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Title:
Indentation plastic joining of steel rod and polycarbonate plate

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Abstract

A plastic joining method for fixing rods and plates, called "indentation plastic joining", was applied to join a steel rod with a polycarbonate plate. The relationship between the indentation conditions and the joining characteristics was investigated in joining and pullout experiments. The joining strength of the indented rod–plate was approximately 40 MPa in shear bonding stress (70 N/mm in pullout energy per unit area of the interface) in pullout test of the indented rod from the plate. The clamping associated with piercing of the plate was dominant in the joining strength of the indented rod–plate. This was confirmed from pullout test of the indented rod–plate under a releasing condition of the residual strain of the plate and the finite element analysis of the strain distribution of the plate. This was strongly derived from the Young's modulus–yield strength relationship of polycarbonate. To verify the unique characteristics of polycarbonate in indentation plastic joining of the steel rod and the polycarbonate plate, the indentation in an aluminum plate and the indentation of a steel rod with a notch were demonstrated.

Keywords: Plastic joining; Composite component; Polycarbonate; Mechanical clamping; Mechanical interlock; Residual strain

1. Introduction

In order to enhancement the strength-weight relationship of structural component of vehicles such as automobile and aircraft, the use of multi-material structural component is rapidly expanded (Bader, 2019). In the multi-material component, dissimilar materials such as high-strength material and lightweight material are used in the optimal places in consideration of materials properties in order to obtain the required characteristics of the component. In addition, the multi-material structure has a potential to produce high-functional components with unique characteristics in such as conductive, magnetic field and corrosion properties. For the production of the multi-material component, joining and forming technologies of dissimilar materials are essential technologies (Martinsen et al., 2015). Especially combination of metal and resin is attractive attention for realizing high strength and lightweight of the component.

In joining of combination of metal and resin, adhesive bonding with glue and mechanical fastening with bolts or rivets are conventional methods (Kedward, 1981). Besides these conventional methods, some advanced joining methods are also developed. In recent developments, Taki et al. (2016) proposed a direct joining method for aluminum alloy sheet and polymer. In this method, the polymer was injection molded to the sheet surface with micro square grids engraved by laser ablation. Lucchetta et al. (2011) investigated correlations between the surface topography of shot peened aluminum sheet and polymer in joining by injection molding of the polymer on the aluminum sheet. Huang et al. (2018) proposed a friction stir lap welding (FSLW) method for aluminum alloy sheet and polyether ketone (PEEK) plate. In this method, the sheet was pressed to the plate by a special-designed rotating tool.

Plastic joining process using plastic deformation of workpiece is one of the joining processes. Plastic joining process are conventionally classified by metallurgical joining and mechanical joining. In metallurgical joining such as cold welding by forming and friction stir welding, the interface between workpieces is plastically deformed and bonded by high contact pressure. In mechanical joining such as self-pierce riveting and mechanical clinching, workpieces are mechanically interlocked by plastic deformation. Mori et al. (2013) and Groche et al. (2014) reviewed joining methods, mechanisms and applications on joining process by plastic forming. With respect to plastic joining of rod (shaft) and plate (disk, sheet), Kitamura et al. (2012) proposed a cold plastic joining method for high-strength shaft with serrated teeth and thick disk with hole. In this method, the teeth shape of the shaft was transcribed to the inside hole surface of the disc. Alves et al. (2019) proposed a cold plastic joining method for rod and annular sheet. In this method, the rod was mechanically interlocked with the sheet by boss forming of the outer radius of the rod. The author (Matsumoto et al., 2008) proposed an indentation plastic joining method for fixing cold steel rod and hot steel plate. In this method, an indented cold rod was fixed to a pierced hot plate by combination of thermal shrinkage and seizure of the plate. To pierce the plate without deforming the rod, the plate needed to be heated in joining of the rod and plate with same metal.

In this study, indentation plastic joining is applied to join a steel rod and a polycarbonate plate at room temperature. The joining characteristics are investigated on performing joining and pullout experiments. The joining mechanism is discussed from the points of view of the residual strain and seizure of the plate. To verify the unique joining characteristics of the steel rod and the polycarbonate plate, the indentation in an aluminum plate and the indentation of a steel rod with a notch are demonstrated.

