

Multi-field dynamic modeling and numerical simulation of aluminum alloy resistance spot welding

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Abstract: In order to explore the influence of welding parameters and to investigate the Al alloy (AA) nugget formation process, a comprehensive model involving electrical–thermal–mechanical and metallurgical analysis was established to numerically display the resistance spot welding (RSW) process within multiple fields and understand the AA-RSW physics. A multi-disciplinary finite element method (FEM) framework and a empirical sub-model were built to analyze the affecting factors on weld nugget and the underlying nature of welding physics with dynamic simulation procedure. Specifically, a counter-intuitive phenomenon of the resistance time-variation caused by the transient inverse virtual variation (TIVV) effect was highlighted and analyzed on the basis of welding current and temperature distribution simulation. The empirical model describing the TIVV phenomenon was used for modifying the dynamic resistance simulation during the AA spot welding process. The numerical and experimental results show that the proposed multi-field FEM model agrees with the measured AA welding feature, and the modified dynamic resistance model captures the physics of nugget growth and the electrical-thermal behavior under varying welding current and fluctuating heat input.

Key words: resistance spot welding; aluminum alloy; multi-field modeling; simulation; finite element method; dynamic resistance; transient inverse virtual variation effect

1 Introduction

The trend of automotive weight reduction inspires the extensive usage of aluminum alloy resistance spot welding (AA-RSW) for the body-in-white manufacturing. Resistance welding is accomplished by passing a controlled density of electrical current (I) through the resistance of the metallic workpieces (R) over a specified amount of time (t). Due to its inferior weldability, the aluminum alloy faces a major problem of determining the optimal parameters in the RSW process and it is difficult to evaluate the welding procedure quantitatively [1]. Compared with costly experimental investigations, an alternative way to extend insight into the effects of welding parameters and evaluate the joint design is to simulate the RSW process numerically in quantitative detail.

The AA-RSW is a nonlinear time-varying uncertain process that strongly couples the thermal, electrical, mechanical dynamics and metallurgical transitions, which poses challenges for the simulation. It was pointed

out that conventional modeling and simulation approaches for RSW process are no longer sufficient for obtaining the complicated process details associated with aluminum alloy RSW [2]. Some further researches using numerical simulation for the temperature distribution, nugget formation and the microstructure evolution have been conducted [3–6]. MATSUYAMA [7] advocated a hybrid simulation method to visualize the nugget formation and to operate it as weld quality management system. Experimental tests were accordingly carried out to embody the consistency between experimental and numerical results, showing that the adopted models are effective enough to interpret and predict the welding phenomena. These existing techniques focused on describing the mono-field and analyzing the effects of process parameters while neglecting the synchronically coupled welding factors. Moreover, the effects of welding parameters on the temperature of faying surface, the metallurgical phase change and convective transport in the weld pool were studied in Refs. [8,9]. And latent heat of fusion and solidification have been considered to estimate the final weld dimensions [10]. However, the

effects of welding parameters are specified as a constant instead of a varying value, causing the incremental effect hard to be observed. Hence, a reasonable modeling and simulation scheme is required to complete simulating the interaction and transient effects in the multiple physical fields.

In this work, the finite element analysis is employed to explore the coupled electrical–thermal behavior of the AA-RSW process. Analysis of the electrical–thermal behavior focuses on the current distribution and the variation of electrical resistance between two electrode tips, namely the dynamic resistance, since the dynamic resistance indicates the nugget growth process and the ultimate weld quality. Further, the phenomenon of transient inverse virtual variation (TIVV) effect is observed and theoretically explained. Subsequently, a comprehensive model which takes into consideration of the empirical TIVV behavior is proposed to simulate the AA-RSW process. Finally, experiments are conducted to verify the modeling and simulation accuracy, and the dynamic resistances during both the stable and unstable welding processes are discussed in light of the presented results, which paves way for optimizing the AA-RSW parameters and improving its real-time quality control performance.

