DEVELOPMENT OF NEW TOOL FOR FSW OF ALUMINUM AND STEEL WITH ENHANCED WEAR RESISTANCE

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ABSTRACT:

Honda developed a technology for joining aluminum and steel in automobile parts using friction stir welding (FSW). It is applied to the mass production of front subframe, which is an important structural component of vehi- cles, and about 2.3 million units have been manufactured over a six-year period. In this technology, wear of the tool is more severe than in the conventional aluminum-to-aluminum FSW. In order to address this problem and improve the competitiveness of this FSW method, we developed a new tool with enhanced wear resistance as well as adequate productivity, based on high-speed steel. The key is controlling hardness distribution in the tool by applying a special heat treatment technique. In a welding test using mass production welding equipment, it was confirmed that the wear resistance of the developed tool improved by nine times compared to the conventional tool.

Key Words: FSW, tool, dissimilar material welding, mass production, wear resistance

1 Introduction

Recently, increasing amounts of aluminum is applied to automobile bodies aiming for weight reduction, due to the demands for suppressing global warming by improving the fuel efficiency of automobiles. The current trend is the use of both aluminum and steel, considering the balance of weight and cost. In this case called as ``multi-material body", mechanical joining using bolts or rivets are widely applied to join aluminum and steel. This is for avoiding the formation of brittle intermetallic compounds (IMC), which is significant in fusion welding. However, the use of these secondary materials increases the weight and cost. Friction stir welding (FSW) is one of the ways to join aluminum and steel, which does not use secondary materials and canminimize the amount of IMCs. Honda developed a technology for joining aluminum and steel in automobile parts us- ing FSW1),2). It has been applied to the mass production of front subframe, which is an important structural compo- nent of commercial vehicles (Fig. 1). More than 2.3 mil- lion vehicles have been produced with this technology over a six-year period. In the current mass production, Ni base alloy is used for the tool. However, tool wear is remarkably accelerated compared to conventional aluminum-to-alumi- num FSW. Therefore, a new tool with enhanced wear resistance is required. The wear resistance of FSW tool is related to the hardness at high temperature. In some cases in FSW of steels, hard Ir alloy3) and silicon nitride4) are ap- plied to the tool in order to improve the wear resistance. However, these materials are difficult to be applied to themass production of automobile parts, due to their poor procurability and high cost. We focused on high-speed (HS) steel, having good procurability and even higher hardness compared to the Ni base alloy. The issues when applying HS steel is to keep both high hardness and tough- ness at high temperature. High hardness secures the wear resistance, but has a risk of fracture of the tool. To address this issue, the hardness distribution of the whole tool was controlled by applying a special heat treatment technique. In this paper, the concept and basic properties of this developed tool is introduced first. Then, test results for optimi- zation of welding conditions, and verification of resistance of the developed tool are shown and discussed.

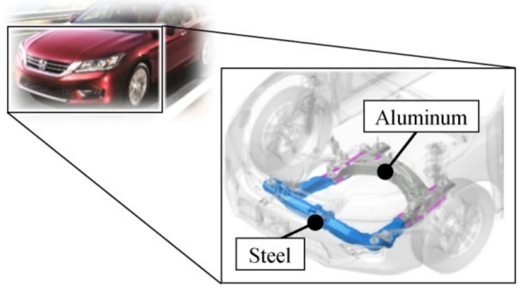


Fig. 1 Mounting position of front subframe in a vehicle.

2 Material Properties Demanded for Aluminum-Steel FSW

Fig. 2 shows the detail of the developed FSW method. The steel part, which has been already painted and coated with sealer to prevent electrolytic corrosion, and the aluminumpart is stacked. Then, the tool is inserted from the aluminum side, and intruded into the steel by a certain amount in order to create a fresh surface of steel. This means that the probe tip is heated significantly compared to the conventional aluminum-to-aluminumFSW. The temperature near the tip of the Ni base alloy tool during welding has been measured to be 530°C, indicating that high hardness at 500 to 600°C is required for the tool. In addition, a greater load is applied to the probe along the welding direction, which means high risk of fracture at the base part of the probe, where severe stress concentration occurs. Therefore, it is required to satisfy both conflicting properties of high hardness at the tip and high toughness at the base of the probe.