2. Experimental procedures of indentation plastic joining and pullout test

2.1. Indentation plastic joining method

Figure 1 shows the schematic illustration of indentation plastic joining method for fixing a cold rod to a cold plate. In this method, the rod is pressed into the plate without lubrication on a press until the plate is pierced. Since the strength of the rod must be higher than that of the plate for piercing the plate without deforming the rod, the plate is kept with high temperature during piercing. In this condition, the indented rod is fixed to the plate with combination of clamping of the indented rod by the residual stress of the plate and seizure of newly created surface of the plate. In addition, the indented rod may be fixed unevenness of the indented rod–plate interface. In indentation plastic joining of a cold metal rod and a cold resin plate, it is expected that the seizure between the rod and the plate hardly occurs. In our previous research works of indentation plastic joining of a cold metal rod and a hot metal plate (Matsumoto et al., 2008, 2014), the indented rod was fixed to the pierced plate by combination of thermal shrinkage and seizure of the plate. In this condition, joining strength was mainly due to the seizure.

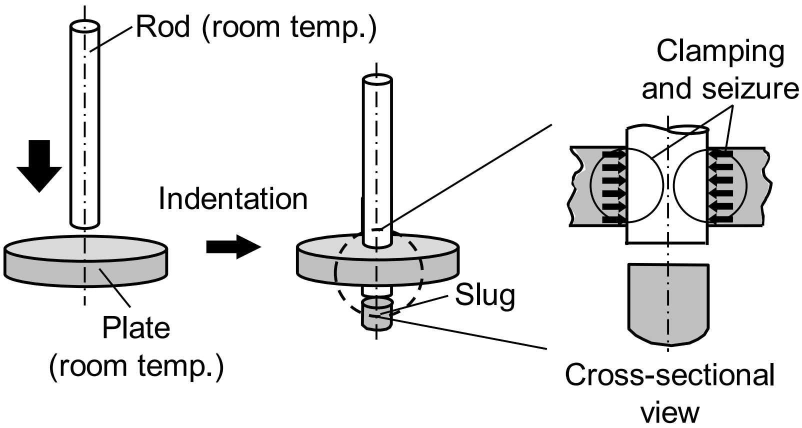

Fig. 1 Schematic illustration of indentation plastic joining method for fixing a cold rod to a cold plate.

2.2. Indentation plastic joining conditions

Figure 2 shows the die arrangement used for indentation plastic joining of a rod with a plate. The dies used in our previous research works (Matsumoto et al., 2008, 2014) were used. The rod held by the rod holder was pushed into the plate without lubrication at room temperature. The materials of the rod and plate were a Cr-Mo low alloyed steel (JIS: SCM435, yield strength at room temperature σ_{Yr} = 780 MPa) and a transparent polycarbonate (thermoplastic, yield strength at room temperature σ_{Yp} = 64 MPa, shear yield strength at room temperature $k_p = \sigma_{Yp}/\sqrt{3}$ = 37 MPa), respectively. The diameter of the joining part of the rod was d_r = 8.0 mm with a surface roughness Ra = 0.6 μm. The inner diameter of the die was 8.4 mm. The clearance between the rod and the die was 0.2 mm. The diameter and thickness of the plate were 48 mm and t_p = 8.0 mm (t_p/d_r = 1.0), respectively. To reduce the indentation load of the rod, a hole with a diameter d_h = 0–7.0 mm (d_h/d_r = 0–0.88) was prepared by drilling at the center of the indentation in the plate. The plate with/without the hole was heat treated at a temperature of 140 °C for two hours in oil bath before indentation plastic joining (Lee et al., 1975). The dies were installed on a 450 kN servo press (Komatsu Industrial Corp., H1F45) by a servomotor through a mechanical link. The rod was pressed into the plate by (t_p+2.0 mm) with an initial velocity of approximately 100 mm/s (a mean velocity of 40 mm/s).

