Title:

Influence of the Press Ram Motion on the Joining Characteristics during Indentation Plastic Joining Using a Servo Press

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Abstract

A plastic joining method for fixing bars and hot plates, called “indentation plastic joining”, was carried out using a servo press with press ram speed control. The influence of the press ram motion control on the indentation joining characteristics of an aluminum alloy bar and plate was examined. The accelerated ram motion was effective in reducing the bar indentation pressure by approximately 15% and the bonding strength of the indented bar–plate was improved by approximately 7%. The bonding mechanism underlying the indentation joining method under press ram motion control is discussed in terms of the seizure of the plate and the mechanical clamping associated with the process. It is found that the accelerated ram motion produces heavier seizure at the indented bar–plate interface, whereas the decelerated ram motion reduces the degree of the seizure.

Keywords: Plastic joining; Servo press; Press ram motion; Seizure; Mechanical clamping

1. Introduction

A variety of automotive parts, particularly those associated with the driving chain, have components with long shafts or axes with a wide plate-shaped body. The complicated

shapes of these parts are difficult to manufacture from a single billet using plastic working processes, such as hot forging. Instead, such parts are usually joined by means of bolting, welding, or plastic joining. Some plastic joining methods have been proposed in an effort to realize a simple and high-strength joining of a bar with a plate. For example, Machida (1987) and Yanagihara et al. (1987) proposed shave-joining and shear joining methods, respectively. Among the more recent developments, Kitamura et al. (2012) proposed a cold plastic joining method by which a high-strength shaft with serrated teeth was joined with a flange. Matsumoto et al. (2008) proposed a plastic joining method, “indentation plastic joining”, for fixing cold bars and hot plates. In this method, a cold bar was directly pressed into a hot plate to pierce the plate without lubrication using a conventional mechanical press, and the bar was then fixed to the plate after piercing. Matsumoto et al. (2009) applied this method to the joining of a steel bar and an aluminum plate as well as a steel bar and a steel plate.

Servo presses which permit control over the ram speed and motion, have been rapidly adopted by the metal forming industry to both improve the accuracy of conventional forming processes and to enable the development of novel forming processes (Osakada et al., 2011). Mori et al. (2007) described controlling the spring-back during bending of ultra-high-strength steel sheets. Kaya et al. (2008) included a heating process with the ram motion just prior to applying a drawing operation. Groche et al. (2010) developed a 3D servo press that could realize flexible forming processes. Servo presses have also been applied to indentation joining method. Matsumoto et al. (2011) proposed an indentation joining method in which the bar was oscillated using a servo press immediately after piercing the plate. The bonding strength of the indented bar–plate was obtained approximately 1.5 times value without the bar oscillation. Other ram motion controls using the servo press may have a potential to improve the bonding strength of the indented bar–plate in indentation joining method. Further improvement of the bonding strength is desirable for putting the indentation

plastic joining method to practical use.

In this study, indentation joining of a bar and a plate is carried out using a servo press with ram speed control. Three types of the press ram motion: standard (without press ram motion control), accelerated, and decelerated ram motions are tested to investigate the indentation joining characteristics of the resultant bar–plate. These press ram motions were explored in an effort to improve the workability of magnesium alloy in a warm forging process (Matsumoto and Osakada, 2010). The decelerated ram motion was found to improve the ductility by the constraining the degree of localized plastic deformation. In this study, the influence of the press ram motions on the indentation joining characteristics of aluminum alloy bar–plate is examined. The bonding mechanism underlying the indentation joining method under press ram motion control is discussed in terms of the seizure of the plate and the mechanical clamping associated with the process.

2. Indentation plastic joining

Figure 1 illustrates the indentation plastic joining method, a plastic flow joining method developed for fixing a cold bar to a hot plate. A cold bar is pressed into a hot plate without lubrication on a press until the plate has been pierced. The bar is then fixed to the plate after piercing. In this method, the newly created surface of the hot plate is expected to undergo seizure, which would lead to a high joining strength. After the plate has cooled, thermal shrinkage of the plate may increase the strength with which the bar is clamped.

