Analysis of the influence of spinning temperature on the coordinated deformation of Mg/Al composite tube

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Abstract. Currently, the focus of research in the realm of Mg/Al layered metal composites predominantly lies within the domain of plate structures, while the development of Mg/Al bimetallic composite tubes (BCTs), which hold significant utility, remains in its nascent exploratory phase. Among the various forming methodologies applied to BCTs, the spinning process has garnered considerable attention due to its advantageous attributes encompassing minimal forming loads, uncomplicated tooling requirements, cost-effectiveness, and high dimensional precision. This study delves into the outcomes of forming Mg/Al BCTs at diverse spinning temperatures via a synergy of theoretical frameworks and simulation experiments facilitated by the Simufact Forming software platform. A novel approach is presented for assessing the degree of coordinated deformation at the interface by scrutinizing the interface strain gradient, elucidating the intrinsic correlation between the interface strain gradient and the bonding strength at the interface. Through meticulous analysis, it is discerned that the BCTs exhibit the least interface strain gradient and axial extension disparity when subjected to a spinning temperature of 350°C. Consequently, in the context of spinning preparation for Mg/Al BCTs, a spinning temperature of approximately 350°C is recommended to engender Mg/Al BCTs characterized by enhanced harmonized deformation properties.

Introduction

In response to the escalating demands for materials with enhanced comprehensive performance in modern production, single-metal materials have encountered limitations in meeting the requisite utilization prerequisites. Consequently, over the past few decades, researchers have increasingly turned their attention towards composite materials, leading to a proliferation of diverse composite materials and corresponding fabrication methodologies. One notable avenue within this landscape is Laminated Metal Composites (LMCs) [1]. LMCs represent a class of composite materials that are synthesized via various composite technologies, facilitating the establishment of robust metallurgical bonding at the interface between two or more metals possessing disparate physical, chemical, and mechanical properties [2]. By harnessing the potential of LMCs, it becomes feasible to amalgamate the exceptional attributes inherent to each constituent material, while simultaneously leveraging a "phase compensation effect" that enables the preservation of the distinctive characteristics of individual metal or alloy components[3]. Through judicious combinations, LMCs possess the capacity to compensate for inherent weaknesses and engender superior comprehensive performance.

Magnesium alloys have garnered significant utilization in a diverse range of industries such as aerospace, electronics, automotive, and high-speed rail due to their notable attributes including low density [4], high specific strength [5], and elevated stiffness [6]. However, owing to the inherent chemical reactivity of magnesium and its alloys, the formation of loose and porous oxide films when exposed to atmospheric conditions [7] restricts their application in corrosive environments. On the other hand, aluminum alloys possess good corrosion resistance attributed to the formation of a thin and compact oxide layer on their surface [8]. Consequently, the development of Mg/Al bimetallic composites presents an opportunity to expand the potential applications of Mg alloys while capitalizing on the excellent properties offered by both lightweight metals to compensate for their respective limitations, thereby offering a wide-ranging scope for practical implementation.

Due to the hexagonal close-packed (HCP) crystal structure of Mg and its alloys, only two slip systems can be activated at room temperature, leading to distinct plastic deformation characteristics compared to Al alloys [9]. This discrepancy poses challenges in achieving metallurgical bonding at the bimetallic interface through solid-state bonding methods. Therefore, thermal processing techniques, such as hot rolling, casting, annealing, and hot spinning, are commonly employed in the solid-state bonding of Mg/Al bimetallic composites. Currently, research on Mg/Al layered metal composites primarily focuses on sheet configurations (Al/Mg clad sheets), with the exploration of Mg/Al BCTs for broader applications still in the preliminary stages [10]. Numerous traditional material forming process can be employed in the fabrication of BCTs. For instance, Zhan et al. [11] investigated the bulging formation of square Mg/Al BCTs and observed that the bulging process only achieved mechanical bonding at the interface, lacking metallurgical bonding. Zhang et al. [12] explored the effect of interlayer chromium (Cr) on the bonding interface of composite cast Al/steel BCTs, revealing that the incorporation of interlayer Cr effectively impeded the formation of intermetallic compounds (IMCs) and enhanced the interface bonding strength. Notably, the spinning process offers distinct advantages such as low forming loads, simplicity in tooling requirements, cost-effectiveness, and excellent dimensional accuracy, thus finding extensive application in composite pipe fabrication [13,14]. As an example, Samandari et al. [15] successfully fabricated Al/St BCTs utilizing the spinning process. In the study of spinning processes for Mg/Al BCTs, Zheng et al. [16] identified that multi-pass spinning process significantly improved the surface quality of the composite tubes.

