Formability of laser welded steel/magnesium dissimilar metal with Sn powder-adhesive interlayer

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The exploratory experiments of laser fusion welding with Sn powder and the automotive adhesive addition were conducted for DP590 dual-phase steel and AZ31B magnesium alloy in an overlap steel-on-magnesium configuration. The characteristics of metal vapor/plasma were analyzed by collecting and analyzing plasma shape and welding spectra. The microstructure of the welded was characterized by scanning electron microscopy (SEM), X-ray diffraction (XRD), energy dispersive X-ray spectrometer (EDS). The temperature field distribution of the joint was simulated by COMSOL finite-element software. The results showed that the transfer of heat from steel to the magnesium alloy is hindered by the adhesive layer, which is conducive to the simultaneous melting of steel and magnesium with large differences in melting and boiling points. In addition, the width of the molten pool increases, but the depth is shallow on the magnesium side. Meanwhile, the recoil pressure induced by the splashing of the molten pool reduces, and the surface quality of the weld is improved. Some intermetallic compounds (IMCs), such as FeSn, Fe_{1.3}Sn, and Fe₃Sn, are formed inside the molten pool, while columnar dendrite Mg₂Sn phase is also produced. The presence of these phases helps realize the bidirectional metallurgical bonding of steel/magnesium dissimilar metals.

Keywords: *dissimilar metal welding, micro-structure, numerical simulation, Sn-adhesive interlayer*

1. Introduction

Magnesium alloy is the lightest structural material with a high strength-to-weight ratio and its excellent formability, which has aroused common attention in many fields [1–3]. Steel is one of the leading materials widely used in the automotive field. Therefore, it is of great significance to joining steel to magnesium for achieving lightweight, saving energy, and environmental protection [4, 5]. However, there is a big difference in the physical and chemical properties of iron and magnesium, such that the melting point of iron and the boiling point of magnesium are 1536°C and 1090°C, respectively, it is difficult for iron and magnesium to get melted simultaneously. According to Mg-Fe binary phase, it is found that no solid solutions or intermetallic compound (IMC) makes metallurgical bonding unattainable [6, 7]. Hence, a great chal-

lenge should be considered for achieving an effective fusion welding of steel and magnesium alloys.

Up to now, various welding techniques have been used for steel and magnesium connections, including solid-state connection technologies such as friction stir welding [8–11], diffusion welding [12, 13], and ultrasonic spot welding [14, 15], as well as fusion welding technology, for instance, resistance spot welding [16], MIG welding [17], and composite heat source welding [18–20]. However, these welding techniques are of limited use in practical industrial applications. As for the application of laser sources [21], which have the characteristics of a large temperature gradient, high energy density, high efficiency, good process repeatability, and narrow heat-affected zone, they are widely used in dissimilar metal welding in recent years [22, 23]. Miao et al. [24] studied the laser brazing welding technique with steel and magnesium, and they found that steel/magnesium metallurgical bonding can be achieved because steel reacts with alloying elements of magnesium alloy to form a diffusion layer. Liu et al. [25] studied the laser

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brazing welding process of AZ31 magnesium alloy and galvanized steel, and they thought that the presence of galvanized layer promotes the wetting of the brazing filler metal on the steel substrate, and the interface between the magnesium alloy and the galvanized steel is heterogeneous interfacial reaction layer which realized effective metallurgical bond of the steel and magnesium. Gang et al. [26] suggested reducing some defects by controlling welding parameters, and they showed that the metallurgical connection between steel and magnesium can be strengthened by adding an intermediate layer. Liu et al. [27, 28] used a laser and tungsten inert gas (TIG) composite heat source to overlap weld AZ31 magnesium alloy and Q235 steel plate of which adding inter-layers such as Cu, Ni, and Sn between the magnesium and steel, and they declared that the inter-layer element and magnesium formed a metal compound with a Fe-containing solid solution formed on the steel side, and the addition of the intermediate interlayer enabled an effective metallurgical bond of the steel and magnesium joint. Gang et al. [29] researched hybrid laser-TIG welding technology for joining steel to magnesium with Cu-Zn interlayer, and they found that Cu set a bridge between the steel and Mg weld seam. Based on the above results, the research on steel/magnesium welding mostly focuses on the selection of the intermediate layer and welding heat source. However, there are a few research projects on the influence of the adhesive layer on microstructure and properties of welded joints.

