Impact Joining of Metallic Sheets and Evaluation of its Performance

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Abstract. Similar or dissimilar metallic sheets were joined at their edges by the original impact joining method developed by one of the authors. Surface layers of both sheet edges activated by high-speed shear are immediately contacted with sliding motion in the joining process. The whole processing time is within a few milliseconds. The materials tested were mild steel and titanium sheets. Drop-weight impact testing machine was used. Joining performance of the fabricated sheets was evaluated by tensile test, etc. The joining was not available all over the thickness between sheets, in which sharp notch was observed near both sheet surfaces. The central portion was successfully joined without cavity. The joined specimen of mild steel and titanium was sliced to remove surfaces with such notch. Fracture occurs at the part of mild steel whose strength is lower, then the joining boundary was not damaged.

Introduction

It is well known that time and temperature effects have important role in solid state joining by atomic diffusion at elevated temperature. On the other hand, under cold condition, if the surface expansion is relatively large, two metal parts can join at the newly created surface, in which the brittle oxidized surface layer fractures. Joining strength in solid state welding was found to be approximately equal to the normal applied stress during the process in the absence of oxide films for the case of aluminum welded together in 1970 [1]. The film theory of such kind of welding or bonding was established, in which roll bonding was applied in 1983 [2]. Recently the film theory was used to derive a model that quantifies the relevance of these parameters to the weld strength [3]. Cold bonding may have a potential for recycling scrap aluminum [4].

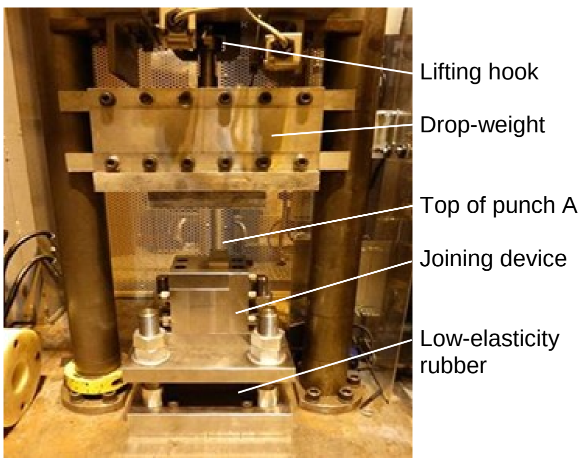
The diffusion bonding is usually achieved by very high compressive stress with large plastic deformation. The shape drastically changes from the initial one and the joining strength also depends on the initial surface condition. Surface treatment is necessary for removal of the dirty surface layer. Experimental results in diffusion bonding were summarized for various metals including superplastic alloys [5]. Joining of different metals were tested [6] and experiments were carried out using super plastic materials [7, 8]. Hot isostatic pressing was also effective for the diffusion bonding of the nickel powder onto alumina tubing [9]. Divergent extrusion was used for bonding of aluminum by means of two opposing punches and finite element simulations was conducted [10]. However, the method requires very special conditions in temperature, atmosphere, surface treatment, etc. and they are very time consuming.

One of the authors proposed a novel joining method for sheet metal [11]. The edge of the sheet is joined to another edge, where the sheet thickness is unchanged, because the plates are not plastically compressed. In the present study, the materials are mild steel and pure titanium sheets. Main objectives are to observe the motion of the tools and the materials in the device, and to check the deformation performance of the sheet composed of different materials by tensile and bending tests. The boundary was also inspected by elemental analysis.

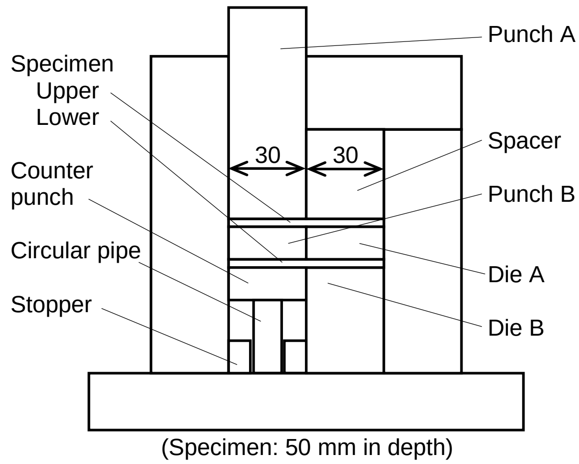
Experimental device and materials tested

