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Key factors for warm rolled bond of 6111-aluminium strip

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Abstract: Based on rolling tests and simulation, the bond behavior and its mechanism of 6111-aluminum alloy commonly used in auto industry were studied. As main factors, the effects of different heating stratagem, rolling speed and reduction on bond were tested. The effect of rolling speed on bond was produced by the synthetical result of contact time and temperature of rolling zone. Higher speed creates higher temperature of rolling zone but decreases contact time of interfaces, and bond strength decreases accordingly. The bond strength increases along with the increase of entry temperature before a turning point, after the turning point bond strength changes gently. Cold rolling is hard to get a satisfying bond result although the rolling parameters are adjusted, while warm bond reaches a higher strength that is comparable to the parent material. The analysis of surfaces separated by shear test shows that for warm bonding the rolling texture disappears on the bond area but the scratch track remain on the bond area for cold bond. There is no gap at the position of interface for well-bond sample. The results of this study are helpful to create well-bond materials for auto industry.

Key words: 6111-aluminum alloy; rolling; bonding

1 Introduction

The bonding of structure materials is a crucial developing area of modern material. Using special techniques to bonding materials with different features can overcome the localization of single material, and get a composite with several good natures. Therefore, bonding of materials has been studied in many aspects especially in the area of cold bonding by rolling[1−8].

Intending to get optimum conditions for good bond, many researches have been done to investigate the mechanism of cold bond by BAY and ZHANG. Those factors included surface preparation, annealing temperature, process reduction, contact friction, grain size and so on[1, 9−11]. At the same time, the microstructure features of bond interface and intermetallic compounds around bond area have been cheeked[2, 3, 8, 9, 11, 12]. In order to enhance bond strength, different coating materials and techniques have been studied[7, 13, 14]. The methods to measure bond strength were promoted[3, 6]. Based on the structure of interface, HWANG et al studied the theoretical models of bond strength, bond process[4, 5, 15−18]. MADAAH-HOSSEINI and KOKABI[3] also built a method to evaluate the bond efficiency.

Useful rules for cold bond have been suggested in different researches. Annealing temperature, reduction, effective time, proper surface treatment were considered main factors affecting bond result. Good bond has been introduced by using suitable technological processes that usually include annealing. Annealing was an impactful way to reduce the energy needed for bond, but it also reduced the whole strength of material including the bond strength.

In this paper the warm rolled bond was mainly studied compared to cold bond. The objective was to search proper condition for rolled bond of 6111 aluminum which is a common auto material, and the difference was found between warm bond and cold bond.

2 Experimental

2.1 Equipment

The two-high experimental mill is 249.8 mm in diameter by 150 mm in length, tool steel rolls, and hardened to R_c=63. The surface roughness is R_a=0.4 μm, and the roughness direction is random, created by

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manually finishing the surface using 100 grit carbide paper. The mill is driven by 42 kW, constant torque, DC motor. Two force transducers are located under the bearing blocks of the lower work roll, measuring the roll separating force. Two torque transducers are placed in the drive spindles, leading to the roll torque. A shaft encoder monitors the rotational velocity of the roll. In computing the forward slip the minor slowdown of the motor under load is accounted for. A digital data acquisition is used to collect and process the results. The screwdown is by a hydraulic feedback control system.

2.2 Material properties

Aluminium alloys Al 6111, commonly used in the automotive industry, was studied with in the tests. The chemical compositions of the alloy are listed in Table 1.

Table 1 Chemical compositions of alloys (mass fraction, %)

Cu	Mn	Si	Zn	Mg	Al
0.82	0.21	0.21	0.02	<0.01	Bal.

The stress－strain curve of the 6111 alloy, obtained in a uniaxial tension test, is closely approximated the relation as $\sigma=(1+157\,\varepsilon)^{0.245}$ MPa. The pre-rolling roughness of Al6111 strips was R_a= 0.5 μm.