In this study, the experiments of laser fusion welding of DP590 dual-phase steel to AZ31B magnesium alloy with the addition of Sn powder and the automotive adhesive were performed in an overlap steel-on-magnesium configuration. The influence of the Sn-adhesive interlayer on the characteristics of steel-magnesium joints was analyzed from the weld formability, stability, and microstructure of the weld. Moreover, the finite-element model of steel and magnesium laser welding was established by COMSOL finite-element software, and the distribution of temperature field was analyzed. Through the above research, the project results will provide technical guidance and laid a theoretical foundation for the application of

welding of steel and magnesium dissimilar metals.

2. Experimental

2.1. Materials and experimental procedure

DP590 dual-phase steel and AZ31B magnesium alloy were selected as experimental materials whose chemical compositions are listed in Table 1, the dimensions of which are 100 mm × 30 mm × 1.4 mm and 100 mm × 30 mm × 1.5 mm, respectively. The Sn powder is made by Titi Metal Material Co., Ltd. with a diameter of 20–50 μm, and Ergo[®] automobile adhesive was used for the laser welding process. Before welding, the oxide film of the surface on the steel and magnesium plate was removed with 800# sandpaper. After sanding, the ethanol was used to ultrasonically clean the surface of the material. To analyze the effect of adding automotive adhesive, two sets of experiments have been carried out that one is to only add Sn powder interlayer and the another is to add Sn-adhesive interlayer. A layer of automobile adhesive with a thickness of 0.1 mm was evenly coated on the surface of the polished and cleaned magnesium alloy on which a layer of Sn powder with a thickness of 0.15 mm was applied after solidification for 2 h. The materials, with the steel plate on the top, the Sn-adhesive interlayer in the middle, and the magnesium plate at the bottom were fixed on the workbench by the fixture. The welding diagram was shown in Figure 1.

The welding experiments were achieved by a 4 kW fiber laser (YLS-4000-CL) with the beam wavelength being 1,070 nm. The laser spot diameter of 0.4 mm was accomplished through a focusing mirror with a 200 mm focal length. And the angle alpha of the beam divergence was <0.15 rad under the laser mode of TEM00. When the defocusing amount was zero, the distance from the welding head to the surface of the workpiece was 192 mm. Argon (high purity argon, purity 99.999%) gas with a flow rate of 15 l/min was used as the protective gas to prevent oxidation of magnesium alloy. A sound joint could be obtained by adjusting the welding parameters. The optimized process pa-

Table 1. Composition of welding base material (wt%).

Materials	Al	Zn	Mn	Si	C	S	P	Fe	Mg
DP590	0.02	–	1.60	0.0446	0.068	0.015	0.011	Bal.	–
AZ31B	3.12	0.95	0.15	0.10	–	–	–	0.03	Bal.

rameters were shown in Table 2. During the welding process, the infrared spectrometer and high-speed camera were used to analyze the metal vapor/plasma and the characteristics of the welding spatter. After welding, the welded joints were cut to be inlaid, ground, polished, and etched in sequence by standard metallographic specimen preparation steps. The steel side was etched with nital (4% HNO₃, 96% C₂H₅OH) and the magnesium side was etched with trinitrophenol solution (15 ml CH₃COOH + 50 ml C₂H₅OH + 3 g C₆H₃N₃O₇ + 5 ml H₂O). The analysis of the data collected from the experiment in Ocean Optics SpectraSuite software shows the infrared spectrums. The intensity of metal vapor/plasma was analyzed by infrared spectrum. The microscopic morphology of the welded joint was observed by Quanta 250 FEG scanning electron microscope (SEM) and the chemical composition and phase composition of the joint were examined by ESCALAB 250 type energy-dispersive X-ray spectrometry (EDS) and D500X type X-ray diffraction (micro-XRD).

Fig. 1. Schematic illustration of the steel/magnesium welding.

Table 2. Optimized process parameters used in present work.