The impact joining setup is shown in Fig.1. The device is driven by an impact of drop-weight. The mass was 22 kg and the impact velocity was 10 m/s. The left half of the lower sheet is supported by the counter punch, whose reactive force is given by compressing the circular pipe (A6061, 12 mm diameter and 1 mm thick wall). The top edge of punch A is impacted then the simultaneous shearing commences. The upper sheared face slides to fit the lower sheared face. The motion stops at the prescribed position. The device is mounted on the low-elastic rubber that is pre-compressed to avoid the damaging excessive force.

Test materials are mild steel sheet SPC of 1.0 or 3.2 mm thickness, and pure titanium sheet TP340 of 1.0 or 3.0 mm thickness. Their tensile strengths were 303, 317 and 427, 401 MPa, respectively. Overlap length in sliding stage was varied.



(a) Photo of setup



(b) Joining device

Fig.1 Experimental setup

Motion of tools and sheets in joining device

Motion of the tools and the sheets were observed with a high-speed video camera, in which the joining of TP340 (Upper specimen) and SPC (Lower one) was carried out. Progressive pictures are exhibited in Fig.2. The shear deformation and fracture of SPC are captured at time t: 87.7 and 439 μs, respectively. The left half of SPC moves downwards, then the TP340 also moves downwards after shear fracture. The TP340 appears at 2456 μs thereafter the edges of both materials slide each other with the prescribed overlap length at 3018 μs.

The sliding stage terminates at 3333 μs. The device sags due to the redundant energy of the drop-weight, where the low-elasticity rubber is compressed. It recovers at 6368 μs. Repulsion and contact between the tool and the drop-weight may occur in addition to the deceleration of the drop-weight, this causes the differences in moving distance of the tools calculated the impact velocity of 10 m/s.

Experimental result and discussions

Examples of joined specimens are exhibited in Fig.3 for the joining of different materials. No warping of the joined sheet with 1.0 mm thickness is observed, though the joining is not achieved all over the thickness. Sharp gap is observed at both surfaces of 1.0 and 3.0 mm thick sheets. The

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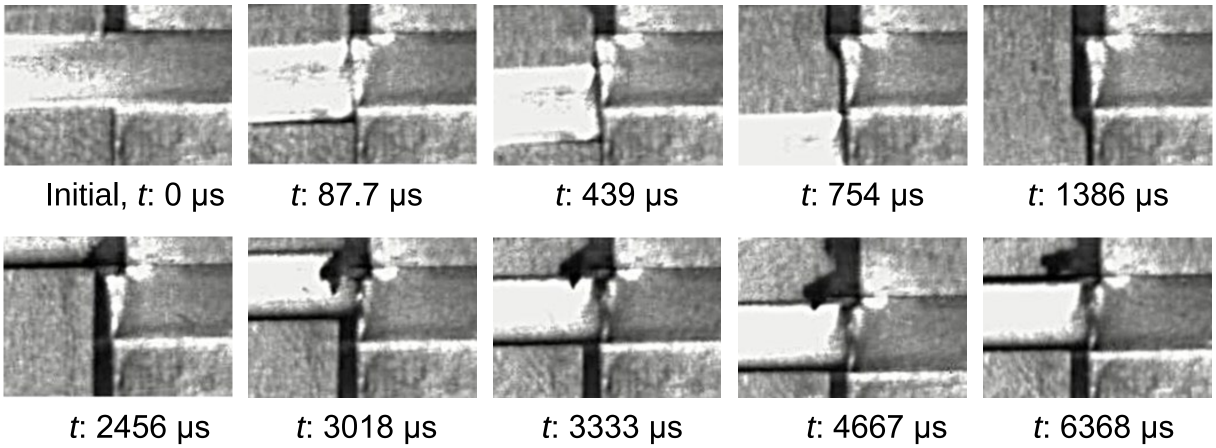
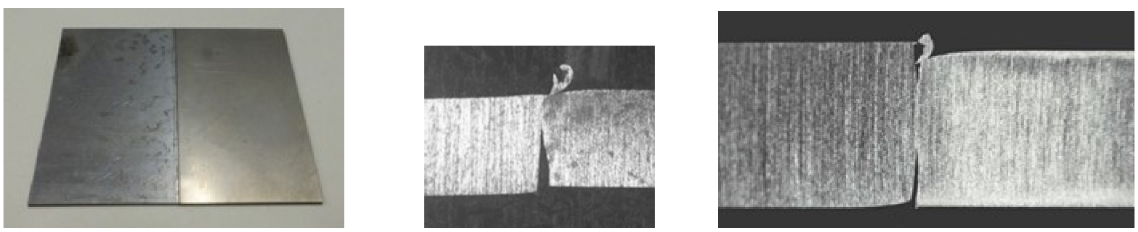


