Study on Rotating Speed Control of Dissimilar Metal Friction Stir Welding based on Fuzzy PID

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Abstract—The demand for lightweight vehicles that achieve energy conservation and emission reduction continues to grow. Aluminum alloys were commonly applied to the automotive industry to reduce the structural weight of the entire vehicle. However, the cost of aluminum alloy was higher than that of steel, so the industry considered the use of aluminum in combination with low-cost materials such as steel. Traditional welding technology was limited by the great physical difference between aluminum alloy and steel. Friction Stir Welding, a solid phase welding technology, can overcome the connection problem of aluminum and its alloys with steel, but the process parameters of FSW directly affect the welding quality. This paper established the FSW process of two different metals of DC05 and AL6061. Aiming to get a good welding joint, the error of tool speed is reduced by fuzzy PID system established in this paper, and the tool speed is controlled stably. Simulink simulation was established, and compared with the simulation results, fuzzy PID control can control the precision and stability of the tool speed of FSW, improve the welding quality, and provide a certain theoretical basis for the tool speed control.

1. Introduction

With the increasing demand for lightweight automobiles, aluminum alloys were commonly applied in the automobile industry to reduce the overall structural weight of automobiles, thereby achieving energy saving and emission reduction, and improving cost-effectiveness. In some cases, a large part of auto parts have been widely used in aluminum alloy materials[1]. Figure 1 shows the application of aluminum-steel hybrid structures in automobiles. The introduction of aluminum alloy engineering materials into the standard steel body is a balance between cost and performance. However, due to the different lattice parameters, thermal conductivity and thermal expansion coefficients between steel and aluminum alloy[2], it is difficult to connect them together. It is still unrealistic to use all-aluminum alloy body design in ordinary cars, so it is desirable to achieve the use of relatively low-priced materials, which involves the connection of aluminum alloy and other materials[3].
Friction Stir Welding (FSW), a new solid-phase welding technology, invented by The Welding Institute (TWI)\textsuperscript{[4]}. Compared with traditional fusion welding, the FSW process occurs in solid phase, and temperature was lower than material’s melting point, so it will not encounter problems related to resolidification. In addition, the lower process temperature allows the connection to have lower distortion and lower residual stress and does not require filler materials. In most cases, shielding gas is not required. In addition, this process lacks pollution with most fusion welding technologies\textsuperscript{[5]}. The principle is to use a rotating stirring head to insert into the base material to be welded. Friction workpiece produces heat to make welding part temperature rise, plastic deformation, moving the mixing head extrusion to complete the thermoplastic deformation welding process.

In this context, the FSW process of DC05 and AA6061 was established in this study. Process parameters directly affect the quality of FSW. In order to achieve a good welding joint, the process parameters of FSW not only include the traditional welding process parameters, such as tool speed, welding speed, welding depth, axial force, etc., but also the parameters involved in the tool, especially the ratio of shoulder diameter to shoulder diameter pin diameter. Tool offset and tool Angle are also important when welding dissimilar materials\textsuperscript{[6]}. M. Wasif Safeen et al.\textsuperscript{[7]} studied the FSW process of two different metals, DC05 and AA6061, and pointed out that the speed of 2500r/min was sufficient to produce good joints at all welding speeds tested. S. Sree Sabari et al.\textsuperscript{[8]} studied the influence of tool speed in FSW and found that when the speed is satisfied, sufficient heat can be generated and appropriate materials can be mixed to form a good joint.

Yet, In the process of FSW, due to the different welding materials, the downforce will change, thus affecting the spindle speed, affecting the welding quality. The traditional PID control method has some disadvantages such as poor compliance and easy to be affected by other machining environment. In order to make up the above shortcomings, this paper proposes a fuzzy PID system for FSW to realize the control of spindle speed and better realize the smooth processing process.

2. Mathematical Model

The brushless DC motor consists of a permanent magnet rotor, a multipole winding stator and a position sensor. It not only maintains the wide and smooth speed regulation performance of the brush DC motor. At same time, it has the advantages of high torque, strong overload capacity, high operating efficiency and good speed regulation performance. Therefore, the mathematical model in this paper is based on a milling machine based on a three-phase brushless DC motor.

First, the model needs to establish some assumptions for the brushless motor, ignoring the influence of factors such as motor commutation time, eddy current, magnetic loss, etc.; assuming that the inverter circuit components have ideal switching characteristics, taking the armature voltage of the DC brushless motor as input, Rotation speed is output. The balance equation of the motor voltage is:

\[ U = L \frac{df}{dt} + RI + k_e n \]  \hspace{1cm} (1)

where \( U \) is the motor voltage; \( L \) is the stator winding inductance; \( f \) is the current; \( R \) is the stator winding resistance; \( k_e \) is the motor back EMF coefficient; \( n \) is the motor speed.