In the fabrication process of bimetallic composite materials, if the deformation of the two constituent materials is not synchronized, shear stress and tensile stress may arise at the interface. When these stresses exceed the shear strength of the interface, separation of the composite parts occurs. Hence, in order to mitigate excessive stresses and ensure proper coordination of deformations, appropriate processing parameters must be carefully chosen to harmonize the deformation of the two materials comprising the bimetallic composite pipe. Bambach et al.[17] suggested that similar flow stress between the two materials is essential during bimetallic rolling to facilitate coordinated deformation of the composite plate. However, the concept of coordinated deformation observed in rolling forming of composite plates does not directly apply to spinning process due to the asymmetrical distribution of rolls in the spinning process. In the context of bimetallic composite plates, where the rolling forces on the two plates are equal, achieving similar flow stress aids in coordinated material deformation. Nevertheless, this principle is not universally applicable beyond sheet rolling processes [18].In the spinning process, differing pressures are exerted on the inner and outer tubes, resulting in a lower radial stress on the inner tube. Consequently, when both tubes exhibit similar flow stress, their deformations become uncoordinated. Thus, the principle of similar flow stress, although conducive to coordinated material deformation in theory, is not suitable for spinning forming. Typically, the outer tube necessitates higher flow stress or the inner tube requires lower flow stress to ensure harmonized deformation of both tubes.

Drawing from the aforementioned concepts, this study employs finite element simulation experiments. The spinning simulation experiment is conducted on a composite tube comprising 7075 Al alloy and AZ31b Mg alloy within a temperature range of 300-400°C. Throughout the spinning process, variations in stress and strain at the interface of the inner and outer tubes are observed. These discrepancies evolve with temperature fluctuations, resulting in non-synchronized deformation at the interface, as evidenced by axial displacement of the two tubes. Analysis of the results indicates that maintaining an optimal spinning temperature of approximately 350°C for Mg/Al BCTs is crucial. This research serves as a foundational framework for the development of Mg/Al BCTs with tailored structural characteristics and performance attributes.

Finite element simulation setting and material parameter analysis

The spinning forming method is shown in Fig. 1, and the Mg/Al BCTs is assembled on a fixture equipped with a triangular chuck. During spinning, the triangular chuck drives the Mg/Al BCTs to rotate, and the mandrel also rotates. At the same time of rotation, the roller starts to feed radially from one end of the triangular chuck. When the preset thinning rate is reached, it begins to feed axially.

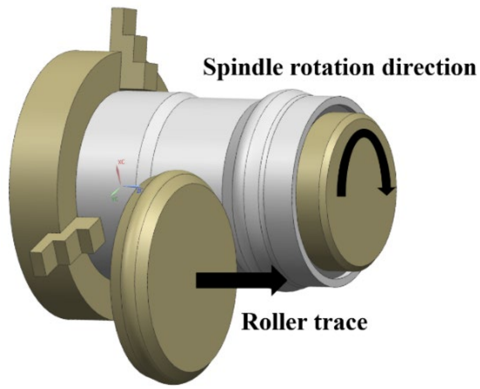

Fig. 1. Composite tubes spinning process diagram.