2 Multi-disciplinary modeling of AA-RSW process

2.1 Classical electrical–thermal–mechanical model for RSW

The mathematical formulation with respect to the coupled effects of electrical–thermal–mechanical phenomena associated with the resistance spot welding process is briefly presented, hereby the theoretical framework is built to lay a foundation stone for the consequent simulation research.

The governing differential equation for the electrical potential field is obtained as

$$\frac{\partial}{\partial z} \left(\frac{1}{\rho} \frac{\partial \varphi}{\partial z} \right) + \frac{\partial}{\partial r} \left(\frac{1}{\rho} \frac{\partial \varphi}{\partial r} \right) + \frac{1}{\rho r} \frac{\partial \varphi}{\partial r} = 0 \quad (1)$$

where z and r are the axial and radial coordinates; φ and ρ denote electrical potential and electrical resistance, respectively.

The 2- dimensional differential equation governing heat conduction with internal heat source can be presented as

$$\frac{1}{r} \frac{\partial}{\partial z} \left(k_z r \frac{\partial \theta}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(k_r r \frac{\partial \theta}{\partial r} \right) + \dot{Q} = \rho_t U \quad (2)$$

where z and r are the axial and radial coordinates; k_z and k_r are the thermal conductivity in z and r , respectively; θ and Q are the temperature and the heat generation rate

per unit volume, respectively; U at the right side of equation is the accumulated internal energy; ρ_t is the thermal conductivity of the aluminum alloy.

Targeting the welding of 5xxx series aluminum alloy sheets, in this work the aluminum alloy metallurgical model adopts the proposed approach for AA5754 in Ref. [11]. And the final microstructure and hardness of the weld nugget is obtained accordingly.

The mechanical model calculates the deformation and geometry of the materials, the contact area at the interface and the stress and strain fields with consideration of both volume changes due to phase transformation and transformation plasticity. It is worth mentioning that the dynamic electrical resistance analysis is subject to the mechanical and electrical models, and the numerical method describing the physics is derived using the formulation provided by Ref. [12].

In summary, the proposed theoretical framework for AA-RSW simulation comprises the electrical field and heat transfer model presented by the partial differential equations, the metallurgical model with temperature-dependent database and the mechanical model with piecewise analytical functions. The couplings among the models are shown in Fig. 1.

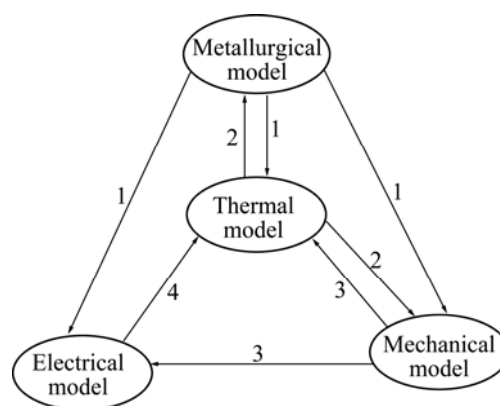


Fig. 1 Couplings among models: 1—Material properties; 2—Temperature field; 3—Contact conditions; 4—Electrical current field

2.2 Empirical model for dynamic resistance transient inverse variation effect

The dynamic resistance reflects the nugget growth of aluminum alloy during the welding process and has a marked influence on the required magnitude of welding current. The most advanced control strategy for the aluminum alloy RSW is to adaptively track the optimal trace of the electrical resistance. Hence, it is important to investigate the resistance for completely understanding the resistance spot welding physics and the heat generation.

