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Production of AZ80/Al composite rods employing non-equal channel lateral extrusion

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Abstract: In order to simultaneously take the advantages of magnesium and aluminum alloys, AZ80/Al composite rods were produced using non-equal channel lateral extrusion (NECLE) process at different temperatures. Scanning electron microscope (SEM) and energy dispersive spectrometer (EDS) tests as well as the shear punch test were employed to study the quality and strength of the bond between the two alloys. It was found that the process temperature was an important factor affecting the level of interfacial bonding, such that increasing the temperature from 250 to 300 °C has improved the strength by 37% and the thickness of the bond between the layers by 4.5%. Moreover, this temperature rise reduced the maximum required forming load by 13%. However, the hardness tests showed that this increase in the process temperature resulted in 4% decrease in the hardness of the composite bar.

Key words: bimetallic composite; magnesium alloy; aluminum alloy; mechanical properties; co-extrusion welding; non-equal channel lateral extrusion

1 Introduction

During the last decade, magnesium (Mg) alloys have increasingly been used in various industries such as aerospace, automotive, computer and electronic industries. This is mainly due to low density, high specific strength and stiffness and good damping capacity of these alloys as demonstrated by JUNG et al [1]. However, because of hexagonal closed-packed (HCP) crystallographic structure of the Mg alloys, they possess poor ductility and formability at room temperature. Moreover, their corrosion and wear resistances are relatively low. These limitations have made the applications of the Mg alloys not as extensive as other light alloys such as aluminum (Al) alloys in various industries [2]. On the other hand, Al alloys with FCC structure usually represent much better formability at room temperature. The corrosion resistance of these alloys is also very good, although their density is about 60% greater than that of the Mg alloys.

Combining valuable properties of dissimilar metals can be possible by fabricating bimetallic composite [3]. Manufacturing composite rods including Mg and Al layers can compensate the weak points of these materials and simultaneously take their interesting advantages. However, as demonstrated by TYLECOTE [4], macro-composites are usually manufactured by solid state welding process. For solid state welding, different techniques such as diffusion bonding used by ESLAMI and KARIMI-TAHERI [5] to joint aluminum to copper, friction stir welding shown by PARK et al [6] to joint two plates of AZ61 magnesium alloy, roll welding used by HOSSEINI et al [7] to produce bi-layer copper alloy strips, screw extrusion applied by SKORPEN et al [8] to make Al/Mg macro-composites and co-extrusion welding employed by HE et al [9] to joint titanium alloy to a stainless steel with an aluminum alloy interlayer, can be applied.

In a co-extrusion welding operation, two or more parts with the same or different materials are put together and extruded through a die. During the plastic deformation of the billet, metallic bonds appear at the interfaces of the parts and, in this way, they are welded to each other. GRAVIER et al [10] have claimed that the main advantage of this technique is the high isostatic pressure created during the welding process, which is beneficial for forming and welding of alloys with low ductility. PARAMSOTHY et al [11] conducted hot extrusion operation in order to produce Mg/Al bimetal macro-composites. They found that both the stiffness and fracture strain of the magnesium in the composite

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product were improved. PARAMSOTHY et al [12] also reinforced AZ31 Mg alloy with short Al cores and concluded that the new AZ31/AA5052 composite represented higher ultimate strength and toughness, compared with AZ31. THIRUMURUGAN et al [13] employed Al wires for reinforcing rods made of ZM21 magnesium alloy and, hereby, increased both the strength and ductility of the product. They used co-extrusion technique for ensuring the solid state welding of the two materials.