The mold model are imported into Simufact Forming finite element analysis software after modeling in NX10.0. Among them, 7075 Al alloy material uses the material model provided in the software, and the material parameters of AZ31b Mg alloy use the stress-strain curve studied by Zhang et al. [19], which is imported into the finite element software and simulated. The specific finite element simulation parameters are shown in Table 1.

Table 1. Finite element simulation setting.

The parameter name	The numerical
Spindle speed/ (r/min)	300
Roller feed ratio (mm/r)	3
Spinning temperature (℃)	300/325/350/375/400
Thickness of Al tube (mm)	6
Thickness of Mg tube (mm)	6
Tube length (mm)	150
Thinning rate (%)	30

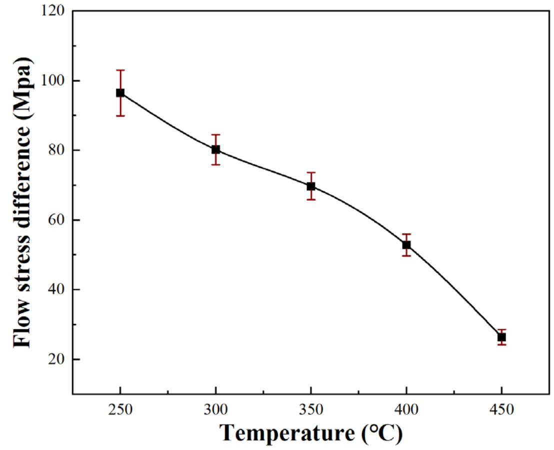

Fig. 2. The difference of flow stress at different temperatures.

In the spinning process employed in this study, the high-speed rotation of the spindle maintains the strain rate of the deformation zone of the composite tube material at approximately 20/s. Consequently, the primary factor influencing the material's flow stress during spinning is the forming temperature. An analysis of the average flow stress difference between Mg alloy and Al alloy within the temperature range of 250°C-450°C was conducted, with the results depicted in Fig. 2. The analysis reveals that the flow stress disparity between Mg alloy and Al alloy decreases as the spinning temperature increases. Specifically, the maximum difference is recorded at 96.5MPa at 250°C, while the minimum difference is observed at 26.45 MPa at 450°C. Contrary to composite rolling processes, in spinning process, the proximity of the flow stress values of the two materials does not necessarily yield optimal results. It is imperative to regulate the spinning temperature to maintain a specific stress difference between the inner and outer tubes, ensuring coordinated deformation. Therefore, a detailed analysis of the simulation results within the temperature range of 300°C-400°C is essential to ascertain the optimal spinning conditions for preserving deformation coordination.

Analysis of results
Axial displacement analysis of Mg/Al BCTs.