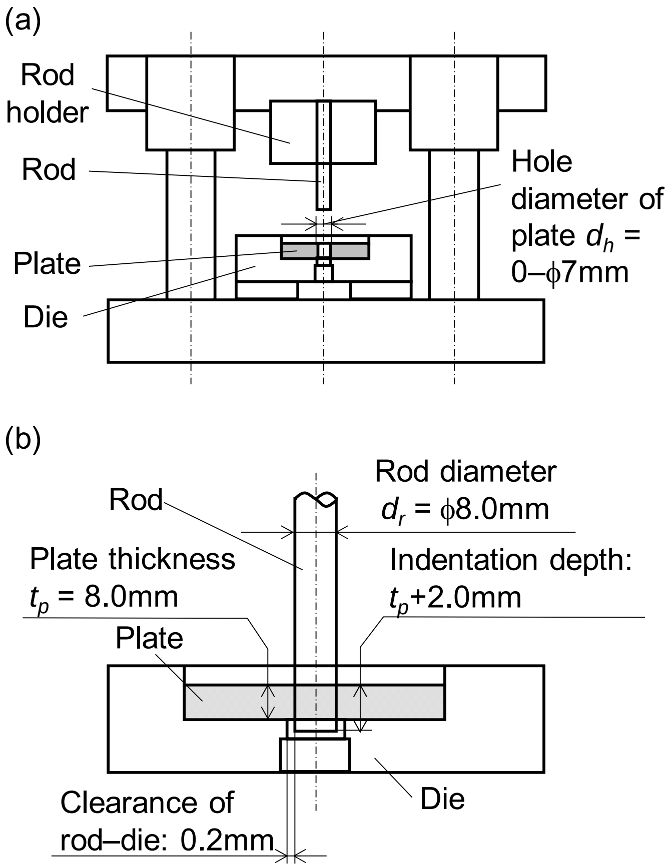

Fig. 2 Die arrangement used for indentation plastic joining: (a) die set, (b) detail of joining part.

2.3. Pullout test conditions

The joining strength of the indented rod–plate was measured by performing pullout (drawing) test. In pullout test, the indented rod was pulled away from the plate at room temperature using a material testing machine with a pulling velocity of 5 mm/min as illustrated in **Figure 3(a)**. The shear bonding strength (P_D) and pullout energy (E_D) during pulling were calculated as follows:

$$P_D = F_D/\left(\pi d_r t_p\right) \tag{1}$$

$$E_D = \int_0^{s_{Dmax}} F_D ds \tag{2}$$

where F_D and s_{Dmax} were the pull load and maximum stroke in pulling, respectively. To release the clamping force of the indented rod by the plate, two slits illustrated in Figure 3(b) were prepared in the plate using a cutter after indentation of the rod. The joining strength of the indented rod–plate with slits was mainly resulted from seizure of the plate, however the clamping force was not completely released because the slits were cut to a distance of 1 mm in the radial direction from the outer of the indented rod.

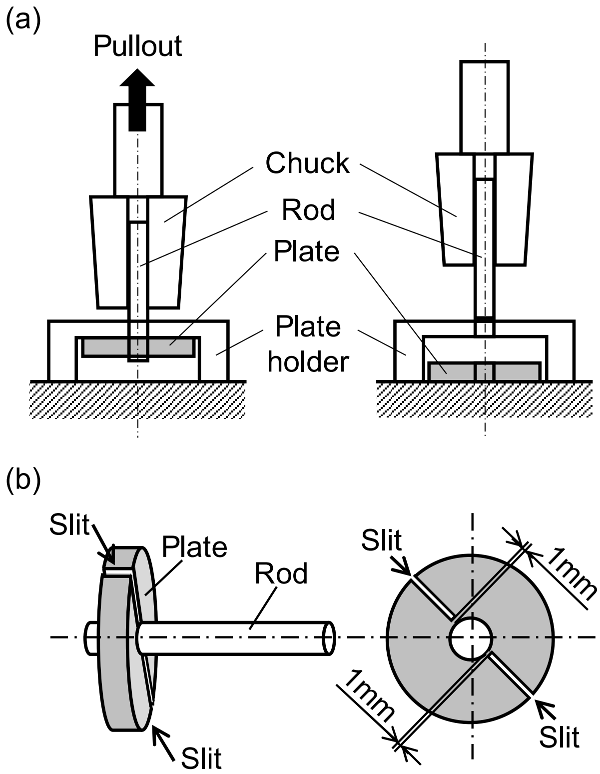

Fig. 3 Pullout (drawing) test of indented rod away from plate after indentation plastic joining of rod and plate: (a) die arrangement, (b) slits in plate.