Parameters	Value
Laser power (W)	1,500
Laser defocus (mm)	+2
Welding speed (mm/s)	40
Flow rate of Ar gas (L/min)	15

2.2. Numerical simulation of temperature field

Laser welding owns the feature of rapid heating and rapid cooling [30]. The temperature field of the welded joint could be simulated by COMSOL where the temperature distribution could be obtained, which provides the theoretical analysis for the heat transfer in the process of steel and magnesium overlap welding. Since the welded joint was approximately a symmetrical section, a 4 mm × 4 mm weld area was selected as the simulation analysis area. Considering the significant difference between the base metal and the interlayer in thermophysical properties, the mesh generation of the interlayer and the base material should be different. Figure 2 shows the final finite element model. The mathematical expression of the heat source of a rotating Gaussian surface heat source is [31]:

$$q(x, y, z) = \frac{3c_s Q}{\pi H \left(1 - \frac{1}{e^3}\right)} e^{\frac{-3c_s(x^2+y^2)}{\log\left(\frac{H}{z}\right)}} \quad (1)$$

$$c_s = \frac{3}{R_0^2}$$

Where H was the heat source height; Q was the heat input rate; C_s was the heat source opening radius; R_0 was the heat source radius, and the heat source radius was generally 0.5 times the weld width, here $R_0 = 0.4$ mm.

Fig. 2. Finite element model of welding: (A) Sn powder interlayer (B) Sn-adhesive interlayer.

3. Results and discussion

3.1. Analysis of weld surface formability

Figure 3 shows the surface morphology of steel/Mg welded joint. When Sn powder is added, the welding pool surface is concave and the weld is narrow even the hole appears, and there is an indication of penetration and burning. As a result, the surface formability of the weld is relatively poor. Under the same process parameters, as compared to the Sn-added joint, it is found that the weld surface of the steel-magnesium welded sample with Sn-adhesive interlayer is formed well (Figure 3C and 3D). The weld seam is continuous, uniform, and wide, which is 1.2 times wider than the weld without adhesive. The weld surface is well-formed and no welding defect appears, because the adhesive layer has a certain hindrance to the transfer of heat to the magnesium alloy, which reduces the magnesium plate vaporization and spattering. Thus the adhesive layer can increase the width of the weld and improve its surface quality.

Fig. 3. Joint morphologies of Sn powder interlayer laser weld: (A) face (B) root; Joint morphologies of Sn-adhesive interlayer laser weld (C) face (D) root.

3.2. The spatter feature in welding process and the analysis of infrared spectra

Figure 4 shows the high-speed camera image and infrared spectrum image during the steel/Mg welding process with different interlayers. Comparing Figure 4(A) with Figure 4(B), during the process of welding, the number of metal spattering of the joint with Sn powder added is three times more than that with Sn-adhesive interlayer. Moreover, the spatter fluctuates in a wide range, which indicates that the welding process is unstable, presenting that the weld surface formability is poor. This is consistent with the actual situation of the morphology of the weld surface (Figure 3).

Fig. 4. NAC high-speed camera at $t = 20$ ms: (A) Sn powder interlayer (B) Sn-adhesive interlayer; Infrared spectrum (C) Sn powder interlayer (D) Sn-adhesive interlayer.

The infrared spectrums of joint with Sn powder interlayer and joint with Sn-adhesive interlayer, which are shown in Figure 4(C) and 4(D), respectively. The elements such as Sn (396.20 nm), Mg (419.35 nm), and Fe (403.14 nm) [32] are burnt both in the joints above during the welding process. When the wavelength is 403.13 nm, the maximum value of the relative intensity of the metal vapor/plasma spectrum of the welding with Sn powder interlayer is 5,527 counts, and that of the joint with Sn-adhesive interlayer is 1,761 counts. It

can be seen that during the steel-magnesium laser welding process, the electron density of metal vapor/plasma generated by the Sn-adhesive interlayer is significantly lower than that generated by the Sn powder interlayer, which proves that the elements on the Sn-adhesive interlayer are burnt less, which basically agrees with the results captured by high-speed cameras.

During the laser welding process, the laser-radiating material generates metal vapor/plasma, which affects the scattering, reflection, defocusing, and absorption of the incident laser, thereby affecting the stability of the welding process. The data points are both selected near the wavelength of 403 nm in the infrared spectrums of the welding processes with Sn powder interlayer and Sn-adhesive interlayer, and thereby the line broadening of welding is calculated, and also the electron density of the metal/plasma outside the hole during the laser welding process is obtained. In particular, the Doppler broadening and ion field correction are ignored, the width of the infrared spectrum line is measured by the Raman line shape fitting centered on the peak position of the infrared spectrum characteristic line, and the expression of the Raman function is [33]:

$$y = y_0 + \frac{2A}{\pi} \frac{w}{4(x - x_c) + w^2} \quad (2)$$

where y was the dependent variable, x was the independent variable, w was the full width at half maximum of the line, x_c was the center wavelength, y_0 was the background emission, and A was the integral area of the line.