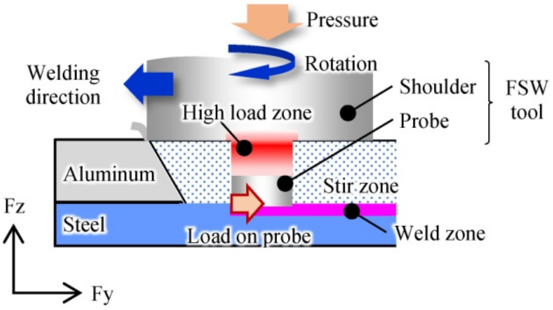


Fig. 2 Schematic drawing of aluminum-steel FSW during welding

3 The Concept of Development of the New FSW Tool

In this section, the concept and details of the development of the new tool, which was proceeded in order to satisfy the required properties.

1) Alloy design for securing wear resistance

In the present FSW method, the wear of the probe is accelerated by the hard steel matrix. In addition, the use of galvaneealed steel, of which the coating layer of Zn□Fe alloy generally has high Vickers hardness of 200 to 500 HV, is supposed. Therefore, the amounts of alloy elements of the material that strengthen the matrix and improve the wear resistance were increased. As was already mentioned, the temperature of the probe tip reaches over 500°C during welding. Furthermore, the tool experiences repeated heat cycles, composed of heating by welding and slow cooling to around room temperature, in mass production. Therefore, it is required to secure both high temperature hardness and resistance against repeated heat cycles. For addressing this demand, the chemical composition of the material was adjusted to create a matrix with good heat cycle resistance.

2) Manufacturing process for securing toughness Generally in tool steels, coarse primary carbides in the microstructure decrease the toughness of the material. Therefore, in order to achieve fine and uniform morphology of the carbides, special melting equipment and casting technology were applied in the manufacturing of the material.

3) Optimization of mechanical properties as an FSW tool As shown in Fig. 2, The FSW tool receives complex load due to the pressing and rotation during welding, resulting in difference in required properties for each part of the tool. High hardness (wear resistance) is the most important at the probe tip, while toughness is also required in the base part of the probe. Therefore, the balance of mechanical properties (hardness and toughness) was optimized for each part, applying a special heat treatment technique. The whole tool was first quenched to be martensite with high hardness. Nest, the tool was tempered to improve the toughness. This tempering process was carried out by a combination of heating at the end of the clamped part and partial cooling of the tool. By controlling the temperature of the clamped part

and the shoulder to be predetermined values, continuous distribution of mechanical properties between the probe tip and the clamped part was achieved. Fig. 3 shows hardness distribution of the tool. It exhibits that the hardness is the highest at the probe tip and is thensuccessively reduced. Consequently, high wear resistance at the probe tip and improved toughness at the probe base were simultaneously achieved.

Fig. 4 shows the hardness of probe tip as a function of temperature. It was confirmed that sufficient hardness is kept at the temperature range of 500 to 600°C. Fig. 5

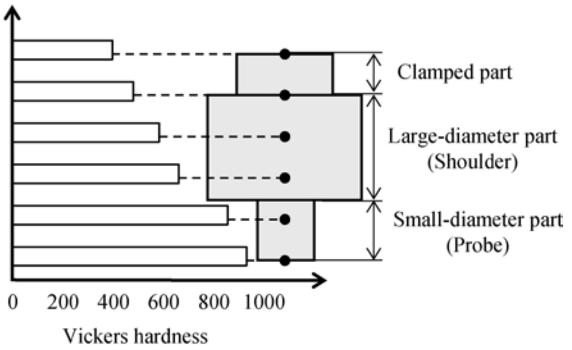


Fig. 3 Hardness distribution of developed tool

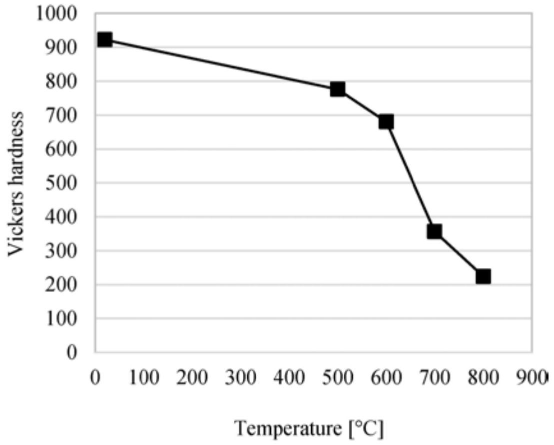


Fig. 4 Relationship between temperature and hard- ness of probe tip of the developed tool