Fig.2 Progressive photos of joining process of TP340 (Left) and SPC (Right) observed by high-speed video (t: Time)



(a) SPC (*t*: 1.0 mm) + TP340 (*t*: 1.0 mm) (b) SPC (*t*: 3.2 mm) + TP340 (*t*: 3.0 mm)

Fig.3 Examples of joined specimen of SPC + TP340

joining is completed only for the central region. Protrusion of the SPC is seen at the upper gap. This is due to that TP340 scratches the softened surface material of SPC by high-speed shear. The sheared profile of thinner titanium sheet is not flat compared with the thicker one. This may be the reason of that the 1.0 mm thick titanium does not join.

Joining performance was evaluated as joining efficiency that is the relative tensile strength to the ultimate strength of the material. The specimen width is 10 mm. The performance is summarized in Fig.4 for the most appropriate overlap length *L*. It was set to 0.1, 0.2 or 0.3 mm. The performance is better for the thicker sheet in joining SPC together. The performance in joining TP340 together is also improved by increasing the sheet thickness or the sliding distance after shear process. Better performance in SPC is due to that the sheared face is flatter than that in TP340. However, the scattering in strength is remarkable. The reason is not clear at present, however, it may be attributable to the tool vibration, because the device is driven by a drop-weight.

The joining portion was specified by observing the boundary with a magnifying glass. Thickness of the specimen is decreased to approximately 0.5 mm by the removal of the both surface layers with sharp notch. The performance only for the apparent joined boundary is shown in Fig.4 (f) for 23 specimens. Over 90 % efficiency is obtained for 43 % of specimens. 100 % efficiency is achieved for 26 % of them, although the cases with very low efficiency also exist.

Figure 5 demonstrates the deformation patterns in tensile test. Initial width of the specimen was 3 ~ 5 mm. The maximum tensile stress can be determined appropriately, because the length is adequately long relative to the width. The specimen with 100 % efficiency exhibits diffuse necking at SPC part. It also fractures at the boundary in the latter case, where the width of SPC part shrinks.