The Raman function is used to fit the infrared spectrum characteristic lines. The three sets of test data are averaged at the same wavelength for a certain time interval to obtain the half-height and full width of the welding processes with Sn powder interlayer and Sn-adhesive interlayer. The fitted results are shown in Figure 5. According to the Stark line broadening theory [34], concerning a neutral atom and its discrete ionization line, the broadening of the line is mainly caused by electron collision, thus the electron density of the metal vapor/plasma

can be calculated by the following simplified formula [33]:

$$N_e = \frac{\Delta\lambda_{1/2}^s}{2a} \times 10^{16} \quad (3)$$

where N_e was the electron density, $\Delta\lambda_{1/2}^s$ was the full width at half maximum of the line, and a was the electron collision broadening.

Table 3 exhibits the calculated metal vapor/plasma electron density of steel/magnesium laser welding with Sn powder interlayer and Sn-adhesive interlayer. It can be seen that the metal vapor/plasma density of the joint with the Sn-adhesive interlayer is reduced, which means that there is less overflow of iron, magnesium, and Sn elements during the welding process. Under the same laser welding parameters, the steel/magnesium joints with the Sn powder interlayer and the Sn-adhesive interlayer absorb the same heat, but due to the heat resistance effect of the adhesive layer, a large amount of heat is absorbed during the burning and vaporization at the adhesive layer, resulting in a sharp decrease of heat transfer from the steel to the magnesium. Therefore, the burning loss of dual-phase steel (Fe element), tin powder (Sn element), and the magnesium alloy (Mg element) is lower than that of the corresponding elements in the joint with the Sn powder interlayer.

Table 3. Electron density of each element in the joints with Sn powder and Sn-adhesive interlayers.

Interlayer	Fe (10^{17} cm $^{-3}$)	Sn (10^{17} cm $^{-3}$)	C (10^{17} cm $^{-3}$)	Mg (10^{17} cm $^{-3}$)
Sn powder	6.5663	4.2696	0.9826	0.5347
Sn-adhesive	6.3263	3.4236	0.6060	0.8751

3.3. Morphology and element distribution in joint cross section

Figure 6 shows the morphology and distribution of elements of joints. As shown in Figure 6(A), some pores appear in the Sn-added joint, and lack of fusion occurs inside the molten pool, which is caused by spatters during the welding process.

Fig. 5. Element fitting spectrum of welding with Sn powder and Sn-adhesive interlayer: (A) Sn (B) Fe (C) Mg (D) C.

From Figure 6(F), it can be seen that there is no obvious defect such as cracks and pores on the weld joint with Sn-adhesive. The joint width of magnesium side molten pool with Sn-adhesive is more 40% than that with Sn powder, increased by 0.23 mm, which is caused by the absorption of a large amount of heat in the adhesive vaporization process. Based on the above analysis, the adhesive layer plays an important role in adjusting the melt depth and melt width. The EDS mappings of Fe, Sn, and Mg elements at the cross section of joints with different interlayers illustrate that the Fe element sinks under the action of gravity, there are an obvious "Mg floating" phenomenon in the Sn-adhesive joint, and more Mg elements are found at the bottom of steel side molten pool and are embedded in Fe elemental void area (Figure 6G). Compared with that shown in Figure 6(C), the Mg element in the Sn-adhesive joint is more integrated into the steel molten pool. Because of the agitation of the adhesive layer caused by gasification during the welding process, more magnesium ele-

ments appear at the bottom of the steel side molten pool. The Sn elements are well distributed on both molten poolsides, where Sn interacts with Mg and Fe by the bottom-up circulation promoted by the agitation of laser [35] and adhesive layer gasification, which facilitates the interaction between Fe and Sn at the joint interface, as well as the mutual fusion of Sn and metal on the molten pool. From Figure 6(J), the incomplete decomposed adhesive remains in the contact area between the fusion zone and the edge, while there is almost no residual carbon element in the molten pool. Therefore, it can be judged that the adhesive layer is nearly completely decomposed and escapes from the molten pool, and the adverse effect on the molten pool caused by the adhesive decomposition is very little.