Nowadays, due to obtaining ultra-fine grain structure, using severe-plastic deformation (SPD) processes increases considerably in different applications. The most commonly used SPD process is equal-channel lateral extrusion (ECLE) or equal-channel angular pressing (ECAP) [14]. This operation has successfully been used for strengthening, grain refinement and improving the ductility of different materials, including various magnesium alloys. JIANG et al [15] investigated the changes in the microstructure and mechanical properties of large AZ61 magnesium components subjected to multi-pass ECAP under various process conditions. They attributed the grain refinement and enhancement of the mechanical properties to dynamic recrystallization of the material during the ECAP operation. With this regard, it was also claimed that the process temperature and the type of the ECAP route played basic and important roles. JAHADI et al [16] studied the influence of the pass number of ECAP operation on the material properties and microstructure of AM30 magnesium alloy. Their experimental findings showed that the grain homogeneity, microhardness and elongation of the deformed alloy increased by increasing the pass number from 1 to 4, whereas its strength decreased. They claimed that these changes in the mechanical properties were mainly due to the texture modification. Quite similar observations were made by RATNA-SUNIL et al [17] for AZ31 alloy.

Some important aspects of ECLE (ECAP) operation, such as good dimensional accuracy, simplicity of the die shape and the compressive nature of the stress state involved, have resulted in extensive applications of this technique for metallic bonding of alloys with quite low plasticity, where traditional processes such as drawing and rolling are not applicable as demonstrated by EIVANI and KARIMI-TAHERI [18] and LIU et al [19] have successfully employed ECLE process for manufacturing AZ31/Al bimetallic products. Non-equal channel lateral extrusion (NECLE) is a new version of ECLE, which was proposed and used by TOTH et al [20]. In this process, the cross section of the inlet channel is greater than that of the outlet one, leading to an extrusion ratio for the operation. Because of more severe plastic deformation involved in an NECLE process, the grain refinement is more complete, compared with a single-pass ECLE operation. Therefore, NECLE would be advantageous for industrial and practical applications [21].

The present research work is concerned with the production of AZ80/Al composite bars by means of the NECLE process. Thereby, the low density of the magnesium alloy and the corrosion resistance of Al can be incorporated in a unique part. The results of this research have shown that the process temperature is an important variable affecting the strength and quality of the metallic bond as well as the strength of the composite product.

2 Experimental

2.1 Materials and equipment

A rolled sheet made of AA1060 aluminum alloy and having a thickness of 15 mm was machined in the rolling direction to produce a rectangular bar with dimensions of 15 mm × 15 mm × 80 mm and as the sheath of the billet. Then, it was drilled to create a hole with a diameter of 10.5 mm and a length of 70 mm at its longitudinal centerline. The core of the billet with 10.5 mm and 70 mm in diameter and length, respectively, was machined from cast AZ80. The diameters of the hole and core were such that the elements of the bimetal billet could be assembled with a gentle force. Table 1 summarizes the compositions of the alloy elements for both the materials. These are obtained by means of a WAS analyzer and using the diffusion spectrometry technique.

Table 1 Chemical compositions of AZ80 and AA1060 alloys employed for bimetal NECLE operations

Material	Mass fraction/%
AZ80 (Core metal)	Mg 90.92, Al 8.2, Zn 0.5, Mn 0.25, Si 0.03, Cu 0.001, Ni 0.001, other impurities 0.1
AA1060 (Sheath metal)	Al 99.6, Mn 0.002, Si 0.08, Cu 0.02, Fe 0.2, V 0.003, other impurities 0.09

The NECLE die involved two halves, which could be fastened together using eight high-tension screws to form two perpendicular channels, namely the vertical (inlet) and horizontal (outlet) channels (Fig. 1). The cross sections of the vertical and horizontal channels were 15 mm × 15 mm and 15 mm × 7.5 mm, respectively. Therefore, there was an extrusion ratio of 2. It was the same die geometry for NECLE proposed by FERESHTEH-SANIEE et al [21]. This extrusion ratio intensified the severe plastic deformation of the specimen at the junction of two channels. The NECLE die set, which was made of H13 ASTM hot-work die steel, was designed such that the deformed composite part could easily be removed from it. Two electrical elements as well as a thermocouple were provided inside the NECLE die set. All the experiments were conducted with a 150 kN servo-electrical testing machine.