Although welding or fixing by bolts is often employed to join bars and axes with forged parts, the productivities of these processes are low. The joining method enables a high-temperature hot-forged plate, as shown in Fig. 1, to be joined to a bar within a hot forging line using a press or other simple equipment. Some examples of the application of indentation joining are shown in Fig. 2: (a) a pipe indented into a plate, (b) a long shaft

indented into a plate, (c) plural bars indented into one plate, and (d) plural bars indented from different directions into one plate. The simplicity of the indentation joining process makes it adaptable to a variety of applications for industrial parts. Because high bonding strengths are critically important for industrial applications, further process improvements are strongly desired.

Fig. 1 Schematic illustration of the indentation plastic joining method used to fix a cold bar to a hot plate.

(a) Indentation of a pipe into a plate

(b) Indentation of a long shaft into a plate

(c) Indentation of plural bars into one plate

(d) Indentation of plural bars into one plate from different directions

Fig. 2 Some applications of the indentation plastic joining method (the bar and plate materials shown are composed of steel).

3. Experimental setups of the indentation plastic joining method and drawing test

3.1 Indentation plastic joining

Figure 3 shows the tool arrangement used for the indentation joining of a bar with a plate. The bar was held by the bar holder at room temperature and pushed into the plate without lubrication. The material of the bar and plate was AA6061-T6 wrought aluminum alloy. The diameter of the joining part of the bar was $D_B = 8.0$ mm with a surface roughness Ra of $1.0 \mu\text{m}$. The inner diameter of the die was 8.4 mm. Thus, the clearance between the bar and the die was 0.2 mm. A plate of 48 mm in diameter and $t_P = 8.0$ mm in thickness ($t_P/D_B = 1.0$) was used for this demonstration. A hole with a diameter $D_H = 7.0$ mm ($D_H/D_B = 0.88$) was created at the center of the indentation in the plate to reduce the indentation load on the bar. The plate was heated to a temperature of 330°C in an electric muffle furnace under an air atmosphere. The bar (at room temperature) was then indented into the plate held at $T_P = 300^\circ\text{C}$ after transferring to the die. The indentation depth of the bar exceeded the plate

thickness by 2.0 mm ($t_p+2.0$ mm). The surfaces of the bar and pate were degreased using acetone prior to conducting the experiment.

A 450 kN servo press (Komatsu Industrial Corp., H1F45) driven by an AC servomotor through a mechanical link (0–70 spm) was employed for the indentation joining experiments. Figure 4 shows plots of the press ram velocity-stroke without press ram speed control during bar indentation under various initial indentation velocities (v_i). The initial indentation speed was arbitrarily adjusted by controlling the motor speed of the servo press; however, the ram speed decreased toward the bottom dead center of the press because the motion of the servomotor was transmitted by a mechanical link. The strain rate was maintained at a relatively constant level. Figure 5 shows the operation mode of the press ram speed control and a plot of the press ram velocity-stroke curves under press ram speed control during the bar indentation process. Three operation modes were tested, each with a different types of press ram motion control applied during the indentation joining process. The standard motion without ram speed control during indentation joining is denoted ram motion (A) in Fig. 5. Accelerated and decelerated ram motions achieved by controlling the ram speed are denoted ram motions (B) and (C) in Fig. 5, respectively. Here, the ram motion (B) was called the accelerated ram motion because the strain rate increases during indentation joining. The initial indentation velocity was set at $v_i = 100$ mm/s in the ram motions. At the start position of the bar indentation process, the ram velocity of the ram motion (B) was programmed twice the velocity of the ram motion (A), whereas the ram velocity of the ram motion (C) was programmed 0.2 times the velocity of the ram motion (A). However, apparent differences in the ram velocity in the ram motions of (A), (B), (C) were appeared later on at an indentation depth of 2 mm.

Fig. 3 Tool configuration used for the indentation plastic joining method.

Fig. 4 Plot of the press ram velocity without press ram speed control during indentation plastic joining on servo press (v_I : initial velocity of the bar during indentation).