3.4. SEM and XRD analysis of joints

Figure 7 shows the microstructures of steel/Mg joints with different interlayers. The morphology of the Sn-adhesive joint is shown in Figure 7(A), and the enlarged images of *a*, *b*, and *c* micro-zones

Fig. 6. Morphology of welded joints: (A) with Sn inter-layer, (B), (C), (D) and (E) Fe, Mg, Sn, and C mapping; (F) with Sn-adhesive inter-layer, (G), (H), (I) and (J) Fe, Mg, Sn, and C mapping.

in Figure 7(A) are given as Figure 7(B), Figure 7(C) and Figure 7(D), respectively. It can be that region I is mainly composed of magnesium matrix, which is caused by the floating of magnesium. Region II contains Fe and a small amount of Sn. According to Fe-Sn binary phase diagram, a solid solution can be formed between Fe and Sn at high temperatures. The supersaturated solid solution undergoes a phase transition during rapid cooling, generating a large amount of α -Fe and trace FeSn IMCs. During the rapid solidification of the molten pool, the off-white FeSn phase precipitates along the Fe grain boundary. Due to the similar atomic solubility of FeSn and $\text{Fe}_{1.3}\text{Sn}$ [36], a certain amount of $\text{Fe}_{1.3}\text{Sn}$ with a hexagonal crystal structure is formed during the peritectic transformation, showing a metastable phase [37]. Region III is the boundary of the molten pool on the magnesium side, which mainly contains Mg and Sn with an atomic ratio being close to 2:1, which is presumed to be the Mg_2Sn phase [38]. Many dendritic intermediate layers in region IV mainly contain Mg and Sn and the atomic ratio is close to 2:1. From the Mg-Sn binary phase diagram, the dendritic structure in region IV is Mg_2Sn . The results of micro-area EDS are shown in Table 4. Comparing the steel/magnesium joints with Sn powder interlayer (Figure 7E) and Sn-adhesive interlayer (Figure 7A), in the same area (Figure 7G and 7H), there is a large amount of steel sinking into the magnesium molten pool for the joint without an ad-

hesive layer. The severe burning at the magnesium side induces several cracks and pores, which is not conducive to the formability of the joint.

Table 4. EDS spot composition analysis results in Figure 7 (at%).

Regions	Fe	Sn	Mg
I	–	–	100
II	63.23	36.35	–
III	–	31.66	62.63
IV	00.33	36.41	62.85

EDS, energy dispersive X-ray spectrometer.

To further determine the phase composition of the joint, XRD analysis was performed on the Sn-adhesive interlayer on the steel/Mg joint. The results are shown in Figure 8. It was found that IMCs, such as FeSn_2 , $\text{Fe}_{1.3}\text{Sn}$, Fe_3Sn and Mg_2Sn , are formed at the joint interface, which is basically consistent with the EDS results of Table 3. From the above analysis, it can be seen that when Sn foil is added to steel/magnesium laser welding, Fe-Sn phases such as FeSn_2 , $\text{Fe}_{1.3}\text{Sn}$, Fe_3Sn , etc. are formed in the transition area on the steel side, and the Mg_2Sn phase with columnar dendrites is formed in the transition area on the magnesium side. The existence of these new phases realizes the "two-way" metallurgical connection of steel/magnesium dissimilar metals.

Fig. 7. Morphology of joints: (A) with Sn-adhesive inter-layer cross-section (B) region a (C) region b (D) region c; (E) with Sn inter-layer cross-section (F) region d (G) region e (H) region f.

Fig. 8. XRD analysis of the weld joints with Sn-adhesive interlayer. XRD, X-ray diffraction.