2.3 Experiment procedure

Experiments were conducted as the following steps: 1) Cut the samples to dimensions of 15 mm× 200 mm×0.97 mm. 2) Decreased the pre-bond surface with acetone. 3) Wrapped two pieces of strip with soft metal wire. 4) Heated or annealed. One way was to heat samples just before rolling, then rolled the hot samples immediately, here called it warm bonding. Other way was to anneal specimens at different temperatures, then roll them after cooled down to room temperature. It is cold bonding. 5) Rolled specimens to create bond. 6) Slutted sawing on bond specimens for shear strength test. The detail approach referred to Ref.[6]. 7) Tested shear strength with Instron System. Crosshead speed was 5 mm/m, relative humidity was 50% and temperature was 22°C. The bonding area A was measured using an optical microscope.

3 Simulation

According to principle of bonding, temperature, pressure and time are three key factors. The temperature of strip, reduction and rolling speed are the main factors affecting bonding result. In order to understand the roles of primary parameters on rolled bond, here used special software Eroll to simulate the temperature, contact time, pressure in rolling zone under different technological conditions. Eroll software was developed by the cooperation of University of Waterloo, Canada, and AGH University of Science and Technology, Poland. Symmetrical rolling was assumed.

The coefficient of friction between roll and strip was set as 0.4 (un-lubricated). The hardening of 6111 aluminum follows the equation listed in section 2.2. Initial thickness and width of strip were 1.94 mm (two layers) and 15 mm, respectively. Ambient temperature was 22 ℃. The finite element grid is built as shown in Fig.1.

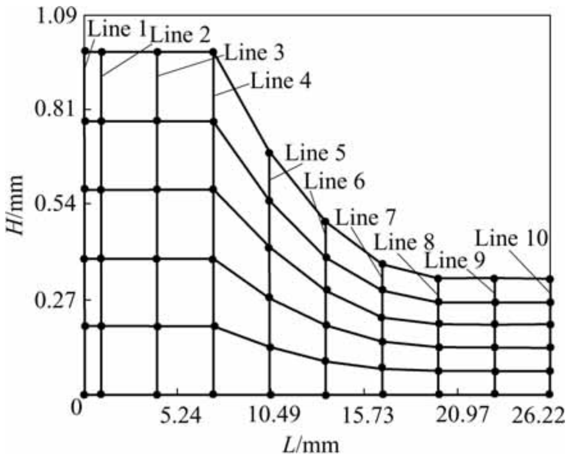

Fig. 1 Finite element model of strip

At reduction of 50%－70%, different rolling speeds of 4－12 r/min (52.3 to 157 mm/s) and entry temperature of 280 ℃, the simulation results of temperature distribution of interface along rolling direction are shown in Fig.2. It indicates that the

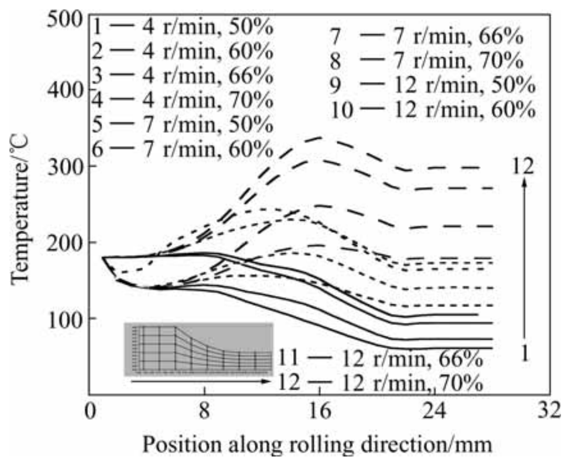

Fig.2 Temperature distribution of strip along rolling direction at different rolling speeds, reductions and entry temperatures

reduction and rolling speed has clear effect on the temperature of interface. Higher reduction and speed cause higher temperature. It can also be found that the change of rolling speed causes the change of tendency of temperature distribution and the highest temperature changes to rolling zone after rolling speed becomes higher.

Fig.3 reveals the average temperature of rolling zone at different entry temperatures and rolling speeds. It presents that rolling speed has significant effect on the average temperature of rolling zone while the entry temperature has little influence.