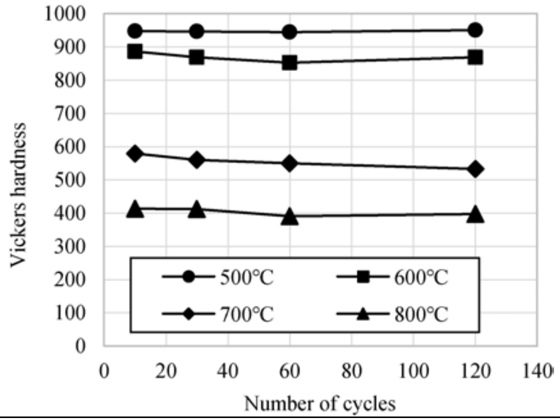


Fig. 5 Relationship between number of thermal cy- cles and hardness of the developed toolshows room temperature hardness of the probe tip after ap- plying various cycles of heating and cooling, which simu- late the actual welding condition. It was also confirmed that the hardness of the probe tip does not change after 120 cy- cles of heat treatment, regardless of the maximum temper- ature in the thermal cycle.

4 Test Procedure

4.1 Optimization of Plunging Depth

In the application of the developed tool to the mass production, welding condition should be optimized. Here, optimization process of plunging depth of the tool from the aluminum/steel interface into the steel side is described. That is the most important process parameter in the present FSW. Welding tests were performed using test pieces. The materials used were 3.0 mm thick die-cast alu- minum developed based on JIS H 5302 : 2006 ADC3 (Cu 0.6 mass% or less, Si 9.0 to 11.0 mass%, Mg 0.4 to 0.6 mass%) (hereafter, ADC3 equivalent material) and 2.0 mm thick 270 MPa class hot-dip galvanized steel sheet (hereafter, GI steel sheet). Two materials both having the size of 300 mm×100 mm were stacked and welded out at the speed of 700 mm・min－1, rotation of 850 min－1, and various plunging depth (set depth). The tests were carried out by mounting the tool in a machining center made by Shin Nippon Koki Co., Ltd. Each set of test pieces was FSW processed with a weld length equivalent to that of one front subframe, and totally 50 test piece sets were welded with various plunging depth. The temperature of probe during welding was measured by mounting a K thermocou- ple, having a diameter of 0.1 mm, inside the probe at a posi- tion of 1 mm from the tip surface (Fig. 6). The axial load applied to the tool during welding (hereafter, load) was measured using a four-component fixed-type dynamometer made by Kistler Japan Co., Ltd. (Fig. 7). In addition, after welding, Vickers hardness was measured at the cross sec- tion of the probe tip at room temperature (hereafter, room temperature hardness), by a load of 300 g, in order topredict the reached temperature during welding.

Fig. 6 Cross-section of FSW tool used for

temperature measurement

Verification of Wear Resistance

The wear resistance of the developed tool was verified by a welding test using the front subfrrame and the weld- ing equipment in mass production. The appearance of the equipment, made by F-TECH, Inc. and F&P America Mfg., Inc., is shown in Fig. 8. 3.0 mm thick ADC3 equiva- lent material and 2.0 mm thick270 MPa class GI steel sheet were welded at a speed of 700 mm・min−1 and a rotation of 850 min−1. The probe plunging depth was set at the op- timal amount determined in section 4.1. The test was per formed using the same procedure as that in actual mass production as shown in Fig. 9. Materials adhered to the probe tip was automatically removed. The probe length was automatically measured each time one subframe was welded. Both the developed tool and conventional one us- ing Ni base alloy were applied, and each 50 subframes were welded. Vickers hardness at room temperature was meas- ured at the cross section of the tool after the test, in order to predict the reached temperatures and to clarify the change in hardness during welding.