3.5. Temperature field analysis of welded joint cross section

To analyze the influence of the adhesive layer on the weld joint in terms of the heat transfer, steel/magnesium laser welding temperature field of adding Sn powder and Sn-adhesive interlayer is simulated under the welding power of 1,500 W and welding speed of 40 mm/s. The isotherm diagrams of the welds with Sn powder and Sn-adhesive interlayer are shown in Figure 9(A) and 9(B), re-

spectively. In Figure 9(A), due to the presence of Sn powder and the difference in thermal conductivity of the three dissimilar metals, a temperature layer at 600–1,000 °C appears, which reaches the melting point of Sn powder and magnesium alloy. Hence, the Sn powder and magnesium alloy melt at the same time, the upper liquid steel sheet and the lower magnesium alloy diffuse into each other through the Sn interlayer [39]. The surface temperature of the weld central area on the magnesium side reaches 2,800 °C, which is much higher than the boiling point of a magnesium alloy of 1,107 °C. Therefore, in the magnesium side molten pool, magnesium alloy is severely burnt, and a large amount of metal vapor is generated. When magnesium vapor escapes from the molten pool, a large recoil pressure impacts the molten pool and causes a lot of spatters, which seriously reduces the weld formability. In Figure 9(B), the adhesive layer has an obvious thermal resistance effect, and a large temperature buffer zone appears at the Sn-adhesive interlayer. On the upper surface of magnesium alloy, the highest temperature reaches 1,500 °C, which is significantly lower than that of the joint with Sn powder. Meanwhile, for the magnesium side, where the temperature is above the melting point of Mg (650 °C), the depth is significantly reduced and the width is obviously in-

Table 5. Comparison of experimental weld size and simulation results (mm).

P = 1,500, V = 40 mm/s		Steel plate surface melt width	Magnesium plate surface melt width	Magnesium plate melt depth
Sn-adhesive interlayer	Experimental	0.849	1.48	0.997
	Simulation	0.93	1.45	0.89
Sn powder interlayer	Experimental	0.827	1.38	1.27
	Simulation	0.90	1.36	1.10

creased, resulting in a shallower but wider molten pool. The burning and spattering of magnesium alloy are apparently weaker than the joint with Sn powder. Therefore, the adhesive layer plays a significant role in regulating the temperature field of the weld.

Figure 9(C) and 9(D) show the weld temperature cloud distribution of the steel/magnesium joint with Sn powder interlayer and the Sn-adhesive interlayer. By comparing with the actual shape of the weld in Figure 6, the simulated weld size and the actual dimensions are shown in Table 5. The simulation results are basically consistent with the actual weld profile. It is found that melt depth on the magnesium side of the joint with the Sn-adhesive interlayer is reduced by 32% compared with that with the Sn powder interlayer. Under the same process parameters, the presence of the adhesive layer acts as a hindrance to the transfer of heat from the upper steel to the lower magnesium alloy, reducing the melt depth on the magnesium side. In addition, the adhesive layer also acts as a buffer of temperature in the interlayer to make the lateral temperature widening region appear and the width of molten pool on the magnesium side increase, which is beneficial to simultaneous melting of steel and magnesium and promotes the mutual diffusion of three elements of steel, magnesium, and Sn.

4. Conclusions

The following conclusions can be made concerning the formability of laser-welded steel/magnesium dissimilar metal with Sn powder-adhesive interlayer:

1. The buffering effect of the adhesive layer makes the temperature of the molten pool stable.

Fig. 9. P = 1,500 W, V = 40 mm/s laser welding isotherm diagram (A) with Sn powder interlayer (B) with Sn-adhesive interlayer. P = 1,500 W, V = 40 m/s steel magnesium laser welding temperature cloud distribution (C) with Sn powder interlayer (D) with Sn-adhesive interlayer.

The steel/magnesium joint with an Sn-adhesive interlayer has a lower melt depth and a larger melt width on the magnesium side. The melt width at the bottom of the steel side slightly increases.

2. The adhesive layer has the effect of heat insulation and can effectively control the temperature field, the recoil pressure induced by the splashing of molten pool reduces, and the surface quality of the weld is improved.

3. The transfer of heat from steel to the magnesium alloy is hindered by the adhesive layer, which

is conducive to the simultaneous melting of steel and magnesium with large differences in melting and boiling points.

4. Some IMCs, such as FeSn_2 , $\text{Fe}_{1.3}\text{Sn}$, Fe_3Sn , are formed inside the molten pool, while columnar dendrite Mg_2Sn phase is also produced. The presence of these phases helps realize the bidirectional metallurgical bonding of steel/magnesium dissimilar metals.

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