(a) Operation **program** of press ram speed control.

(b) Press ram speed.

Fig. 5 Operation modes for the press ram speed control, and a plot of the press ram velocity with press ram speed control during the indentation plastic joining process on a servo press ($v_1 = 100 \text{ mm/s}$). (A) Standard ram motion (without press ram speed control), (B) accelerated ram motion, (C) decelerated ram motion.

3.2 Drawing test

The bonding strength of the indented bar–plate was evaluated after indentation joining by pulling the indented bar away from the plate (in a drawing test) at room temperature using a material testing machine with a drawing velocity of 0.08 mm/s as shown in Fig. 6. The bonding strength was evaluated in terms of the maximum drawing load of the indented bar during the drawing test. The shear bonding stress (P_D) during drawing was calculated as follows:

P_D = Maximum drawing load of the indented bar/

Interface surface area of the indented bar–plate (1)

where the interface surface area of the indented bar–plate was $\pi D_B t_P$. The shear droop of the plate at the upper corner of the indented bar (see Fig. 11) and the burr of the plate at the bottom corner of the indented bar were very small relative to the plate thickness; therefore, these artifacts were not considered in the calculation of the indented bar–plate interface surface area.

Fig. 6 Drawing test of the indented bar from the plate after indentation plastic joining of the bar and plate.

4. Finite element analysis conditions

The deformation behaviors of the bar and plate during the bar indentation process were examined using finite element analysis. A commercial three-dimensional finite element method code, DEFORM-3D ver.10.2 SP1 (Scientific Forming Technologies Corporation) was employed. In the simulation, a rigid-plastic finite element method for plastic deformation and a heat conduction finite element method for temperature changes were employed to calculate the stress, strain states, and temperature distributions of the bar and plate at each calculation step during the bar indentation process. The dies were treated as rigid bodies. The dimensions and geometries of the bar and plate used for the simulation were the same as those used in the

experiments. A 30 degrees section of the bar and plate were analyzed with consideration for the symmetry of the geometries of the bar and plate. A tetrahedral mesh was employed to model the bar and plate. The average volume of the initial mesh was about $3.7 \times 10^{-2} \text{ mm}^3$. The elements were automatically re-meshed, depending on the plastic deformation of the each element. The analysis model was shown Fig. 7.

The flow stress curves of the bar and plate materials (AA6061-T6 aluminum alloy) employed in the simulation are shown in Fig. 8. The flow stress was measured at several temperatures using the upsettability test (Osakada et al., 1981). In the upsettability test, a cylindrical specimen of the aluminum alloy was compressed between grooved platens that restricted sliding of the end surfaces, and the flow stress was determined from the load-stroke data. The value of the strain rate sensitivity exponent (m) for the aluminum alloy was set to 0.10. The flow stress–equivalent strain relations at every 0.05 equivalent strain interval were used as input data for the finite element analysis, and the flow stress at an arbitrary equivalent strain was obtained by linear interpolation. The temperature dependences of the flow stress curves were obtained by linear interpolation. The coefficient of shear friction at the bar–plate contact was assumed to be 0.5 based on the results of the ring compression test (Male and Cockcroft, 1964-65) at elevated temperatures. The frictional conditions at the bar–bar holder contact and at the plate–die contact were assumed to be sticking (no sliding).

Fig. 7 Finite element analysis model for indentation process.

Fig. 8 Flow stress curves for the AA6061-T6 wrought aluminum alloy measured using the upsettability test at several temperatures (initial strain rate: 0.62 s^{-1}).