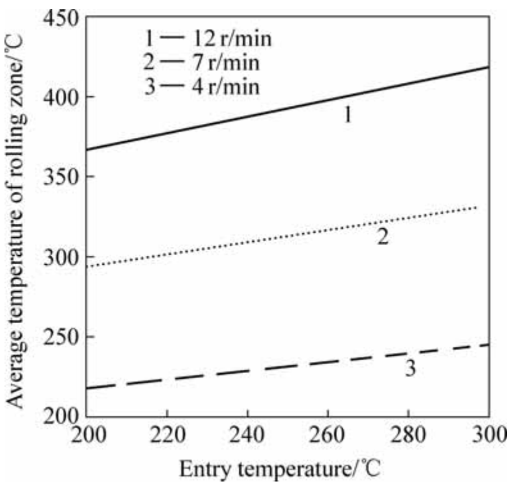

Fig.3 Average temperature of rolling zone at different entry temperatures and rolling speeds

Fig.4 shows the contact time between strip and rolls at different rolling speeds and reductions. Contact time is approximately in inverse proportion to rolling speed, and the effect of reduction on contact time becomes bigger at higher rolling speed.

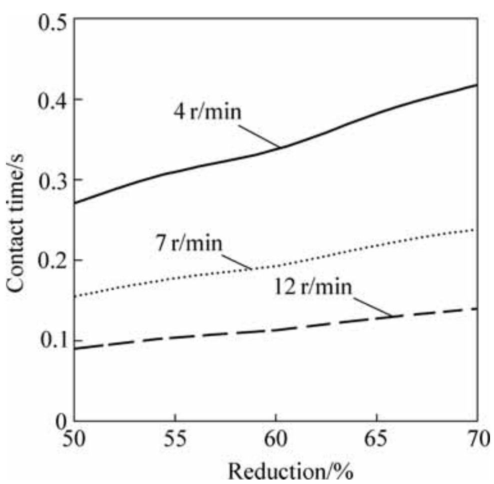

Fig.4 Contact time of strip to roll at different reductions and rolling speeds

Nearly the rolling pressure has a linear relation with reduction as shown as Fig.5. The average pressure in rolling zone is much higher than that in the case of normal diffusion bond.

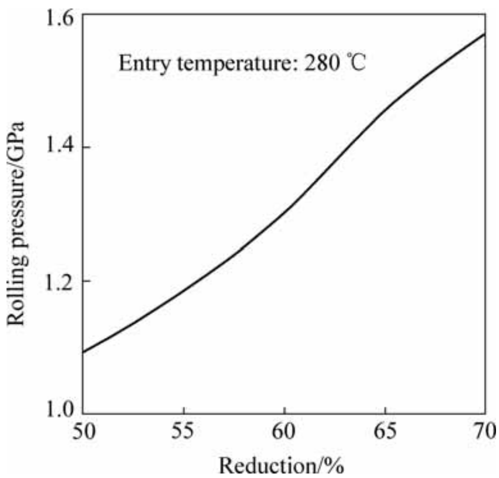

Fig.5 Relation between rolling pressure and reduction

4 Results

4.1 Effect of entry temperature or annealing temperature

4.1.1 Warm bonding

The relationship between shear strength of the bond and the entry temperature of the strips is shown in Fig.6, at reduction of 66% and velocity of 52.3 mm/s. It is observed that with increasing temperature the shear strength of bond also increases. The rate decreases and a maximum strength reaches at 280 ℃ ith no significant change beyond that temperature. It also indicates that good bond has been gotten in the period of 250−300 ℃.

For normal diffusion bond, the suitable tempera-

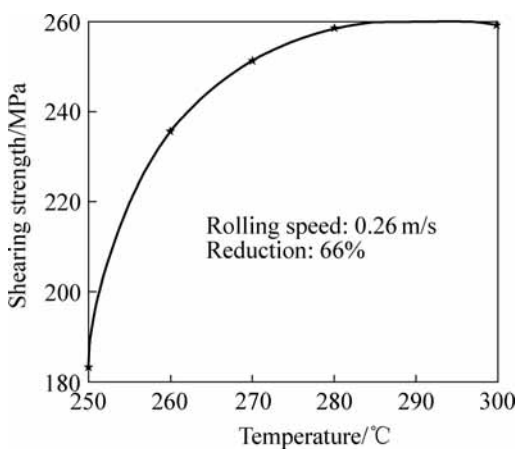

Fig.6 Relationship between shear bond strength and entry temperature of strips

ture is $(0.5-0.7)T_m$ (T_m is the melting point)[19]. Thereby the most suitable temperature for bond of 6111 aluminum is about 325 to 455 ℃. But from the simulation result (Fig.2) the temperature in rolling zone under the technological condition listed above is much lower than the temperature suitable for normal bond. It is the difference from normal diffusion bond. It may be the result of higher pressure or larger expending. Further study is needed in future.