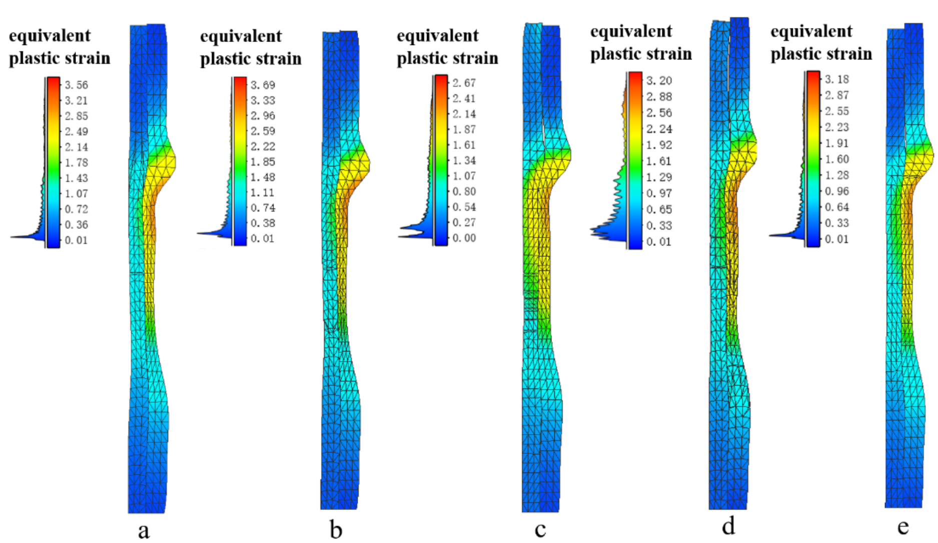

Fig. 3. Finite element simulation results at different temperatures (a) 300°C, (b) 325°C, (c) 350°C, (d) 375°C, (e) 400°C.

The finite element simulation outcomes are depicted in Fig. 3, which illustrates the equivalent strain cloud diagram of the spinning temperature range between 300°C and 400°C. The results indicate that the maximum equivalent strain value of the Mg/Al BCTs is 2.67 at a spinning temperature of 350°C, while it reaches 3.69 at 300°C.To better assess the coordinated deformation degree of the Mg/Al BCTs, this study adopts the axial displacement of the BCTs as a measure of the deformation level. In particular, the axial displacement difference between the Mg tube and the Al tube is utilized to characterize the coordinated deformation degree of the BCTs. The resulting outcome is displayed in Fig. 4.

Figure 4 illustrates that as the spinning temperature increases, the overall axial displacement of the Mg tube and Al tube demonstrates a decreasing trend. However, the axial displacement difference between the two tubes exhibits an initial decrease followed by an increase, resulting in an overall upward trend in displacement difference. Notably, at 350°C, the displacement difference becomes negative, reaching -0.51. This signifies that at 350°C, the axial elongation of the Mg tube surpasses that of the Al tube. Furthermore, it is evident from the figure that for spinning temperatures exceeding 350°C, the axial displacement difference between the two tubes exhibits a notable increasing trend. This can be attributed to the decreased deformation resistance of the Al tube and an associated increase in its plastic deformation ability as the processing temperature rises. Consequently, the axial displacement of the Al tube increases, leading to a larger axial displacement difference between the two tubes. Thus, the elevation of the spinning temperature does not promote improved deformation coordination in the Mg/Al BCTs. To gain further insights into this phenomenon, the radial equivalent stress distribution of the spinning simulation results at 350°C is analyzed.

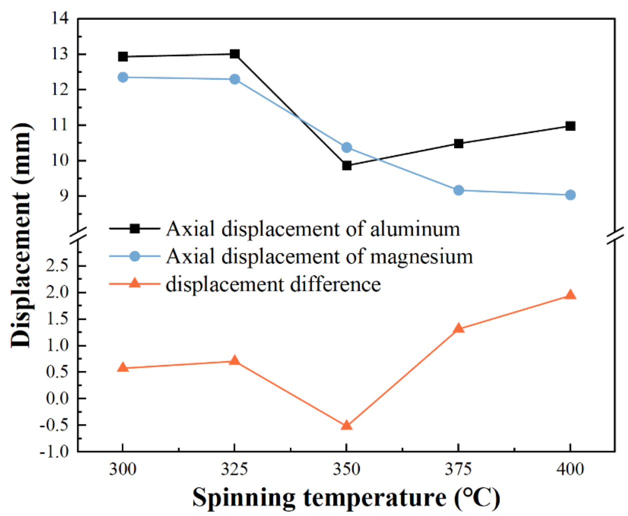

Fig. 4. Axial displacement extension of Mg/Al BCTs at different temperatures.