5. Experimental characteristics of the indentation plastic joining method

5.1 Indentation plastic joining without press ram speed control

Figure 9 shows photographs of an indented bar and plate in indentation joining without press ram speed control. Here, the maximum indentation pressure (P_1) was defined as follows:

$$P_1 = \text{Maximum indentation load of the bar} / \text{Cross-sectional area of the bar} \quad (2)$$

where the cross-sectional area was $\pi(D_B/2)^2$. The bar was plastically deformed and did not

pierce the bottom of the plate so that the bar was not fixed to the plate at $T_P = 200\text{ }^{\circ}\text{C}$. This is a typical failure of indentation joining processes. On the other hand, the bar was successfully fixed to the plate at $T_P > 300\text{ }^{\circ}\text{C}$, and a slug was ejected from the hot plate. The strength ratio of the bar to the plate needed to be approximately 2.5 in order to successfully indent the bar into the plate without causing plastic deformation of the bar under the indentation joining (AA6061-T6 wrought aluminum alloy, $t_P/D_B = 1.0$, $D_H/D_B = 0.88$). Here, the strength ratio was estimated from the flow stress curve of the aluminum alloy (Fig. 8). The strength ratio required to achieve successful indentation joining depends not only on the strengths of the bar and plate, but also on the geometrical shapes of the bar and plate. Matsumoto et al. (2011) confirmed that the bonding strength of the indented bar–plate fixed by indentation joining at $T_P = 300\text{ }^{\circ}\text{C}$ was higher than the bonding strength obtained by indentation joining at $T_P > 300\text{ }^{\circ}\text{C}$. For these reasons, the optimum plate temperature under the indentation joining conditions was determined to be $T_P = 300\text{ }^{\circ}\text{C}$, based on an analysis of the plastic deformation of the bar and the bonding strength of the bar and the plate.

Figure 10 shows the influence of the initial velocity of the bar indentation on the indentation pressure and the shear bonding strength of the indented bar–plate. The indentation pressure decreased considerably with increasing indentation velocity, whereas the shear bonding stress increased slightly with increasing indentation velocity. The shear bonding stress was attained with $P_D = 70\text{--}80\text{ MPa}$. Figure 11 shows the influence of the initial velocity of the bar indentation on the shear droop length of the plate at the upper corner of the bar indentation. The shear droop length of the plate decreased with increasing indentation velocity. Thus, a high-speed indentation effectively reduced the indentation pressure, improved the bonding strength of the indented bar–plate, and shortened the shear droop length of the plate.

Fig. 9 Photographs of the indented bar and plate fixed by indentation plastic joining (T_p : plate temperature, P_l : maximum indentation pressure).

Fig. 10 Influence of the initial velocity of the bar indentation on the indentation pressure and the shear bonding stress in the indented bar ($T_p = 300^\circ\text{C}$, $\sigma_{0.2}$: proof stress of the bar material at room temperature (275 MPa)).

Fig. 11 Influence of the initial velocity of the bar during indentation on the shear droop length of the plate at the upper corner of the bar indentation ($T_p = 300\text{ }^{\circ}\text{C}$).

5.2 Indentation plastic joining under press ram speed control

The indentation joining characteristics were examined under the operation modes having the press ram motions (A), (B) and (C). Figure 12 shows the maximum indentation pressure applied by the bar to the plate ($T_p = 300\text{ }^{\circ}\text{C}$) during indentation joining under press ram speed control. Regardless of the press ram motion, the bar was successfully indented into the plate without bar fattening due to undesirable plastic deformation. The indentation pressure under ram motion (B) condition was 85% of the indentation pressure measured under ram motion (A) condition, whereas the indentation pressure under ram motion (C) condition was 115% of the value obtained under ram motion (A) condition. The shear bonding strength of the indented bar–plate in indentation joining under press ram speed control is shown in Fig. 13. The shear bonding strength under ram motion (B) condition was about 107% of the value obtained under ram motion (A) condition, whereas the shear bonding strength under ram motions (B) condition was 85% of the value obtained under ram motion (A) condition. Figure

14 shows the shear droop length of the plate at the upper corner of the bar indentation after indentation joining under press ram speed control. The shear droop length measured under ram motions (A) and (C) conditions were nearly equal, whereas the shear droop length measured under ram motion (B) condition was 50% of the length obtained under ram motion (A) and (C) conditions.