Bonding experiments were also conducted at 200 ℃ entry temperature at reduction of 66%. No successful bonds were created.

4.1.2 Cold bonding

Roll bonding experiments of the 6111 aluminum at temperatures below 200 ℃ were not successful. But after annealing different bond results emerged. Strips were annealed at various temperatures for 2 h and then cooled down to ambient temperature before roll bonding. The results in Fig.7 show the bond strength in terms of the reduction and the annealing temperature. A reasonable bond can be obtained at room temperature and higher annealing temperature creates stronger bond, but bond strength is lower than that of warm bond. When the reduction is as high as 72%, the bond strength reaches 50 MPa, about 20% of the strength produced by warm bonding.

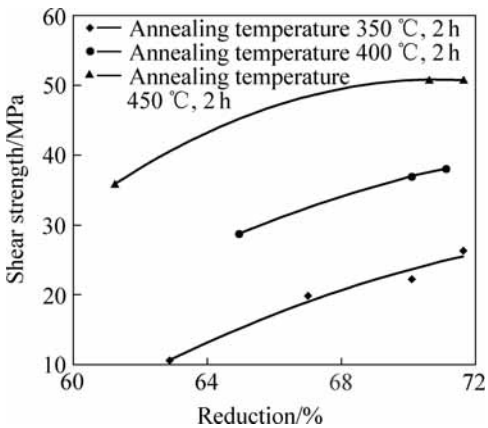

Fig.7 Effect of annealing temperature on shear strength at rolling speed of 260 mm/s

4.2 Effect of rolling speed

Rolling speed affects bond in two sides simultaneously. One side is to affect the interface temperature, high speed causes high temperature that is good for bond. Another is to affect the effective time for bond. The bond shear strength, obtained at an entry temperature of 280 ℃, is presented in Fig.8 as a function of the rolling speed. The shear strength is observed to decrease sharply as the speed increases, leading to shorter time of contact. Also observed is the effect of the reduction. At higher reductions the bond strength are higher, which also supports the effect of contact time. At the low speed of 52.3 mm/s the time of contact is about 380 ms, sufficient to create a bond whose shear strength is 230 MPa, approximately equivalent to the shear strength of the original material. Increasing rolling speed leads to sharply lower bond strength. Here results prove that for effect of rolling speed the factor of time is more important than its temperature utility.

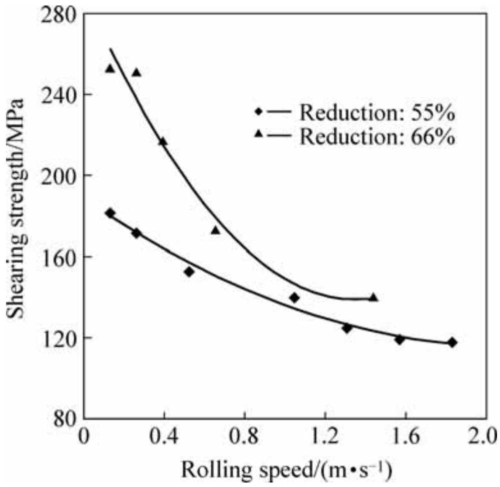

Fig.8 Relationship between shear strength and rolling speed at entering temperature of 280 ℃

4.3 Effect of reduction

Fig.9 shows the relation of reduction and bond strength for warm bonding process. Expectably bond strength increases with increasing reduction particularly in the stage of lower reduction. From Fig.7 similar tendencies can be found for cold bonding at different annealing temperatures. It is understandable that reduction increase contributes to the increase of temperature, rolling pressure, contact time

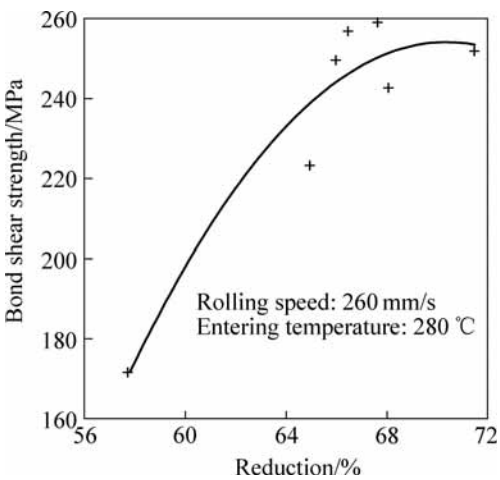

Fig.9 Relationship between bond strength and reduction at rolling speed of 260 mm/s and entering temperature of 280 ℃

and interface extending, etc. All these effects are related to bond results.