The general resistance profile is determined by the total welding heat input; however, the resistance is also

affected by the dynamics of the applied electric current. The shape of the dynamic resistance curve subject to varying welding current, as seen in Fig. 2, has been documented in the aluminum alloy welding process. A conspicuous feature of the aluminum alloy dynamic resistance is its descending profile, which indicates the aluminum alloy forms its nugget at the initial stage of welding. The zoomed windows W1 and W2 in Fig. 2 have shown that the transient inverse virtual variation effect of the dynamic resistance, that is, when the welding current increases from 50 ms to 65 ms, the resistance decreases. And when the welding current decreases during the time 125–135 ms, the dynamic resistance rises and then drops again. The current-induced behavior of the dynamic resistance is counter-intuitive, since the common case is that the resistance changes proportionally to the welding current. In this case, the phenomenon is advocated as “inverse virtual variation”, and this effect just presents for a short time, typically 20 ms for the sheet aluminum alloy, and then the resistance comes to a stable status determined by the welding current. This short acting time is denoted by “transient effect”. The underlying physics is that the electrical current changes faster than the dynamic resistance of the workpiece, which is the indication of the accumulated heat input. The coupled electrical–thermal variables, the electrical current and dynamic resistance, show discrepancy under the dynamic welding current conditions.

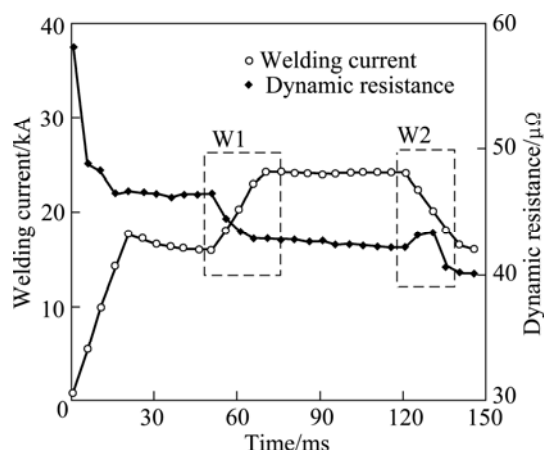


Fig. 2 Transient inverse virtual variation phenomenon discovered by manipulating varying welding current

The transient inverse virtual variation phenomenon is essentially the consequence of the discrepancy between the welding electrical and thermal effects. Generally speaking, the dynamic resistance embodies the accumulated heat input to the welding zone and the temperature distributed. The total heat can be expressed by

$$Q = I^2 R_t \quad (3)$$

Equation (3) shows that the welding heat is proportional to the square of welding current, and the dynamic resistance is a nonlinear function of the square of welding current as well. Since the welding current is an variable with fast response to the control, the dynamic resistance exhibits considerable time-delay for approaching the corresponding stable value. Hence the dynamic resistance is transiently inversely proportional to the current variation. When the welding controller adjusts the welding current according to the resistance target value, the phenomenon of the transient inverse virtual variation takes place. No model has previously been advocated to describe this phenomenon and it is difficult to develop a correctly generalized model of the transient inverse virtual variation effect since it is sensitive to variations and depends on several different physical phenomena. Based on the understanding of the electrical–temperature field physics, an incremental explicit dynamic resistance model for the transient inverse variation effect is built as

$$\Delta R(t) = -\alpha \Delta I \cdot \exp(\text{sign}(t_p - t) / \beta), \quad t \in [1, 2t_p] \quad (4)$$

where ΔR is the dynamics resistance caused by the sudden change of the applied welding current; t_p is the delay time when peak or valley dynamics resistance point emerges; α and β are the parameters obtained by the curve-fitting according to the measured data.

3 Simulation of AA-RSW via FEM

Although various software toolkit can be adopted in solving the aforementioned coupled problem, the finite element method (FEM) is highly desirable due to its flexibility in dealing with complex applications. The commercial software SORPAS [13] and secondary development version are customized including the aluminum alloy metallurgical model database, the above-mentioned transient inverse virtual variation model and the improved welding expulsion model [14].