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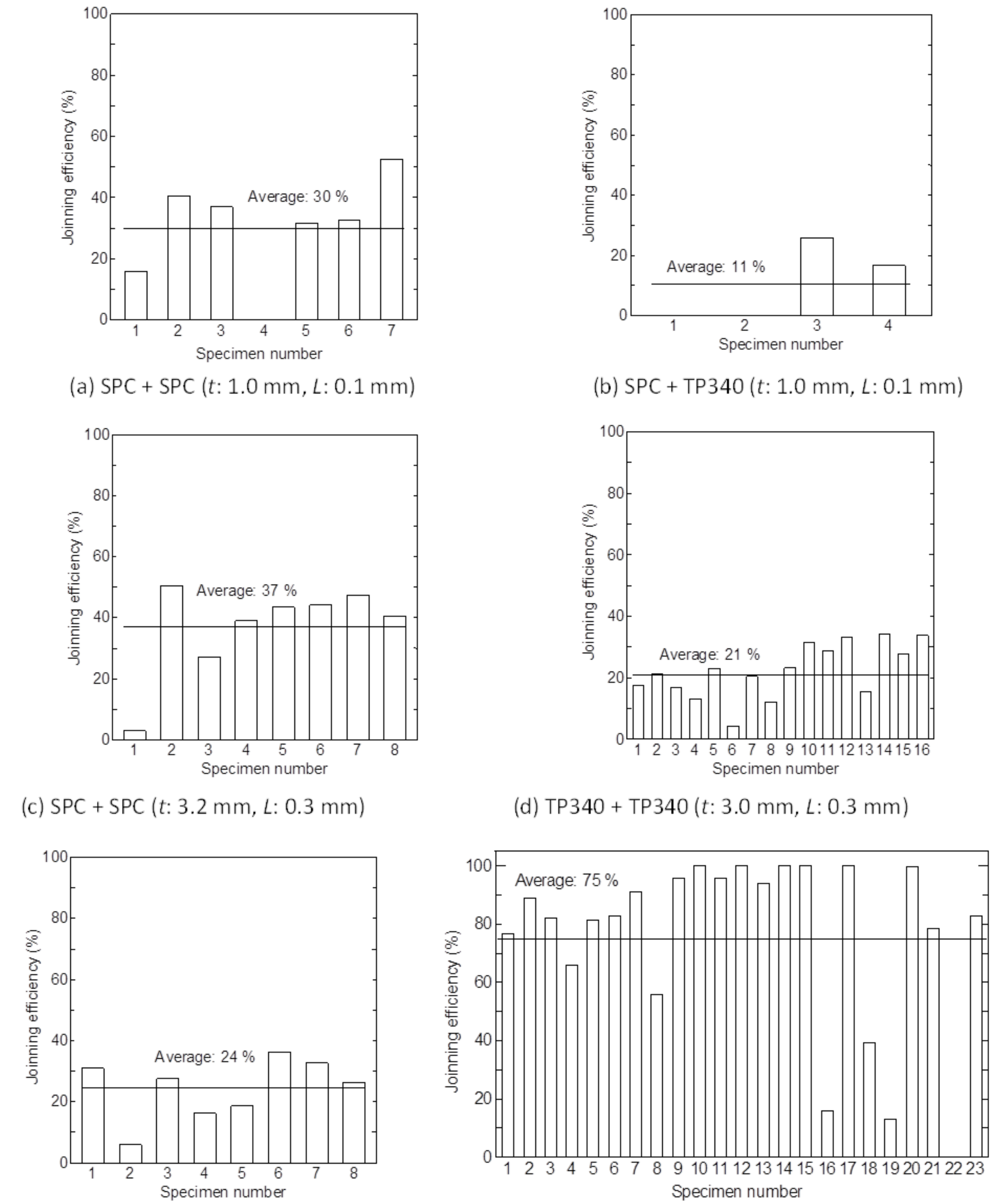

(a) SPC + SPC (t: 1.0 mm, L: 0.1 mm)

(b) SPC + TP340 (t: 1.0 mm, L: 0.1 mm)

(c) SPC + SPC (t: 3.2 mm, L: 0.3 mm)

(d) TP340 + TP340 (t: 3.0 mm, L: 0.3 mm)

(e) SPC + TP340 (t: 3.2, 3.0 mm, L: 0.3 mm)

(f) SPC + TP340 (Only joining part)

Fig.4 Summary of joining efficiency

The boundary of SPC and TP340 was analyzed with energy dispersive X-ray spectrometry as shown in Fig.6. Thin layer of a certain metallic compound was found to be generated. It may be Fe_2Ti or FeTi, which was found when titanium coating to the steel 35 by electro-spark deposition was carried out in argon [12].

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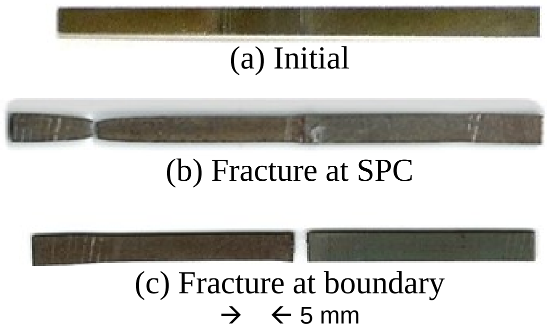


Fig.5 Deformed shapes of tensile test specimen (SPC + TP340, L: 0.3 mm)