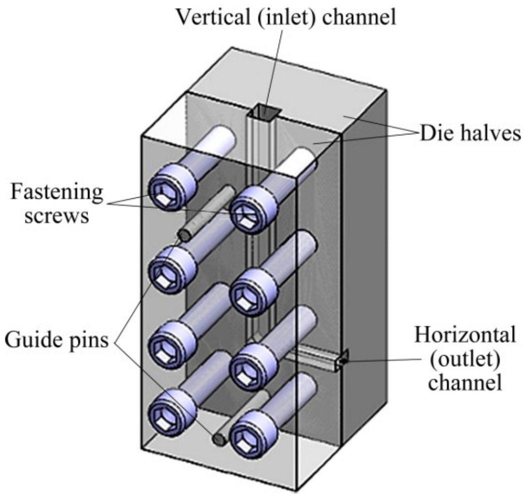

Fig. 1 Schematic illustration of assembled NECLE die

2.2 NECLE tests

Before performing an NECLE test, the composite billet should be prepared following special procedures. After the machining process, the inside of the Al sheath and the outside of the AZ80 core should be ground and, then, cleaned by means in an acetone bath. Afterwards, brushing operation should be performed by means of a milling machine with a stainless steel brushy head. ZEBARDAST and KARIMI-TAHERI [22] have claimed that by this operation, the oxide layers are removed and replaced by brittle work hardened surfaces. These work hardened layers, which are formed outside the AZ80 core and inside the hole of the Al sheath, played an important role in intermetallic weld mechanism.

After the brushing process and before assembling elements of the composite billet, they should be plunged into the acetone bath for further cleaning. As shown in Fig. 2, the Mg core was then fitted into the Al bar to conform the composite billet.

In order to conduct the NECLE process, the die set was preheated to the target temperature, namely 250 or 300 °C. After achieving the thermal equilibrium, the bimetal sample was located inside the vertical channel for 5 min. It is worthy to mention that for lubrication, MoS_2 was sprayed onto the billet and die surfaces before locating the billet inside the NECLE die. The NECLE operation was performed with a ram speed of 2 mm/min. The composite sample was laterally extruded and exited from the horizontal channel. Figure 3 illustrates bimetal sample before and after performing the NECLE process.

In order to observe the microstructure of bonded joints in the transverse section of the composite product, the specimens were cut and polished and, then, etched in

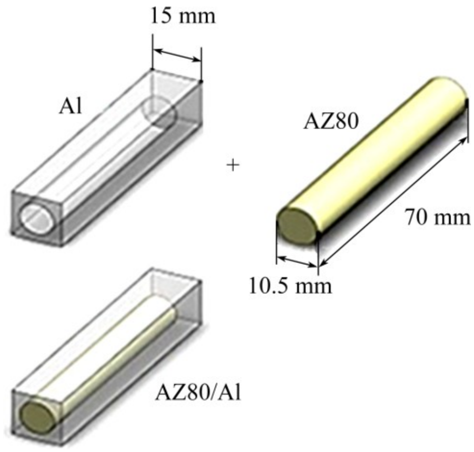

Fig. 2 General dimensions of Al sheath and AZ80 core together with composite billet

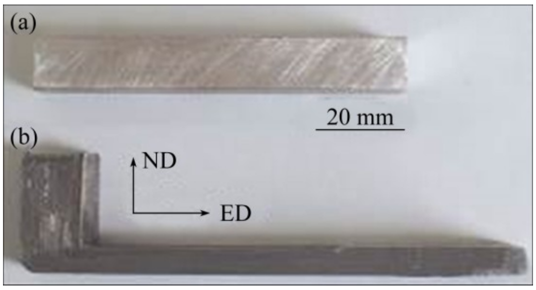

Fig. 3 Billet (a) together with specimen partially deformed by NECLE process (b)

a picric acid solution. The linear intercept method was used to obtain the average grain sizes of the AZ80 before and after the deformation. This grain size was found to be 64 μm before the NECLE operation. For qualitative and quantitative evaluations of the metallic weld between different layers of the product, the bond of AZ80 and Al was examined along their interfaces by scanning electron microscope (SEM) and energy dispersive spectrometer (EDS) analysis. Moreover, shear punch tests at room temperature were conducted to measure the shear strength of the weld between the external and internal layers of the deformed composite part.