The welding process is analyzed by setting a cylindrical coordinate system with the origin on the intersection of the axisymmetric axis and bottom electrode-workpiece interface, as illustrated in Fig. 3. The resolution of coupled electrical and thermal equations is done numerically using a finite volume scheme with SORPAS. The FEM numerical grid is non-uniform, and the perspective nugget zone is refined where the contact area boundaries have significant influence on the welding hear generation. It has been because it is the location of large electrical and thermal gradients.

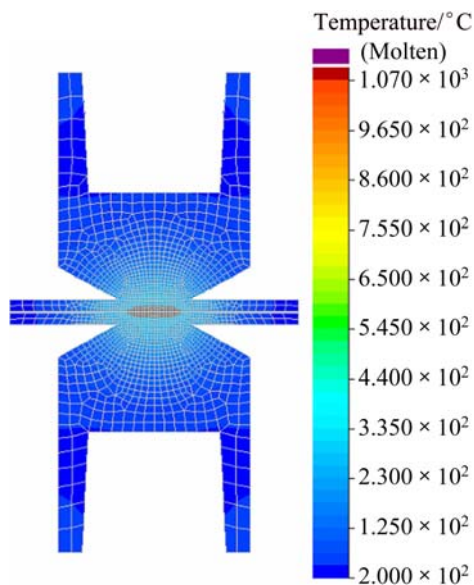


Fig. 3 AA-RSW FEM modeling and its numerical grid

3.1 AA-RSW simulation under constant welding current

The 5182 aluminum alloy is adopted as the computing sample case for the dynamic resistance simulation and nugget size estimation. There are 7 cases whose constant-current ranges from 17.4 to 23.4 kA with the interval of 1 kA. Figure 4 shows the dynamic resistance during 200 ms welding schedule with the assigned welding current. Correspondingly, the nugget sizes obtained are shown in Fig. 5 and the difference between the simulated and measured nugget size is less than 0.4 mm.

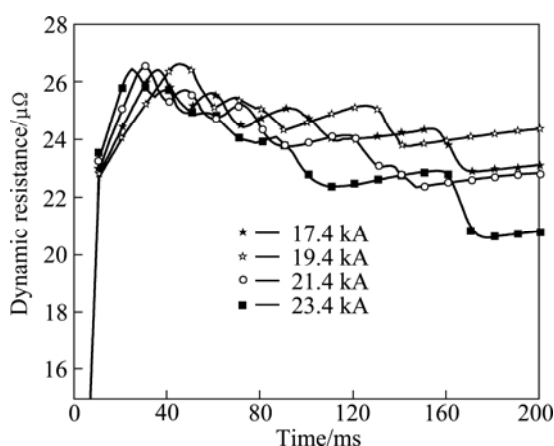


Fig. 4 Simulated dynamic resistance with 17.4–23.4 kA welding current

In the constant current welding schedule for the AA-RSW, the dynamic resistance decreases after the surface film is melt. Generally speaking, the resistance has a tendency of drop. And the greater the welding current is, the sharper the dynamic resistance descent is.

The nugget comes into being in the initial stage of welding process, almost less than 60 ms for 1 mm+1 mm workpiece. It stands to reason that the dynamic resistance drop from the peak value to the lowest ultimately determines the nugget size.

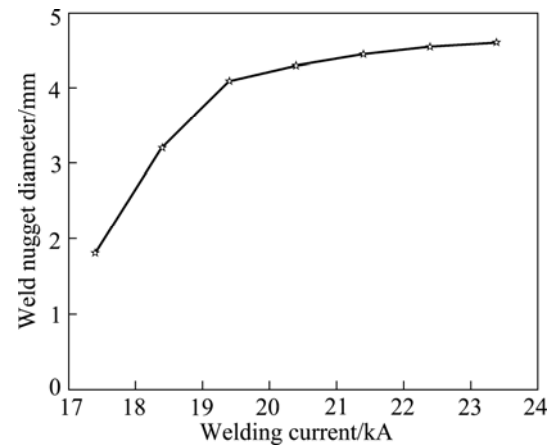


Fig. 5 Simulated nugget size result from 17.4–23.4 kA welding current

3.2 AA-RSW simulation under varying welding current

To simulate the dynamic resistance behavior at varying welding current, the current-dependent dynamic resistance model, as proposed in Eq. (5), is used to join the FEM interface nodes.