3. Experimental results

3.1. Indentation of rod

Figure 4 shows the photographs of an indented rod and plate after indentation plastic joining. In both cases of d_h/d_r = 0 and 0.88, the rod was successfully pierced without deforming the rod and fixed to the plate, while the plate was clouded at the indented rod–plate interface. A slug was ejected from the plate in both cases of d_h/d_r = 0 and 0.88, and the hole diameter of the slug was smaller than that of the plate in joining with d_h/d_r = 0.88 because the plate around the hole was plastically deformed to the radial center during piercing of the rod. This deformation behavior of the plate during piercing was also seen in Figure 14. **Figure 5** shows the maximum indentation pressure and the indentation stroke at maximum indentation pressure. Here the indentation pressure was defined as follows:

$$P_I = 4F_I/(\pi d_r^2) \tag{3}$$

where F_I was the indentation load of the rod. The maximum indentation pressure was lower than that of the yield strength of the rod. Therefore it was confirmed that the rod was not plastically deformed during piercing the plate in Figure 4. As the hole diameter of the plate was large, the indentation stroke at maximum indentation pressure was shifted to middle stage of indentation, and it was scattered. This is because the initial positioning of the plate with a hole in the die and the rod in the die holder was sensitive to the indentation load of the rod in indentation plastic joining of the plate with a large hole.

Figure 6 shows the photographs of the cross-section of the interface of the indented rod–pierced plate after indentation plastic joining. The shear droop and burr in joining with d_h/d_r = 0 were larger than ones in joining with d_h/d_r = 0.88. Some large gaps were observed between the indented rod and the plate in joining with d_h/d_r = 0. The photographs and surface profiles of the pierced plate at the rod indentation after indentation plastic joining were shown in **Figure 7**. Rough fractured surface was observed on the pierced cross-section of the plate in joining with d_h/d_r = 0, while smooth surface was observed in joining with d_h/d_r = 0.88. The fracture occurred in the plate during piercing by the rod because of low ductility of the polycarbonate. **Figure 8** shows the measured contact length of the indented rod and the pierced plate in the interface after indentation plastic joining. The contact length in joining with d_h/d_r = 0.88 was approximately 1.5 times longer than that in joining with d_h/d_r = 0.

The photographs of the surface of the indented rod after indentation plastic joining are shown in **Figure 9**. Seizure and adhesion of the polycarbonate were not observed in both cases of d_h/d_r = 0 and 0.88. It was suggested the bonding of the indented rod and the plate was not due to seizure and adhesion of the polycarbonate.

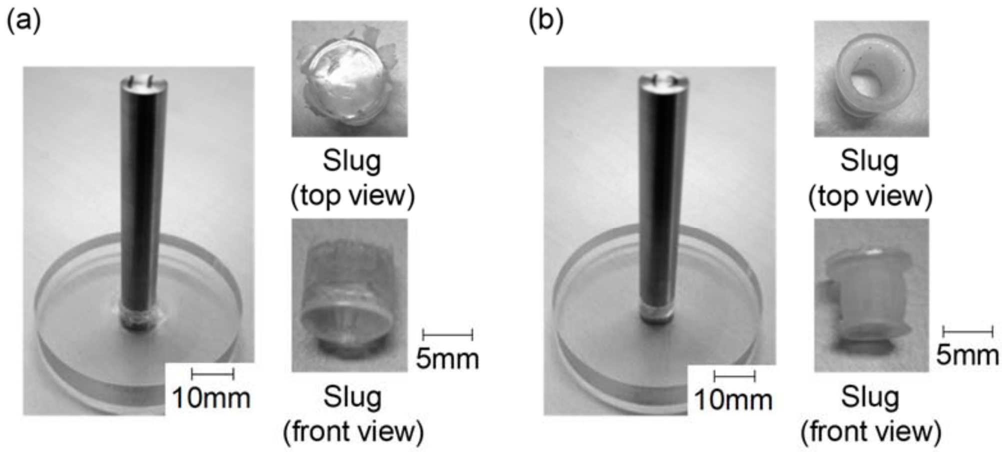

Fig. 4 Photographs of an indented rod and plate after indentation plastic joining: (a) d_h/d_r = 0, (b) d_h/d_r = 0.88.