Figure 4 shows schematically the specimen and the sectioned die set employed for performing the shear punch tests. These tests were carried out based on the guidelines described by ESLAMI and KARIMI-TAHERI [5]. The sample with dimensions of 15 mm × 7.5 mm × 5 mm was cut from the composite product (Fig. 4). The shear punch test was performed after removing the flashes from the sample and polishing its upper and lower surfaces. The die set involved a punch and a die. The section of the punch was elliptical, the same as the core of the specimen. However, the major and minor diagonals of the punch were 0.1 mm less than those of the specimen core. The die cavity was such that the outside of the sample was completely fitted to the die. But, after the action of the punch, the elliptical core could be separated from the outside of Al layer without any prevention. All the shear punch experiments were performed by the 150 kN servo-electrical testing machine with a ram velocity of 0.25 mm/min. After obtaining the load−displacement curve for each shear punch test, the maximum load (F_{max}) was divided by the area of the shear surface (A=127.2 mm^2) to calculate the maximum interfacial shear strength (τ_{max}).

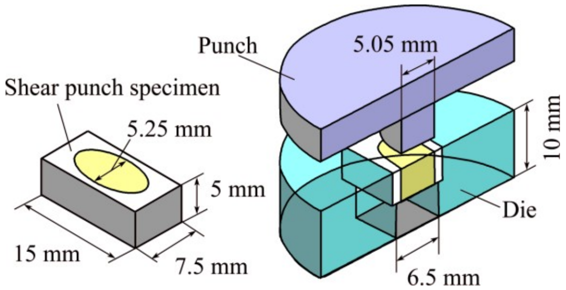

Fig. 4 Schematic diagrams of composite sample and die set up for evaluation of interfacial shear strength

Finally, to study the variation of the material hardness across the product cross section for different process temperatures, microhardness tests were conducted by a Buehler Ltd-Lake Bluff-IL 60044 tester machine. These experiments were necessary in order to investigate the improvement in mechanical properties of both the interior and exterior materials, the uniformity of the product and the effect of the process temperature on the strengths of the core and the sheath of the composite product.

3 Results and discussion

3.1 Width of metallic bond

The transverse and longitudinal sections of a typical AZ80/Al composite part, partially deformed with an NECLE operation, are illustrated in Fig. 5. As can be seen in Fig. 5, the section of the magnesium core is changed from a circle to an ellipse. However, the product section still possesses two vertical and horizontal axes of symmetry. This point means that, despite the deformation zone at the corner of the NECLE die, the Al alloy symmetrically covered the AZ80 core of the bimetal product. It is also worthy to mention that the NECLE die set was designed such that the formation of dead metal zone was avoided (Fig. 5).

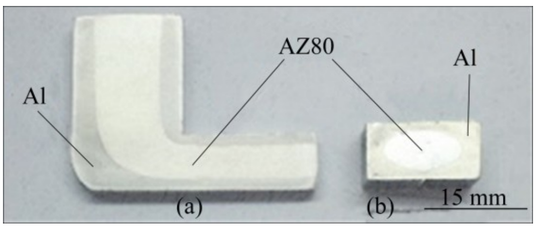

Fig. 5 Longitudinal (a) and transverse (b) sections of NECLE-treated composite specimen

The micrographs of the bimetal bars at the interface of the Al sheath and AZ80 core produced at 250 and 300 °C are shown in Fig. 6. Appropriate proximity of two alloys implies their good contact and welding during the NECLE operation. As claimed by LIU et al [19], some dark areas in vicinity of the interface are caused by different erosion resistances of two alloys. The contact line of two materials in the composite bar deformed at 250 °C is more wavelike compared with that of composite NECLE-treated at 300 °C.