4.4 Examination of interface

The appearance of the bonded surfaces are observed. In order to identify the bonding features of different samples with different bonding effects (lower level, middle level and high level shear strength). Results obtained during warm bonding are given first, followed by the observations in cold bonding.

4.4.1 Warm bonding

Figs.10－ 12 show the micrographs of the bonding areas of the specimens with strong bond, average bond and poor bond, respectively. The differences are clearly observable. Fig.10, showing a strong bond, indicates significant permanent deformation of the asperity tops, giving rise to large true areas of contact. Fig.11, demonstrating the average bond strength, indicates similar behavior but the contact surfaces are somewhat smaller than those in Fig.10. The surface of the poorly bonded samples is show in Fig.12, demonstrates much lower roughness and noticeably smaller true area of contact. The fracture surface is not clearly shown, suggesting that bond only occurred at the top of the asperities.

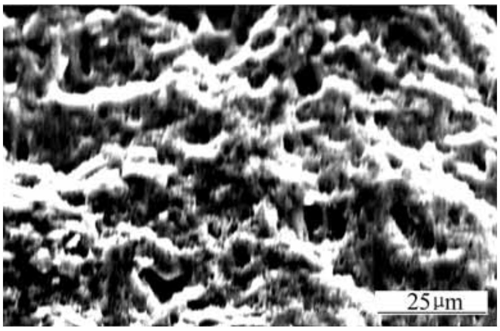

Fig.10 Sheared fracture micrograph of bonding area of well bonded specimen(entry temperature 280 ℃, rolling speed 52.3 mm/s, reduction 66.5%)

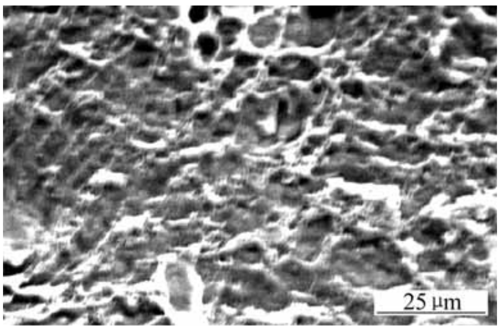

Fig.11 Sheared fracture micrograph for specimen with average bonding effect(entry temperature 280 ℃, rolling speed 78.5 mm/s, reduction 66.5%)

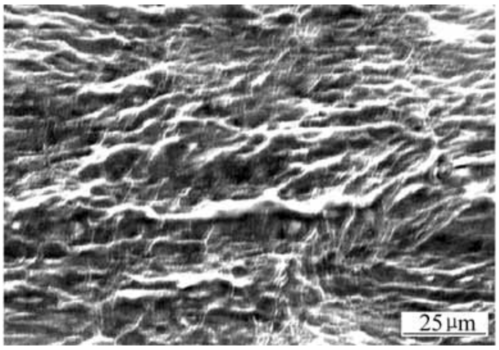

Fig.12 Sheared fracture micrograph of bonding area of poor bonding specimen(entry temperature 280 ℃, rolling speed 78.5 mm/s, reduction 48.5%)

The micrograph of sheared fracture of the strip matrix is shown in Fig.13. Its appearance is close to that in Fig.10, while the sheared fracture section of the matrix is rougher than the surface separated from well bonded specimen.