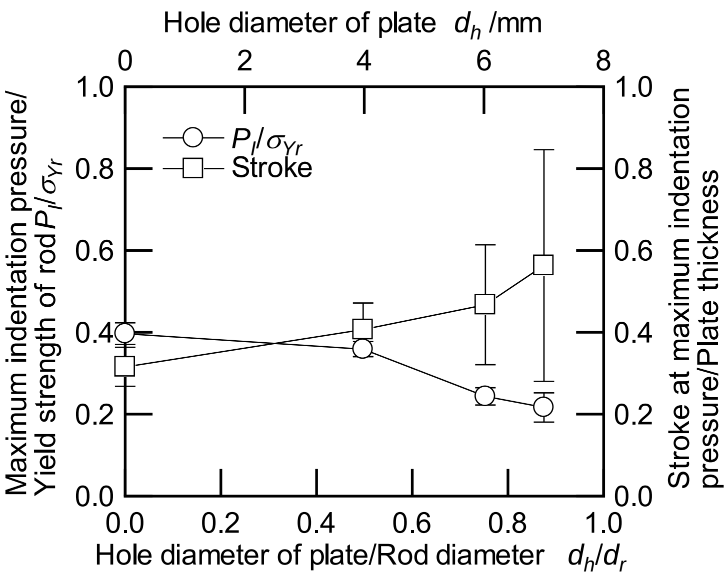

Fig. 5 Maximum indentation pressure and indentation stroke at maximum indentation pressure in indentation plastic joining.

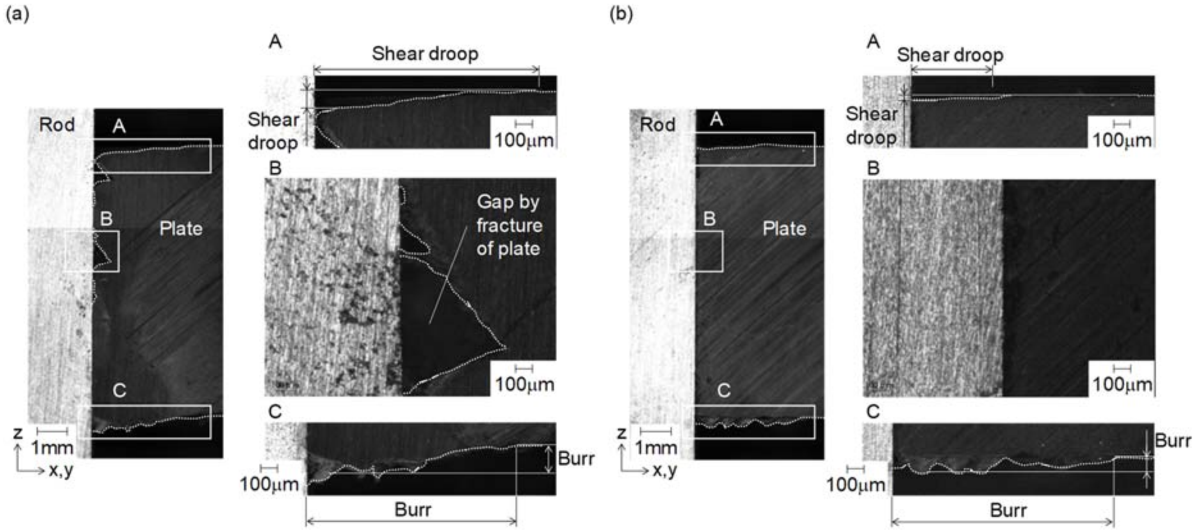

Fig. 6 Photographs of cross-section of interface of indented rod–pierced plate: (a) $d_h/d_r = 0$, (b) $d_h/d_r = 0.88$.