Analysis of equivalent stress and strain of Mg/Al BCTs. Fig. 5 presents the radial equivalent stress distribution of the wall of Mg/Al BCTs during the spinning process, the radial equivalent stress distribution of the BCTs wall shows a stepped distribution, which also corresponds to what has been said before: the inner and outer tubes need a 'flow stress difference' to show a better coordinated deformation state. When the theoretical flow stress difference of Mg/Al BCTs is greater than or less than the actual stress difference of the inner and outer tubes in the spinning forming process, the coordinated deformation state of the inner and outer tubes becomes worse, which also just explains that when the temperature is too high or too low, the axial displacement difference of the inner and outer tubes is at a higher value. Although this stress difference is reflected in the axial displacement, it has a small amplitude change. But the performance is not very obvious. On the bonding interface of the BCTs, although the interface of the BCTs begins to bond with the application of temperature and pressure, the interface will produce tangential and axial stress due to the uncoordinated deformation, thus affecting the bonding strength of the BCTs interface. when the tangential and axial stress is greater than the shear strength of the composite interface, it will directly lead to the separation of the already composite interface.

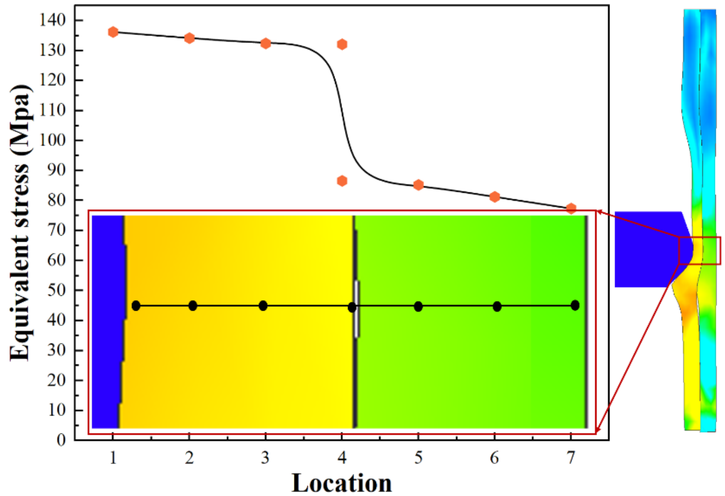

Fig. 5. Radial equivalent stress distribution of BCTs.

The findings from the equivalent strain analysis of the interface, specifically in the radial direction of the Mg/Al BCTs, are depicted in Fig. 6. The figure indicates that at 350°C and 400°C, the radial distribution of equivalent strain in the Mg/Al BCTs exhibits a step-like pattern similar to the equivalent stress distribution. However, a notable distinction is observed at 350°C, where the step at this interface nearly diminishes. This observation aligns with the equivalent strain cloud diagram for Mg/Al BCTs at different temperatures, as illustrated in Fig. 3. In the 350°C cloud diagram, the distribution of strain change appears more uniform, consistent with the axial position difference of the BCTs presented in Fig. 4. Notably, the axial displacement difference at 350°C demonstrates a lesser magnitude compared to other temperatures. Consequently, it can be anticipated that a reduced ladder-like distribution of radial equivalent strain in the Mg/Al BCTs corresponds to an improved coordinated deformation degree. This, in turn, leads to reduced shear stress (impacting the bonding interface) and heightened bonding strength of the interface.

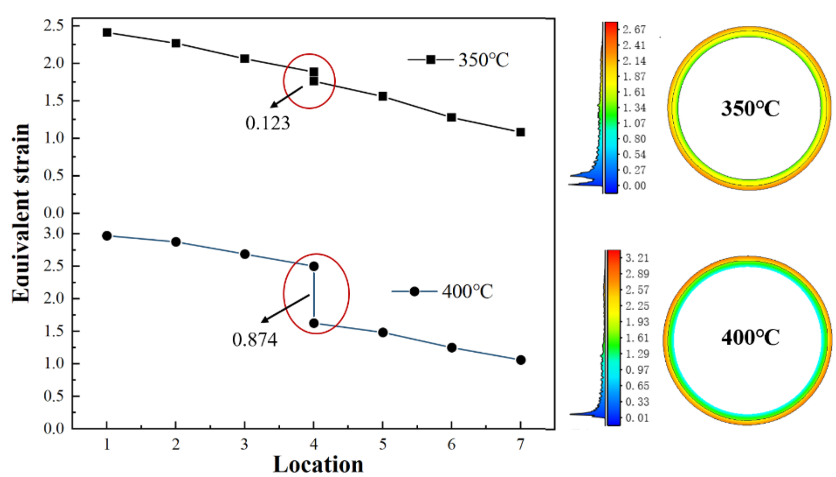

Fig. 6. The radial equivalent strain distribution of the Mg/Al BCTs at 350°C and 400°C.