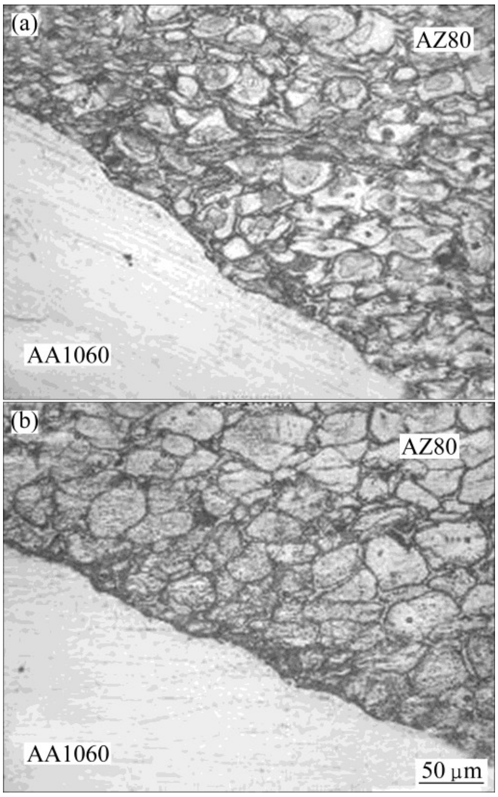

Fig. 6 Micrographs of transversely sectioned composite bars produced at 250 °C (a) and 300 °C (b) in vicinity of interface of two alloys

Figure 7 illustrates longitudinal views of the microstructure of the Mg core deformed at various temperatures. The microstructure of the AZ80 deformed at 250 °C is quite more nonhomogeneous, compared with that NECLE-treated at 300 °C, because some original coarse grains surrounded with new fine grains can be observed in the relevant micrograph. According to LIU et al [19], this situation indicates that the recrystallization process has been quite incomplete at 250 °C. These coarse grains increased the average grain size to 9.2 μm at this temperature, where the mean size of the fine grains was less than 5 μm. ZHAO et al [23] claimed that dynamic recrystallization is a diffusion-controlled process such that the higher the deformation temperature is, the greater the diffusion is. Figures 6 and 7 show that the microstructure of the AZ80 core NECLE-treated at 300 °C, with larger grains, is more homogeneous, compared with that produced at 250 °C. This increase in the process temperature has resulted in an increase in the average grain size from 9.2 to 9.6 μm.

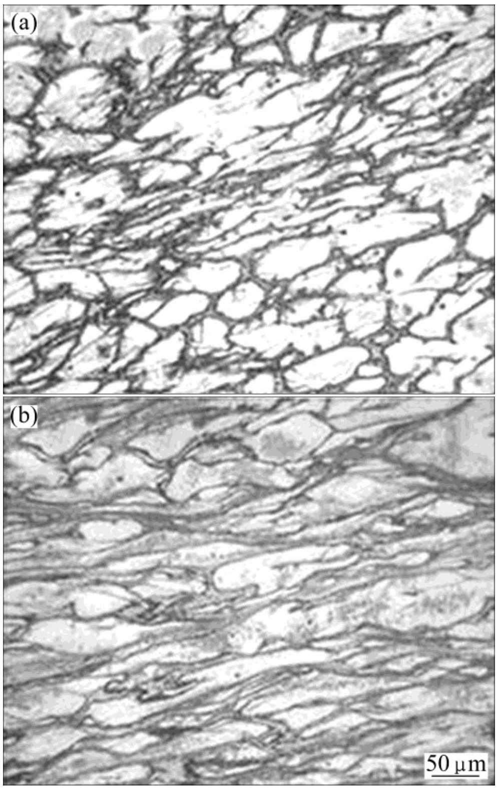

Fig. 7 Longitudinal views of microstructures of AZ80 cores of bimetal components deformed at 250 °C (a) and 300 °C (b)