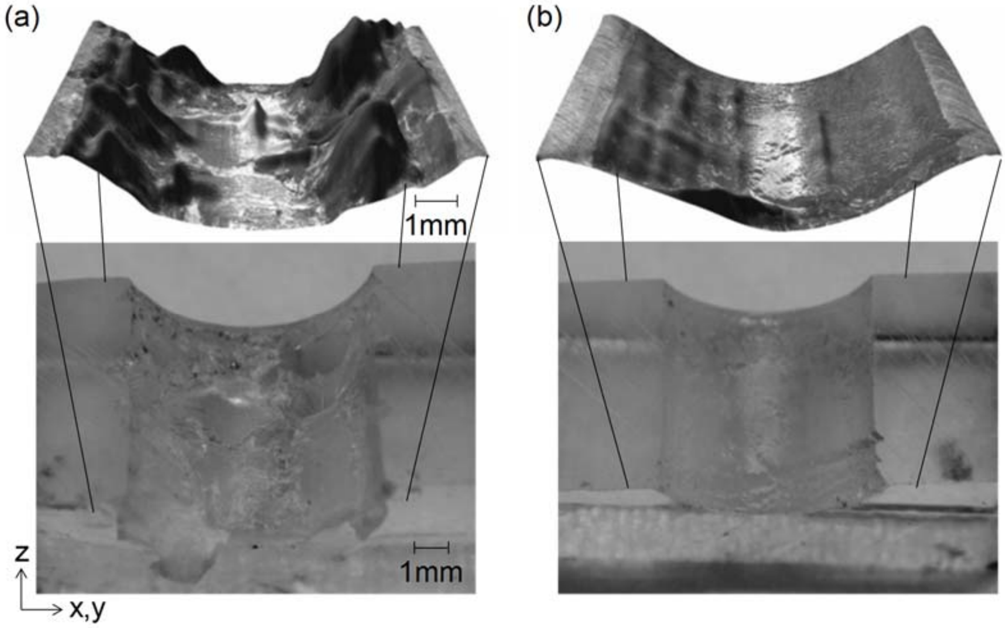

Fig. 7 Photographs and surface profiles of pierced plate at rod indentation after indentation plastic joining: (a) $d_h/d_r = 0$, (b) $d_h/d_r = 0.88$.

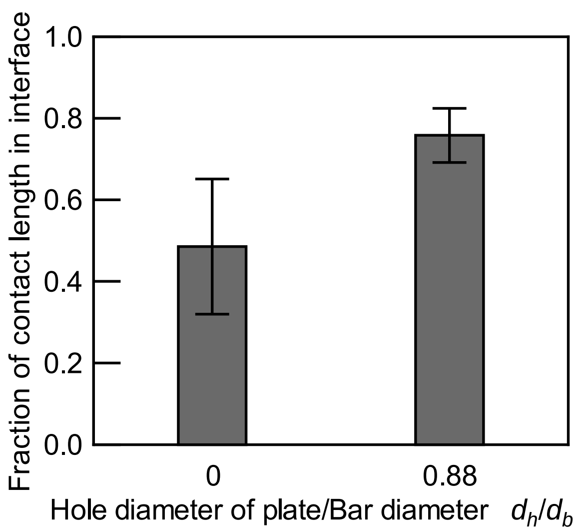

Fig. 8 Fraction of contact length of indented rod and pierced plate in interface after indentation plastic joining.

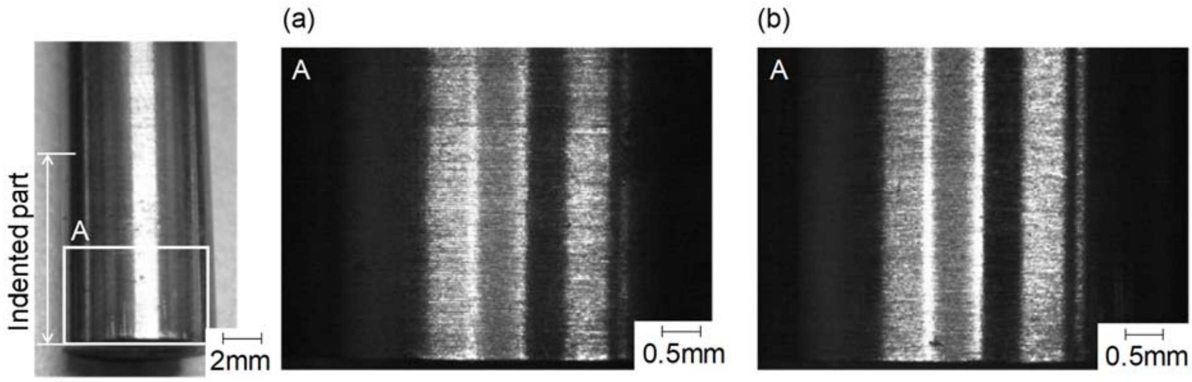

Fig. 9 Photographs of surface of indented rod after indentation plastic joining: (a) d_h/d_r = 0, (b) d_h/d_r = 0.88.