In order to investigate the phenomenon caused by the sudden change of welding current, the current distribution and the temperature distribution of the weld nugget are simulated for 1 mm+1 mm AA5182. The current profile is specified as shown in Fig. 6. Simultaneously, two photographs are taken from the welding current field and the thermal field at the time when the welding current changes suddenly within 1 ms. Figure 7(a) shows that the current distribution retreats from the whole welding pool into the corner of the nugget pool, while Fig. 7(b) shows that the temperature field of the heat affected zone keeps integrity. Simulation results demonstrate that the temperature lags behind the changes of electrical parameter, therefore the dynamic resistance responses to the welding current with a time-delay. Numerical computation for the 1 mm+1 mm AA5182 weld piece indicates that the time difference is about 17 ms. Since the dynamic resistance varies slowly when a sudden change of welding current applies, the electrode voltage is the product of unchanged resistance and newly-built current which lags behind the current change. When the lagged electrode voltage is divided by the applied welding current, the measured resistance displays a virtual variation effect. However, when the temperature field gradually approaches to its stable status under the applied current, the transient process

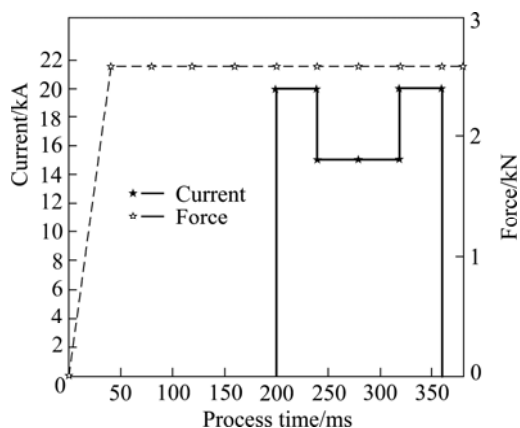


Fig. 6 Varying welding current profile designed for highlighting TIVV phenomenon

distinguished.

This numerical result validates the discrepancy between the general tendency and transient effect, illustrating the importance of the dynamics of the transition process.

4 RSW experimental setup and implementation

A resistance spot welding monitoring system is developed on the welding machine platform of MEDAR (GWS-2D-35) to conduct experiments. Figure 8 shows the photograph of the experimental setup. The workbench records the welding current, electrode tip voltage and the welding current during the RSW process.