The influence of the NECLE temperature on the width of the metallic bond between two layers was also investigated by SEM. By using the linear scan method, EDS analyses were performed at the interface of two alloys and the results are demonstrated in Fig. 8. As can be observed in Fig. 8, the transition from AZ80 to Al at the interface of the bimetal bar deformed at 300 °C is more gently and wider, compared with that at 250 °C. The gradual change in the intensity of Mg started from 52.5% to 62.5% distance at process temperature of 250 °C, showing a bond width of 10%. But this severe decrease in the intensity percentage of Mg was from 51.5% to about 66% distance at 300 °C, representing a bond width of 14.5%. MATSUMOTO et al [2] asserted that the quality of the weld between two alloys, directly depends on the bond width at their interface. Also WANG et al [24] showed that the effective interfacial joint of the substrates and the clad materials was closely related to the thickness of the diffusion layers in the substrates and the clad. LIU et al [19] demonstrated that a more gentle transition from one alloy to the another and a wider bond width could result in a stronger weld.

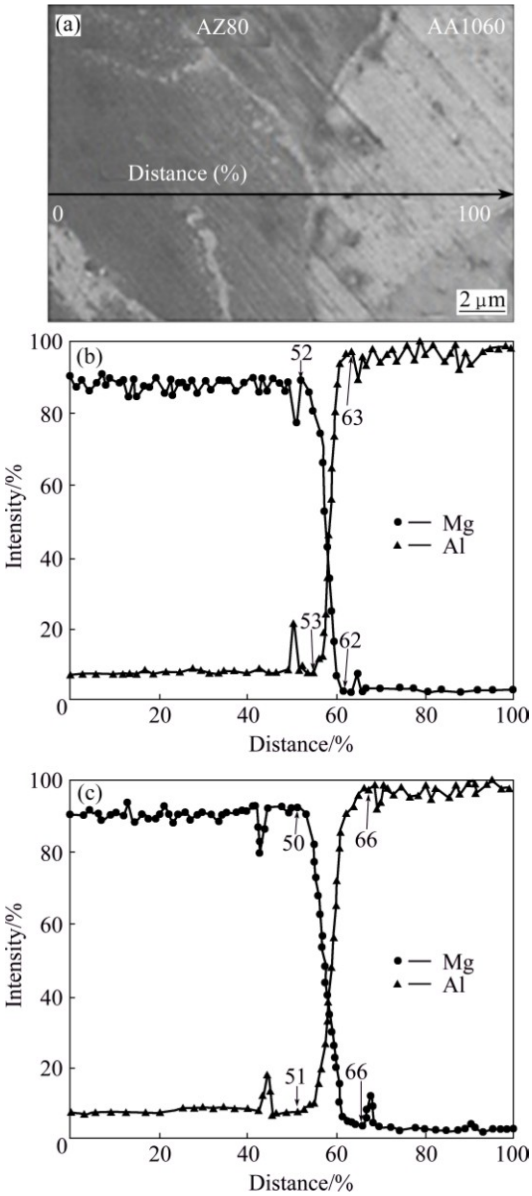

Fig. 8 Results of line scan analyses at AZ80/Al interface (a) of composite products NECLE-treated at 250 °C (b) and 300 °C (c)

HE et al [9] claimed that at lower temperatures, because of higher yield strengths of the materials, the thermal activity was insufficient and, consequently, the atomic diffusivity was low. In this situation, the atomic inter-diffusion across the interface could decrease and as a result, a weaker bond between the layers could be created. The stronger metallic bond obtained in this research work at 300 °C confirms the previous findings. LIU et al [19] asserted that the laminated composite fabricated at higher temperature (300 °C) had thicker bond between the layers than that fabricated at lower temperature (200 °C) under the same condition. It should also be noted that EDS analyses revealed that no crack void or discontinuity was observed in the interfacial regions of the composite bars produced at 250 and 300 °C, implying that there was a sound bond between the layers at both temperatures.