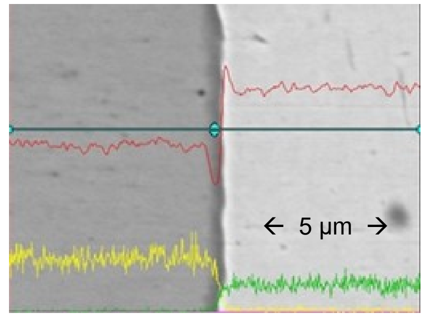
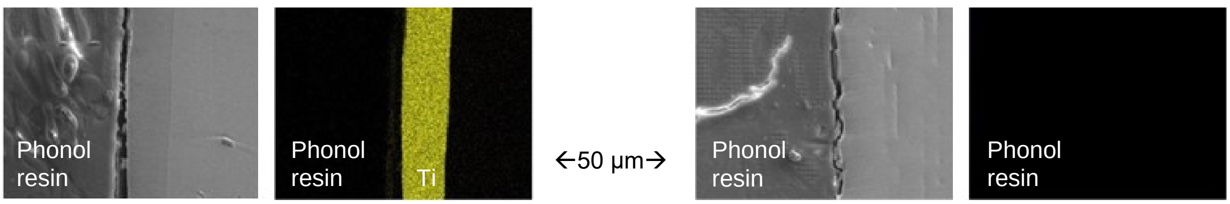


Fig.6 Boundary of joined specimen (Left: TP340, Right: SPC)



SEM photo Detection of Ti SEM photo No detection of Fe

(a) SPC side (b) TP340 side

Fig.7 Elemental analysis of notch portion (Specimen is enbeded in phenol resin.)

The surfaces in the notch are similarly analyzed as shown in Fig.7. The sheared face of the mild steel is covered with about 20 μm thick layer of titanium. This phenomenon reveals that the materials were once joined and separated during the sliding contact stage. However, the steel layer is not found at the surface of titanium. The volumetric heat capacity and the heat conductivity are lower in titanium. On the other hand, the yield stress is higher in the material. It implies that the surface layer of titanium is more softened than mild steel regardless that the melting temperature of titanium is about 200 K higher than steel.

Three-point bending test was conducted as shown in Fig.8. Width of the specimen is 25 mm. The span is 50 mm and the diameter of the anvils is 15 mm. Upper anvil is adhesively bonded to the sheet to avoid the relative slippage. The specimen SPC + TP340 of about 0.7 mm thickness is tested after removal of the surface layers with apparent notch. Figure 9 shows the 90° bent specimen, where the plastic deformation is very limited in the vicinity of the joining boundary. The joining was not achieved for the whole thickness. However, it is not separated. This suggests that the material holds ductility. For the narrower specimen shown in Fig.10, plastic deformation takes place

Fig.8 Three-point bending test

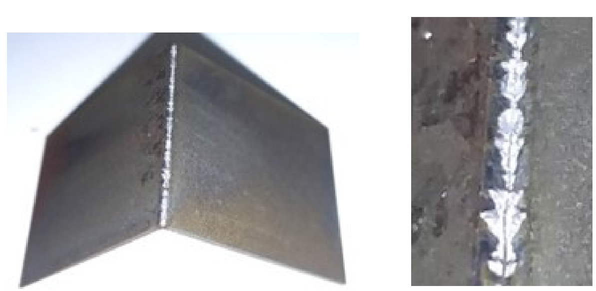


Fig.9 Bent specimen and enlarged view of the boundary

only in the SPC part that is weaker. The boundary is not damaged. The position of the upper anvil deviated from the central position at initial. The adhesive was not used in this case.

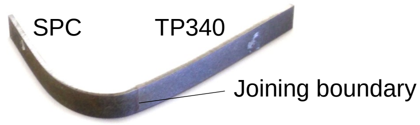


Fig.10 Bent specimen (t: 0.8 mm, w: 3.8 mm)

Conclusions

Impact joining experiment was carried out for mild steel and titanium sheets. Observation of the motion of tools and sheets in the joining device by high-speed camera uncovers that the process terminates at about 3 ms. The joining performance is better for the thicker sheet attributed to that the sliding distance is longer. Tensile test was performed using the specimen after removal of both surface layers with sharp notch. The efficiency over 90 % is obtained for 43 % of test specimens, and that with 100 % was obtained for more than quarter, in which fracture with diffuse necking was observed at SPC part, there was no damage at the joining boundary.

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