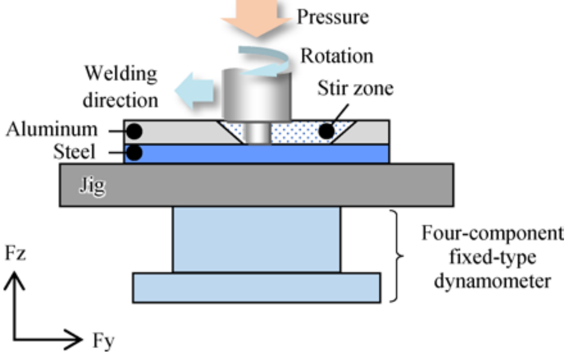


Fig. 7 Axial load applied to FSW tool during welding

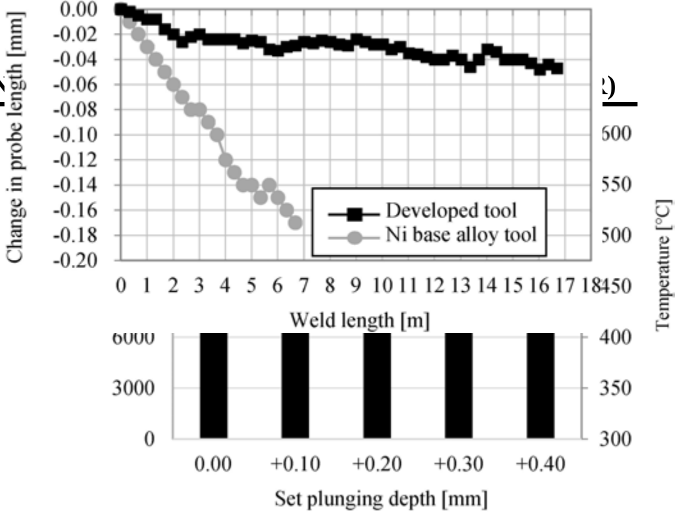


Fig. 8 Welding equipment for mass production

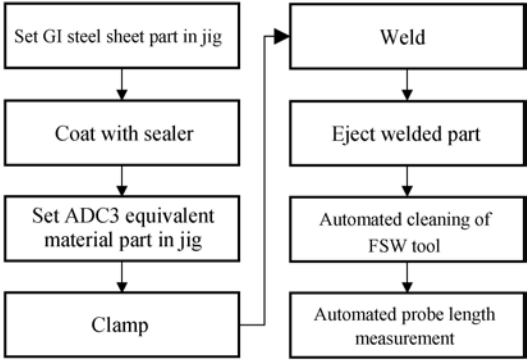
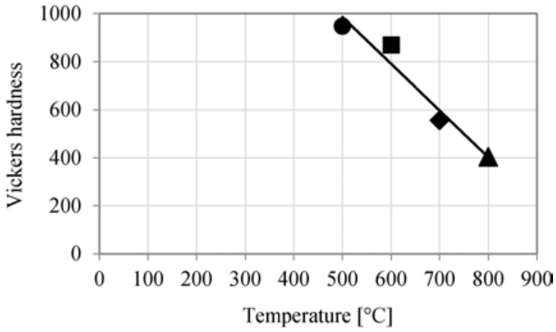


Fig. 9 Procedure of the welding process of front subframe

Fig. 10 Load and probe internal temperature as



a function of plunging depth

Fig. 11 Relationship between maximum tempera- ture in the thermal cycle and average room temperature hardness after thermal cycles of 10, 30, 60 and 120

Fig. 13 Change in probe length in the developed tool and Ni base alloy tool as a function of weld length

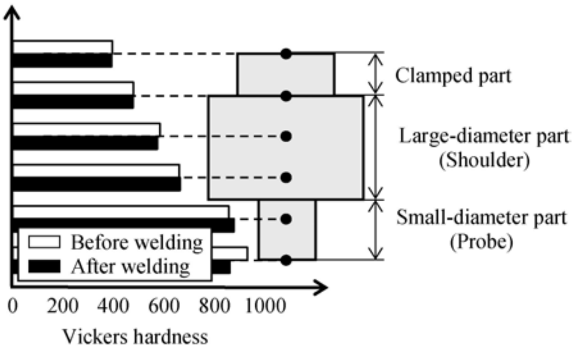


Fig. 14 Hardness distribution of the developed tool before and after the verification test of wear resistance

5 Results and Discussion

5.1 Relationship between Plunging depth, Load and Temperature

Fig. 10 shows the load and the internal temperature of probe as a function of probe plunging depth for the developed tool obtained in the welding tests using test pieces. As the plunging depth increased, both the load and temperature tended to increase. This is probably due to the increase in heat generation at the probe tip by increasing the plunging depth. The load and temperature significantly increased when the plunging depth exceeded ＋0.20 mm. The room temperature hardness of the probe tip after welding 50 sets of test pieces was 575 HV, which was significantly lower than that before testing (939 HV). In contrast, the hardness at a plunging depth of ＋0.10 mm was 922 HV after welding, which was almost the same as that before welding. In Fig. 11, in order to assume the temperature at the probe tip surface during the welding tests, hardness data shown in Fig. 5 are plotted as a function of maximum tool temperature in the thermal cycle. The hardness values are the average of the data for thermal cycles of 10, 30, 60 and 120 at each temperature. The relationship between the temperature and hardness can be approximated as an equation assuming linear relationship:

$$HV = -1.945T + 1958 \qquad (1)$$

where HV and T are the Vickers hardness and temperature in Celsius degree, respectively. Applying equation (1) using the measured hardness values of 922 HV and 575 HV, which were described above, the probe tip temperatures at the plunging depth of 0.10 mm and 0.20 mm are assumed to be 533°C and 671°C, respectively. These data are plotted in Fig. 12, which provides a formula to predict the temperature during welding from the plunging depth as follows:

$$T' = 1331D + 394.7 \qquad (2)$$

where T' and D are predicted temperature and the plunging depth set in the welding, respectively. From equation (2), it is assumed that the target probe tip temperature range of 600°C or less can be achieved by setting the plunging depth to be ＋0.149 mm or less. Therefore, additional welding tests were performed with a plunging depth of ＋0.15 mm. The room temperature hardness of the probe tip after the test was 867 HV, which is only slightly lower than that before welding. This infers that the temperature during welding did not reach 600°C; that is to say, welding could be performed in the target temperature range. Therefore, the optimal plunging depth for the developedtool was set to be ＋0.15 mm or less.

5.2 Enhancement of Wear Resistance

Fig. 13 shows change in probe length as a function of weld length, obtained in the welding of subframes with the mass-production welding equipment. In the Ni base alloy tool, the wear amount per unit weld length was 0.025 mm, while only 0.0028 mm in the developed tool. It indicates that the wear resistance improved by nine times in the developed tool compared to the conventional one. In addition, the room temperature hardness of the tip of the developed tool was 861 HV after the test, showing that the drop in hardness was suppressed by optimizing the plunging depth. All of the welded front subframes were inspected using a nondestructive inspection system, and it was confirmed that all of them satisfy the required quality. The developed tool did not show fracture at the probe after welding of 50 subframes. Fig. 14 shows room temperature hardness of the developed tool at each part, before and after the welding test. Each area except for the probe tip exhibited only small change in hardness before and after the test (only 2.5% or less). This indicates that the targethardness distribution was maintained after the tests, resulting in maintaining the performance during the weld- ing of a number of subframes. The overall results demon- strate that the demands for the tool in the present FSW method (balance of hardness and toughness) were satis- ˆed by the newly developed HS steel tool.

6 Conclusion

In this paper, a new tool for aluminum-steel FSW was in- troduced. The welding condition was optimized and the wear resistance of the tool was veriˆed. The obtained results are summarized below.

☐Based on high-speed steel, the material with good hard- ness at high temperature and enhanced toughness that satisˆes the demands for aluminum-steel FSW wasdeve- loped.

☐It was conˆrmed that the load and temperature at the tool tip can be controlled by the probe plunging depth to the steel side. Based on this result, the welding condition was optimized.

☐50 front subframes were welded in succession using welding equipment for mass-production, under the same conditions as mass production. It was conˆrmed that probe chipping did not occur and wear resistance was enhanced by approximately nine times compared to the conventional tool.

Reference

1) T. Miyahara, M. Sayama, T. Yahaba, S. Ohhama, T. Hata, T. Kobayashi: ``Development of Steel and Aluminum Continuous Welding Technology Using FSW and Application to Sub- frames," Honda R&D Technical Review, Vol.25, No.1, p.71☐77, (2019)

2) S. Ohhama, T. Miyahara, M. Sayama, T. Hata, T. Kobayashi, T. Yahaba: ``Application of an FSW Continuous Welding Technology for Steel and Aluminum to an Automotive Subframe," SAE Technical Paper 2013☐01☐0372, (2013)

3) T. Miyazawa, Y. Iwamoto, T. Maruko, H. Fujii: ``Friction stir welding of 304 stainless steel using Ir based alloy tool," Quarter- ly Journal of the Japan Welding Society, Vol. 29, No.4, p.305☐ 311, (2011)

4) R. Takizawa, N. Nakayama, T. Kosugi, J. Aizawa, Y. Komatsu: ``Study on Friction Stir Welding of Steel (1st Report) ―Behavior of Friction Stir Welding Tool," Research Reports of Nagano Prefecture General Industrial Technology Center, No.7, p.23☐27, (2012)

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