3.2 Interfacial shear strengths

After finishing the NECLE operation, shear punch tests were conducted in order to determine the shear strength of the bond between the AZ80 core and the Al sheath. This was carried out for the bimetal bars produced at 250 and 300 °C. The shear stresses for separating the core from the sheath were found, based on the method described in Section 2.2, to be 35 and 48 MPa at 250 and 300 °C, respectively. These results are in agreement with the findings reported in Section 3.1. In other words, with increasing the NECLE temperature from 250 to 300 °C, the shear bond strength between AZ80 and Al alloys can be increased by about 37%.

3.3 Variations of hardness

To investigate the improvement in the mechanical properties of the alloys involved in the composite bar, Vickers hardness was measured across the section of the products processed at various temperatures. It is worthy to mention that the Al and AZ80 alloys composing the billet for the NECLE operation had initial average hardnesses of HV 34 and HV 61, respectively.

The variations of the hardness of both the alloys in the x direction of the cross section and in terms of the distance from ab interface line are demonstrated in Fig. 9. As shown in Fig. 9, the left side of ab line (x<0) is Al and the right side (x>0) is AZ80. The hardness of Al is increased from its initial value before NECLE operation (HV 34) to about HV 40 or more, depending on the process temperature. However, for both the NECLE temperatures, no significant variation of hardness can be observed in Al part of the composite bar. The hardness of the AZ80 alloy is also improved by the NECLE operation, although this improvement is not completely the same at different locations of the cross section of the bar. The Mg cores deformed at both 250 and 300 °C, represented monotonically increasing changes from the interface line ab to the center of the core, though the variations in the vicinity of the center are not significant. With increasing the process temperature from 250 to 300 °C, the hardnesses and consequently the strengths of various regions of the bimetal product are decreased by about 4%. This finding is worthy to pay attention because the rise in temperature has led to the decrease in the strengths of the materials making up of the composite product, whereas their metallic bond has been improved.

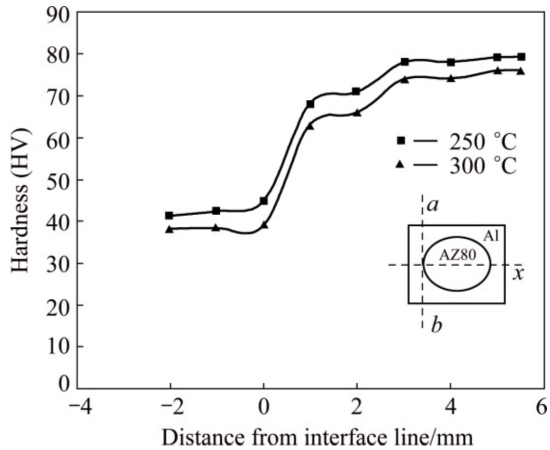

Fig. 9 Distributions of hardness in x direction and in terms of distance from ab interface line of bimetal bars produced at various temperatures