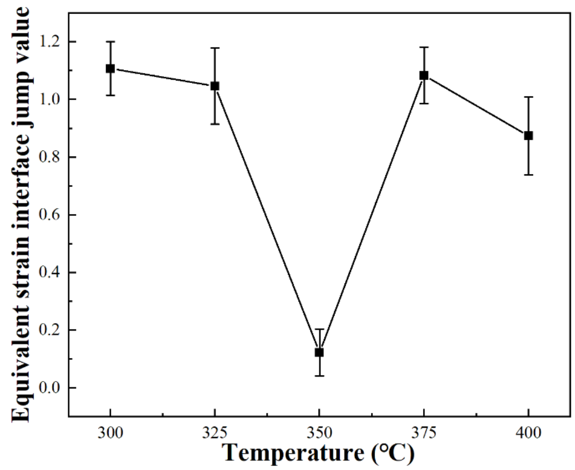

Fig. 7. The change of equivalent strain jump value at the interface of Mg/Al BCTs at different temperatures.

The equivalent strain jump values at the interface of the BCTs mentioned above are analyzed. The results are shown in Fig. 7. The results show that when the spinning temperature is 350 °C, the equivalent strain jump value at the interface of the BCTs is at the lowest level, which is 0.123. This indicates that when the spinning temperature of the BCTs is 350°C, the relative strain generated at the interface of the BCTs is small, and the shear stress generated at the interface due to the relative displacement is also at a low level. When the temperature changes to 300°C-325°C and 375°C-400°C, the jump value of the interface strain of the BCTs is at a high level, and the maximum value reaches 1.108. At the same time, in the two temperature ranges, the difference of the axial displacement of the BCTs also shows a high level.

Conclusion

Different from the process of rolling Mg/Al composite plate, in the spinning process of Mg/Al BCTs, due to the different contact stress between the inner and outer tubes, the conclusion that 'similar flow stress is more conducive to the deformation coordination of composite materials' in the previous rolling research is not applicable to the spinning process of BCTs. Therefore, this paper studies the finite element simulation results of the BCTs in the temperature range of 300°C-400°C, and deeply analyzes its deformation and behavior. The following conclusions are obtained:

1. When the spinning temperature rises, the axial displacement of Mg tube and Al tube shows a downward trend as a whole. However, the axial displacement difference between the Mg tube and the Al tube shows a trend of decreasing first and then increasing, and the overall displacement difference shows an upward trend. The minimum value is -0.51 mm, which is located at the spinning temperature of 350°C.
2. There is a stress-strain jump value in the bonding interface of Mg/Al BCTs. It is precisely because of the jump value of stress that leads to the phenomenon of strain jump value. The larger the jump value, the more unfavorable the interface bonding.
3. At a temperature of 350°C, the minimum strain jump value of 0.123 is observed. This finding signifies that when the spinning temperature of the BCTs is maintained at 350°C, the relative strain generated at the BCTs' interface remains minimal. Consequently, the shear stress arising from the relative displacement at the interface also remains at a low level. Simultaneously, this observation corresponds to the phenomenon of the smallest axial displacement difference among the BCTs occurring at 350°C.These findings provide evidence supporting the recommendation to maintain the spinning temperature within the range of 350°C during the spinning process of Mg/Al BCTs. This temperature range ensures the attainment of coordinated deformation in the BCTs, consequently enhancing the bonding strength of the interface.

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