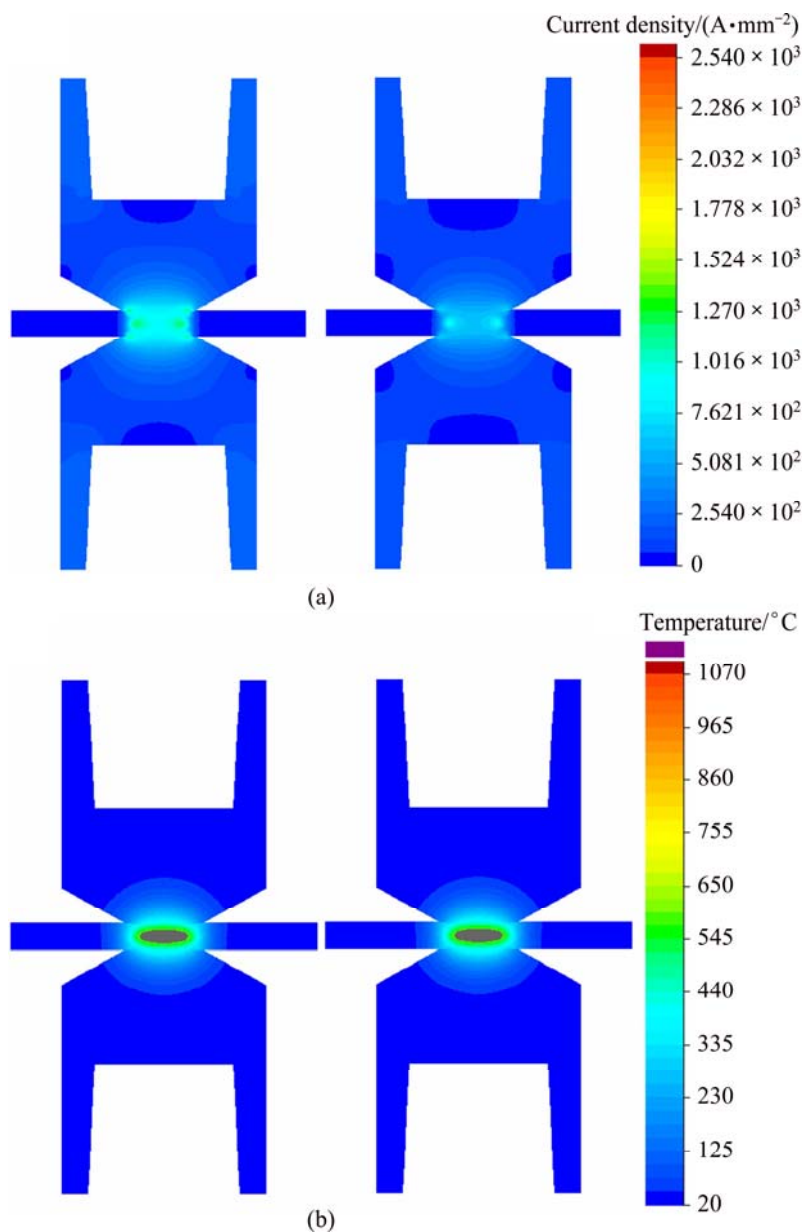
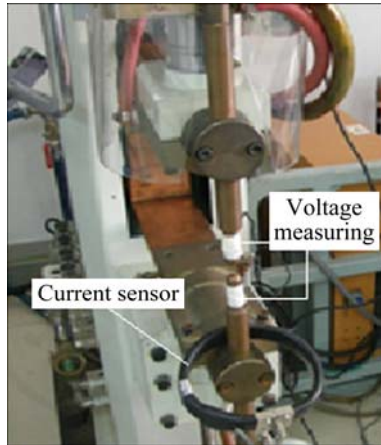


Fig. 7 Current and temperature distribution under varying welding current: (a) Electrical current distribution at steep descent time point of welding current; (b) Temperature distribution at steep descent time point of welding current

Table 1 Mechanical property limits of AA5182

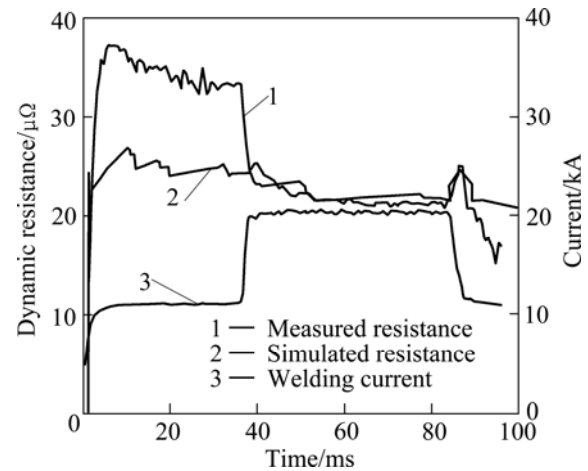
Tensile strength/MPa	Elongation/%	Hardness HB ₅₀₀	Shear strength/MPa	Fatigue limit/MPa	Elastic modulus/GPa
420	4	58	150	140	70–80

*Tested specimens are 50 mm in length, 1.6 mm in thickness.

