and the Metalforming Laboratory (LdTM) for technical support.

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