3.4 Load−stroke curves

Based on the load−stroke curves displayed in Fig. 10, the NECLE operation at 300 °C required a maximum force about 13% less than that of the process at 250 °C. Both the curves illustrated in Fig. 10 represent, more or less, some fluctuations. These alterations in the steady parts of the curves are due to either the microstructural evolutions of the alloys during the severe plastic deformation or slight changes in the workpiece/die or AZ80/Al interfacial conditions. Based on Fig. 10, there are fewer fluctuations in load curve at 300 °C, compared with that of 250 °C. This could mainly be due to more stable dynamic recrystallization of the alloys at 300 °C. In other words, a better equilibrium between creation of the dislocations and their rearrangement and removal is established during the NECLE process of the composite sample at 300 °C. The initial part of the load−displacement curve corresponds to the enlargement of plastic zone at the early stage of the NECLE operation. FERESHTEH-SANIEE et al [25] have shown that since the stress−strain curves of the AZ80 alloys represented significant work softening at both the process temperatures, depending on the amount of the strain induced, there are different parts for the plastic deformation region of this alloy. At low effective strains, AZ80 under consideration is subjected to strain hardening. But after a critical effective strain, dynamic recrystallization takes place and the necessary effective stress for further plastic deformation is reduced. In other words, after a specific peak stress, strain softening occurs. Finally, in the region of the high plastic strains of the deformation zone, the material needs a steady flow stress for continuation of the NECLE process. Observing the load curves shown in Fig. 10, one may remark a very slight reduction in the NECLE force, especially at the end of the process. This is mainly due to the reduction in tool/workpiece contact area, and consequently resulting in the decrease in the frictional force, when the majority of the composite billets are extruded from the inlet channel into the outlet channel.

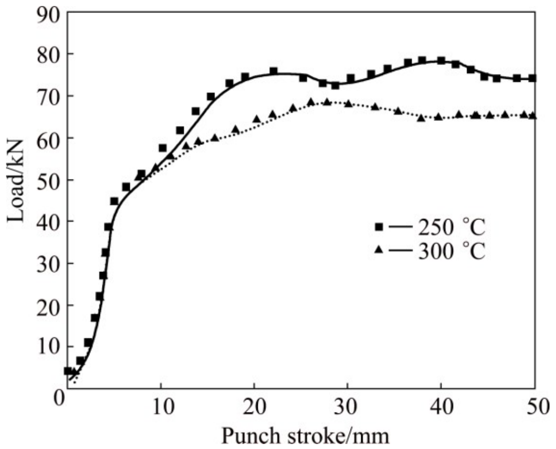

Fig. 10 Load−stroke curves of bimetal NECLE operations conducted at 250 and 300 °C

4 Conclusions

1) Both the aluminum and AZ80 are light structural alloys. AZ80 has a considerably greater specific strength ratio and a significantly smaller corrosion resistance, compared with AA1060 aluminum alloy. By manufacturing composite bars containing these alloys, one can take their advantages in a unique part. In this case, special attention should be paid to the process temperature.

2) When the strength of the metallic bond in a bimetal product is a major concern, the process temperature is a very important factor. Our observations showed that with increasing the NECLE temperature from 250 to 300 °C, the bond thickness between AZ80 and AA1060 as well as the shear bond strength between these alloys increased by 4.5% and 37%, respectively. Another advantage of doing NECLE operation at 300 °C was about 13% reduction in the required maximum forming load.

3) Despite the above-mentioned advantages, increasing the NECLE temperature from 250 to 300 °C resulted in about 4% reduction in hardness of both the AZ80 and Al alloys involved in the deformed composite bar. Therefore, the design requirements of the composite product dictate the desired temperature for performing NECLE of composite billets.

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非等通道横向挤压工艺制备 AZ80/Al 复合棒材

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摘　要：为了兼顾镁合金和铝合金的优异性能，采用非等通道横向挤压工艺在不同温度下制得 AZ80/Al 复合棒材。采用 SEM 和 EDS 技术及剪切冲头测试研究两合金的连接质量和连接强度。结果表明：挤压温度是影响合金界面键合质量的重要参数。当温度从 250 °C 升高到 300 °C 时，合金界面键合强度增加了 37%，界面键合层厚度增加了 4.5%。此外，此温升使成形载荷降低了 13%。然而，硬度测试结果表明，此温升导致复合棒材的硬度降低了 4%。

关键词：双金属复合；镁合金；铝合金；力学性能；混合挤压焊接；非等通道横向挤压

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