The results described above indicate that although the initial bar indentation velocity was held constant for all ram motion conditions, the press ram speed control during the bar indentation was found to affect to the indentation joining characteristics. The accelerated ram motion reduced the bar indentation pressure and improved the bonding strength of the indented bar–plate. This is a common tendency with characterizing indentation joining process without the use of press ram speed control to maintain a high indentation velocity during the bar indentation step. An indentation joining process in which the indentation speed is high during indentation joining produces desirable characteristics in the indentation-joined bar–plate.

Fig. 12 Indentation pressure of the bar during indentation plastic joining with press ram speed control ($T_P = 300\text{ }^{\circ}\text{C}$). (A) Standard ram motion (without press ram speed control), (B) accelerated ram motion, (C) decelerated ram motion.

Fig. 13 Shear bonding stress of the indented bar and plate after indentation plastic joining with press ram speed control ($T_P = 300\text{ }^{\circ}\text{C}$). (A) Standard ram motion (without press ram speed control), (B) accelerated ram motion, (C) decelerated ram motion.

Fig. 14 Shear droop length of the plate at the upper corner of the bar indentation after indentation plastic joining under press ram speed control ($T_P = 300\text{ }^{\circ}\text{C}$). (A) Standard ram motion (without press ram speed control), (B) accelerated ram motion, (C) decelerated ram motion.

6. Discussion of the joining mechanism

The bonding strength of the indented bar–plate is considered to arise from the seizure (metallurgical welding) and clamping of the plate. The joining mechanism was examined by applying the drawing test to the bar indented in a plate with slits, as shown in Fig. 15 to release the clamping force. The shear bonding stress characterizing the bar indented into the plate with slits resulted only from seizure. The slits in the plate were prepared using a cutter after the indentation joining step. Figure 16 shows the shear bonding stress of the indented bar–plate with slits. The shear bonding strength for the plate having slits (the shear bonding strength by seizure) as a result of the ram motion (B) condition was about 20% higher than the value obtained under the ram motion (A) condition. The fraction of the total shear bonding strength due solely to seizure/shear bonding strength was estimated to be 75%, 85% and 70% in the parts under ram motions (A), (B) and (C), respectively, as shown in Figures 13 and 16. This suggested that about 85% of the bonding strength of the indented bar–plate prepared under ram motion (B) condition was due to seizure between the bar and the plate, whereas about 15% of the bonding strength in the part prepared under the ram motion (B) condition was due to the clamping force applied after cooling of the plate. The accelerated ram motion caused heavier seizure at the interface of the indented bar–plate, whereas the decelerated ram motion reduced the degree of seizure.

Figure 17 shows the distribution of the plate temperature at the bar–plate interface during the bar indentation process. The distribution was calculated using the finite element analysis method. The peak temperature of the plate at the bar–plate interface under ram motion (B) condition exceeded the value obtained under ram motion (A) condition by about 50 °C at an indentation stroke of 4.0 mm. This temperature difference mainly resulted from heat generation due to the plastic deformation. Figure 18 shows the distribution of the equivalent strain of the plate at the bar–plate interface during the bar indentation process. The

equivalent strain near the bottom of the plate under ram motion (B) condition was approximately 15% lower than the value obtained under ram motion (A) condition at an indentation stroke of 10 mm (finish of the bar indentation). The press ram motion control during the bar indentation process affected the temperature change and strain distribution in the plate at the bar–plate interface. Because heavy seizure of the metals tended to result from the sliding of the metals at higher temperature, greater seizure at the indented bar–plate interface was thought to be caused by the accelerated ram motion as shown in Figures 13 and 16.

Fig. 15 Slits cut into the plate after indentation plastic joining to release the clamping force applied by the plate.

Fig. 16 Shear bonding stress of the indented bar and plate prepared with or without slits. (A) Standard ram motion (without press ram speed control), (B) accelerated ram motion, (C) decelerated ram motion.

Fig. 17 Temperature distribution in the plate at the bar-plate interface during the bar indentation process (finite element analysis). (A) Standard ram motion (without press ram speed control), (B) accelerated ram motion, (C) decelerated ram motion.