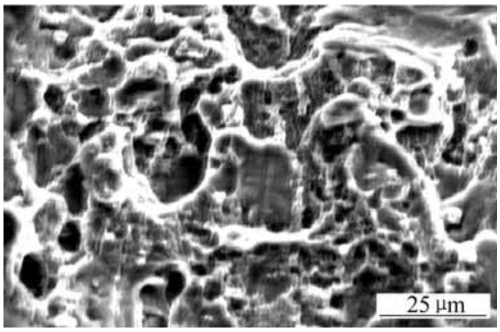

Fig.13 SEM image of sheared fracture of strip matrix

4.4.2 Cold bonding

The surface of contact in cold bonding, after shearing, is shown in Fig.14. The bond strength is 51.2 MPa, obtained at a reduction of 70.7%. The surface structure is significantly different from that of the warm bonded specimens. It is not the netlike structure but the structure with orientation that is the scratch track (it inherited from the rolling track). This indicates that the bond only happens on the micro-peak and the deformation mainly happens in the matrix for surface strengthening of scratch.

4.4.3 Side view of bond

The bond boundary of a two-layer rolled blank is shown in Fig.15. The parameters for creating the specimen were entry temperature of 280 ℃(the temperature of interface was about 440 ℃), rolling speed of 52.3 mm/s, reduction of 65.2%. Its shear strength was 238.7 MPa. Fig.15 also implies that the boundary area between two strips has different structures when compared with other areas. The different chemical composition and deformation have caused the special physical appearance.

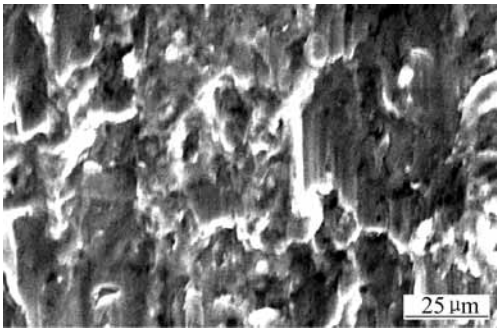

Fig.14 Sheared fracture micrograph of bonding area of cold bonding specimen(annealing temperature: 450 ℃, 2 h; rolling speed: 52.3 mm/s; reduction: 70.7%)

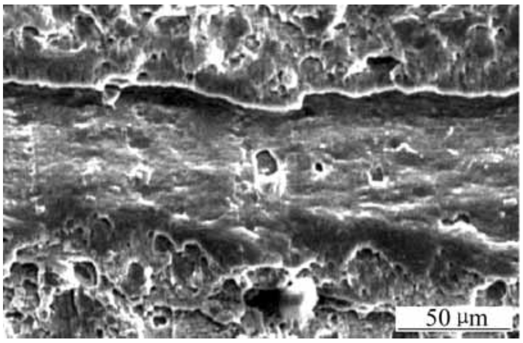

Fig.15 Cross section of warm bonded specimen(entry temperature 280 ℃, rolling speed 260 mm/s, reduction 65.2%)

The cross section of cold bonded specimen is shown in Fig. 16. There is a clear gap between two layers and this is very different from warm bond. It indicates again that bond only happens on the micro-peak of two surfaces. For this reason the strength of cold bond is hard to reach the same level as parent material.

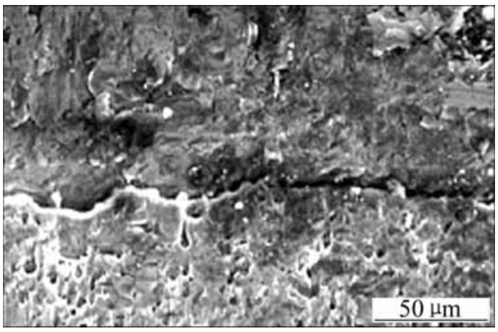

Fig.16 Cross section morphology of cold bond specimen (annealing temperature 450 ℃, 2 h, rolling speed 260 mm/s, reduction 70.7%)

5 Conclusions

1) Simulation results indicate that the tendency of interface temperature varies at different rolling speeds. Reduction affects contact time slightly while rolling speed affects contact time directly. The temperature of rolling zone under the conditions used in this article is much lower than that of normal diffusion bond.

2) Strong bonds whose shear strength are comparable to that of the parent metal can be created with 6111 aluminum alloy, by warm rolling bond.

3) Entry and annealing temperatures, reduction and the rolling speed are the three important parameters of the roll-bonding process. Warm bond creates higher bond shear strength than cold bond. In cold bond, it is impossible to reach the same strength as the parent material.

4) Different structures form at the bonding area under different bonding conditions. For warm bonding the rolling texture disappears on the bond area but the scratch track remains on the bond area for cold bond.

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