**Fig. 8** Photograph of experimental setup

The welding current is measured with a Rogowski Coil with the precision of 20 A, and the electrode voltage normally ranging from 0.3 V to 5 V is directly picked from the tips. The welding piece samples, 1 mm+1 mm AA5182 plates, are prepared as specified in the American Welding Society Welding Handbook. AA5182 is categorized as wrought aluminum alloy. It is composed (in mass fraction) of around 93.2% aluminum (Al), 0.2%–0.5% manganese (Mn), 0.2% silicon (Si), 0.35% iron(Fe), 0.15 copper (Cu), 0.10% chromium (Cr) and 4.0%–5.0% magnesium (Mg). AA5182 has good electrical and thermal conductivities thermal conductivity of 123 W/(m·K) and electric resistivity of 56 nΩ·m at 25 °C, and its mechanical property limits at 25 °C are listed in Table 1 [15]. The listed material characteristics are used for simulation.

Figure 9 presents the simulated dynamic resistance and its measured value under piece-wise constant welding current with one up-step and one down-step respectively. It shows that the outline tendency of the dynamic resistance behaves as a down slope curve, which is verified both in the simulation and the experiment. With a current surge at 35 ms the measured dynamic accelerates its decreasing rate sharply, and the relative deviation between the simulated and measured dynamic resistances is less than 4.5%. At 85 ms the dynamic resistance soars up under a sudden down-step current, and then recovers its down-slope profile after the effective scope of transient inverse virtual phenomenon within 10 ms. The effective time and dynamic resistance variation during the TIVV effect have the accuracies of 15% and 4.5%, respectively. The numerical simulation with dynamic resistance TIVV model has high performance for matching the experiment result with

**Fig. 9** Comparison between simulated dynamic resistance and its measured value of AA5182

dynamic details, which validates the effectiveness of the dynamic simulation process.

5 Conclusions

1) The multi-filed simulation simultaneously describes the coupled thermal–electrical–mechanical effects during AA resistance spot welding process. The static numerical simulation, that is only the ultimate stable effect of the welding parameters, plays a critical role in profiling the dynamic resistance and estimating the nugget formation process in welding aluminum alloys. The difference between the numerically estimated and measured nugget sizes is less than 0.4 mm

2) The proposed TIVV model takes into the dynamic performance of the welding current and the discrepancy between the electrical field and temperature field. The dynamic simulation results could describe the dynamics in detail of the multi-filed mutual effect, and obtain the effective time and dynamic resistance variation of TIVV effect with accuracies of 15% and 4.5% respectively.

3) TIVV effect caused by variations of welding can also be monitored during the dynamic welding simulation. The dynamic simulation approach offers a great deal of insight on the mechanisms for exploring the relationship between the dynamic resistance and the nugget formation, and the analysis procedure can be used as a predictive tool to optimize the electrode design and welding parameters to ultimately enhance the real-time performance of the AA weld quality control.

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铝合金点焊的多场耦合建模与动态过程数值模拟

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摘要: 基于铝合金点焊的热、机、电及相变原理, 建立热-电-力耦合场的轴对称有限元数值仿真模型, 实现对焊接区温度场、电场、应力应变的动态模拟。发现了焊接电流变化激发的铝合金动态电阻“瞬态逆向虚变效应”, 揭示了过程热电耦合瞬态与稳态差异性作用机理, 阐释了焊接电流增加而瞬态电阻骤降的反常现象。基于铝合金点焊稳态仿真与实验结果修正了动态电阻数值计算模型。AA5182 的计算与实验结果表明, 考虑动态电阻“瞬态逆向虚变效应”的动态仿真模型能够精确描述焊接电流调整过程中的电参数动态变化和铝合金焊点熔核的生长过程。

关键词: 电阻点焊; 铝合金; 建模; 仿真; 有限元法; 动态电阻; 瞬态逆向虚变效应

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