Fig. 18 Distribution of the equivalent strain in the plate at the bar-plate interface during the bar indentation process (finite element analysis). (A) Standard ram motion (without press ram speed control), (B) accelerated ram motion, (C) decelerated ram motion.

7. Conclusions

A plastic flow joining method for fixing bars and hot plates, called “indentation plastic joining”, was carried out on a servo press under press ram speed control. The influence of the press ram motion control on the indentation joining characteristics of an aluminum alloy bar and plate was examined. The following conclusions were obtained.

- 1) A high indentation speed during indentation joining produced desirable characteristics in the indentation joining process. The accelerated ram motion reduced the indentation pressure during the bar indentation process by about 15% (relative to the indentation process without ram speed control) and improved the bonding strength of the indented bar–plate by about 7%.
- 2) Under the accelerated ram motion condition, about 85% of the bonding strength in the indented bar–plate was due to seizure between the bar and the plate, whereas about 15% of the bonding strength was due to the clamping force imposed by the plate after cooling. The accelerated ram motion produced heavier seizure at the indented bar–plate interface, whereas the decelerated ram motion reduced the degree of the seizure.

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References

- Groche, P., Scheitza, M., Kraft, M., Schmitt, S., 2010, Increased total flexibility by 3D

servo presses. *CIRP Annals - Manufacturing Technology*. 59(1), 267-270.

- Japan Aluminium Association ed., 2001, *Aluminium Handbook*. 34. (in Japanese)
- Kaya, S., Spampinato, G., Altan, T., 2008, An experimental study on nonisothermal deep drawing process using aluminium and magnesium alloys. *Transactions of the ASME. Journal of Manufacturing Science and Engineering*. 130(6), 061001.
- Kitamura, K., Hirota, K., Ukai, Y., Matsunaga, K., Osakada, K., 2012, Cold joining of rotor shaft with flange by using plastic deformation. *CIRP Annals – Manufacturing Technology*. 61(1), 275-278.
- Machida, T., 1987, Shave-joining process of dissimilar materials and its application for mild steel. *Journal of the Japan Society for Technology of Plasticity*. 28(322), 1158-1165.
- Male, A.T., Cockcroft, M.G., 1964-65, A method for the determination of the coefficient of friction of metals under conditions of bulk plastic deformation. *Journal of the Institute of Metals*. 93, 38-46.
- Matsumoto, R., Chida, T., Utsunomiya, H., 2011, Improvement of bonding strength of bar and plate in indentation plastic joining with bar oscillation using servo press. *Steel Research International*. 82, Special Edition, 634-638.
- Matsumoto, R., Hanami, S., Ogura, A., Yoshimura, H., Osakada, K., 2008, New plastic joining method using indentation of cold bar to hot forged part. *CIRP Annals - Manufacturing Technology*. 57(1), 279-282.
- Matsumoto, R., Osakada, K., 2010, Ductility of a magnesium alloy in warm forging with controlled forming speed using a CNC servo press. *Journal of Materials Processing Technology*. 210(14), 2029-2035.
- Matsumoto, R., Hanami, Yoshimura, H., Osakada, K., 2009, Indentation joining process for steel bar-aluminium plate - Development of plastic joining method using indentation II. *Journal of the Japan Society for Technology of Plasticity*. 50(581), 550-554.

- Mori, K., Akita, K., Abe, Y., 2007, Springback behaviour in bending of ultra-high-strength steel sheets using CNC servo press. *International Journal of Machine Tools and Manufacture*. 47(2), 321-325.
- Osakada, K., Kawasaki, T., Mori, K., 1981, A method of determining flow stress under forming conditions. *CIRP Annals - Manufacturing Technology*. 30(1), 135-138.
- Osakada, K., Mori, K., Altan, T., Groche, P., 2011, Mechanical servo press technology for metal forming. *CIRP Annals – Manufacturing Technology*. 60(2), 651-672.
- Yanagihara, N., Saito, H., Nakagawa, T., 1987, High speed shear joining. *Journal of the Japan Society for Technology of Plasticity*. 28(322), 1181-1185.