The torque equation is
\[ T_e = K_e I \quad (2) \]
\[ T_e = J \frac{dn}{dt} + T_l + B_v n \quad (3) \]

where \( T_e \) is the electromagnetic torque; \( J \) is the moment of inertia of the motor rotor; \( T_l \) is the load torque; \( n \) is the motor speed; \( B_v \) is the viscous friction coefficient; \( K_t \) is the motor torque coefficient.

According to the above formula, the system structure diagram can be obtained as shown in the figure below:

![System Structure Diagram](image)

Fig. 2 System Structure Diagram

3. Controller Design

3.1. Design of Fuzzy Control System

The traditional PID system only contains three control parameters, and has some disadvantages such as poor flexibility and easy to be affected by other machining environment. The usual form of the traditional PID system is:

\[ u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{de(t)}{dt} \quad (4) \]

where \( u(t) \) is the output; the proportional coefficient \( K_p \), the integral coefficient \( K_i \), and the differential coefficient \( K_d \) are the weighting coefficients of the system deviation \( e(t) \) and its integral and differential respectively. Obviously, only when the three parameters of \( K_p \), \( K_i \), and \( K_d \) are determined, the performance of the PID system can be determined. Pure differential operations are usually avoided by optimizing the function as follows:

\[ G(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d s = K_p \left( 1 + \frac{1}{T_i s} + \frac{T_d s}{N s + 1} \right) \quad (5) \]

In general, \( N \) takes \( N=10 \), which can approximate the actual differential effect.

PID control is based on the deviation between the output and the input of the system, weighting the deviation through proportion, integration, and differentiation, so that the error changes in the decreasing direction to adjust the controlled object of the system. However, the traditional PID system has obvious shortcomings when controlling nonlinear objects. Its parameters cannot be self-tuning, and it is difficult to deal with complex nonlinear systems. Self-adjustment of parameters can be achieved through fuzzy PID algorithm.

The principle diagram of speed control composed of fuzzy PID is as follows:
It can be seen that there are two inputs for the fuzzy control system, corresponding to the error amount \( e \) and the error change amount \( ec \), and there are three outputs, corresponding to the proportional coefficient \( K_p' \), the integral coefficient \( K_i' \) and the differential coefficient \( K_d' \):

\[
e = n_j - n \quad (6)
\]

\[
e c = e_i - e_{i-1} \quad (7)
\]

The amount of error \( e \) and error change rate \( ec \) after fuzzification are \( E \) and \( EC \), respectively. Their domain is [-3,3], using triangular membership functions.

\[
E = k_e(e - \frac{e_{max} - e_{min}}{2}) \quad (8)
\]

\[
EC = k_{ec}(ec - \frac{ec_{max} - ec_{min}}{2}) \quad (9)
\]

where \( k_e = \frac{6}{e_{max} - e_{min}} \); \( k_{ec} = \frac{6}{ec_{max} - ec_{min}} \)

Divided the value range 7-level values subsets \{NL, NM, NS, ZE, PS, PM, PL\}, which represents {negative large, negative medium, negative small, zero, positive small, positive medium, positive large}.

### 3.2. Fuzzy Rule

In PID control system, proportional control determines response speed, integral control eliminates steady-state deviation, and differential control changes dynamic characteristics. Based on this, the following fuzzy rule table is established:

| \( E \) | EC | NL | NM | NS | ZE | PS | PM | PL |
|-------|----|----|----|----|----|----|----|----|
| NL    | PL/ NL/ PS | PL/ NL/ NS | PS/ NM/ NL | PS/ NM/ NL | PS/ NS/ NL | PS/ NS/ NL | ZE/ ZE/ NS | ZE/ ZE/ PS |
| NM    | PL/ NL/ PS | PL/ NL/ NS | PS/ NM/ NL | PS/ NM/ NL | PS/ NS/ NL | PS/ NS/ NL | ZE/ ZE/ NS | NS/ ZE/ ZE |
| NS    | PM/ NL/ ZE | PM/ NM/ NS | PM/ NS/ NM | PS/ NS/ NS | ZE/ ZE/ NS | NS/ PS/ NS | ZE/ ZE/ NS | NS/ ZE/ ZE |
| ZE    | PS/ NM/ ZE | PM/ NM/ NS | PS/ NS/ NS | ZE/ ZE/ NS | NS/ PS/ NS | ZE/ ZE/ NS | NS/ ZE/ ZE | NS/ ZE/ ZE |
| PS    | PM/ ZE/ PL | PS/ NS/ ZE | ZE/ ZE/ ZE | NS/ PS/ ZE | NS/ PM/ ZE | NM/ PM/ ZE | PL/ PL/ ZE | PL/ PL/ ZE |
| PM    | PS/ ZE/ PL | PS/ ZE/ NS | NS/ PS/ PS | NM/ PM/ PS | NM/ PM/ ZE | NM/ PL/ PS | PL/ PL/ PL | PL/ PL/ PL |
| PL    | ZE/ ZE/ PL | ZE/ ZE/ PM | NM/ PS/ PM | NM/ PS/ PM | NM/ PM/ PS | NM/ PL/ PS | PL/ PL/ PL | PL/ PL/ PL |

The value obtained by fuzzy control rules and fuzzy reasoning is defuzzified by area-center method. The input of fuzzy PID system is \( E \) and \( EC \), and the output after modification is:
\[ u = \frac{\sum_{i=1}^{n} u_i A(u_i)}{\sum_{i=1}^{n} A(u_i)} \quad (10) \]

where: \( u \) is the exact output value after deblurring, \( u = [K_p, K_i, K_d] \), \( u_i \) is single output of the system, and \( A(u_i) \) is degree of membership at \( u_i \).

Correct the PID parameters through the fuzzy control rule table:

- \( K_p' = K_p + \Delta K_p \) (11)
- \( K_i' = K_i + \Delta K_i \) (12)
- \( K_d' = K_d + \Delta K_d \) (13)

where, \( K_p', K_i', K_d' \) are values corrected by the fuzzy PID system.

3.3. The Results of Simulation

The simulation model of the traditional PID and fuzzy PID control system was designed in MATLAB for analysis.

The result is shown below. The signal is input through two different control algorithms. The yellow line is the input value, the pink line is the output value of the traditional PID system, the blue line is the output value adjusted by the Fuzzy PID system. By comparing the output results of the two, it can be found that \( t = 2.0s \), the output value adjusted by the fuzzy PID system (blue line) basically reaches the equilibrium state, with less overshoot and more stable.

**Fig. 5 Controller Simulation Model**

**Fig. 6 Simulation Comparison Results**

The result shows that the Fuzzy PID system can get quickly response speed, less regulation time and overshoot when processing signal, so that the system can reach steady state faster.
4. Conclusion
In order to improve the accuracy and stability of the spindle speed of FSW, a speed control system based on fuzzy PID is proposed. Through control simulation experiments, the stability of the system is verified. The experimental results show that the fuzzy PID system is suitable for the speed control of the FSW spindle and can be better than the traditional single PID system.

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References
[1] Wan, L. and Y. Huang, Microstructure and Mechanical Properties of Al/Steel Friction Stir Lap Weld. Metals, 2017. 7(12): p. 542.
[2] Wan, L. and Y. Huang, Friction stir welding of dissimilar aluminum alloys and steels: a review. International journal of advanced manufacturing technology, 2018. 99(5-8): p. 1781-1811.
[3] Lee W, Schmuecker M, Mercardo UA, et al. Interfacial reaction in steel–aluminum joints made by friction stir welding. SerMater.2006;55:355–358.
[4] Chen, K., X. Liu and J. Ni, A review of friction stir–based processes for joining dissimilar materials. International journal of advanced manufacturing technology, 2019. 104(5): p. 1709-1731.
[5] Gibson, B.T., et al., Friction stir welding: Process, automation, and control. Journal of Manufacturing Processes, 2014. 16(1): p. 56-73.
[6] Abd Elnabi, M.M., et al., Influence of friction stir welding parameters on metallurgical and mechanical properties of dissimilar AA5454–AA7075 aluminum alloys. Journal of Materials Research and Technology, 2019. 8(2): p. 1684-1693.
[7] Safeen, M.W., et al., Effect of position and force tool control in friction stir welding of dissimilar aluminum-steel lap joints for automotive applications. Advances in manufacturing, 2020. 8(1): p. 59-71.
[8] Sree Sabari, S., S. Malarvizhi and V. Balasubramanian, Characteristics of FSW and UWF SW joints of AA2519-T87 aluminium alloy: Effect of tool rotation speed. Journal of Manufacturing Processes, 2016. 22: p. 278-289.