3.2. Pullout test

Figure 10 shows the pull load–stroke curves of the indented rod and the plate in pullout test. The pull load was maximum at early or middle stage of pullout test in all conditions of indentation plastic joining. The maximum shear bonding stress (P_D) and the pullout energy (E_D) calculated from the pull load–stroke curve are plotted into **Figure 11**. When the diameter ratio of the plate hole to the rod was less than 0.50 in indentation plastic joining, the shear bonding stress of the plate without slits was almost the same with shear yield strength (k_p) of the plate at room temperature. On the other hand, the shear bonding stress and the pullout energy sharply decreased with increasing hole diameter of the plate when the diameter ratio of the plate hole to the rod was more than 0.50 in indentation plastic joining. The shear bonding stress and the pullout energy of the plate with slits were almost constant P_D/k_p = 0.30–0.35 and $E_D/(\pi d_r t_p)$ = 20–25 N/m in joining with d_h/d_r = 0–0.88, respectively. These of the plate with slits were 60–70% lower than those of the plate without slits in joining with $d_h/d_r = 0$, while these of the plate with slits were 20–25% lower than those of the plate without slits in $d_h/d_r = 0.88$. As expected in Section 2.1, it was suggested that the clamping force of the indented rod by the residual stress of the plate was larger than the seizure of the plate.

The elastic recovery strain of the plate in the hoop direction is shown in **Figure 12**. On the assumption of axisymmetric deformation without torsion, the elastic recovery strain (ε_p) of the plate was calculated as follows:

$$\varepsilon_p = (d_{h2} - d_r)/d_r \quad (4)$$

where d_{h2} was the diameter of the hole of the plate after pullout test. The compressive elastic recovery strain of the plate with slits was larger than that of the plate without slits. Regardless of the hole diameter of the plate, the compressive elastic recovery strain of the plate with slits was kept to approximately 0.02. This is because the residual stress was not completely released by the slits as described in Section 2.3. Thus it was suggested that the residual stress was generated in the plate by piercing of the plate, and the clamping force by the residual stress was main in joining strength in indentation plastic joining of a steel rod and a polycarbonate plate.

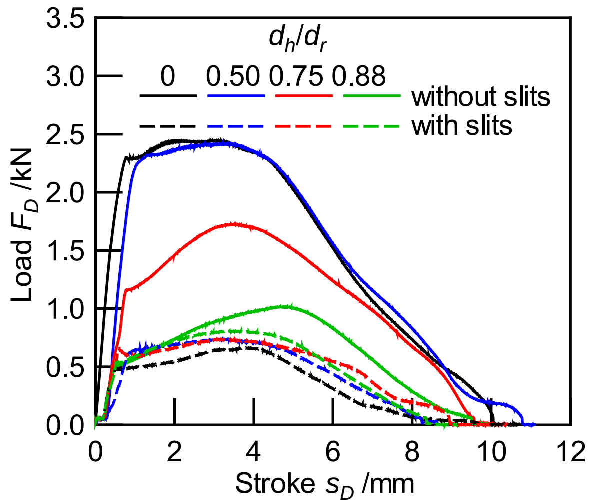

Fig. 10 Pull load–stroke curves of indented rod and plate in pullout test.

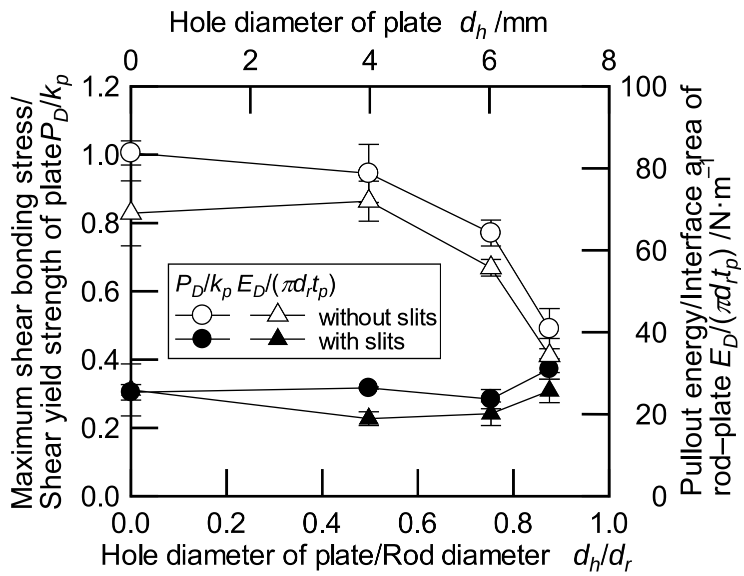

Fig. 11 Maximum shear bonding stress and pullout energy of indented rod and plate in pullout test.

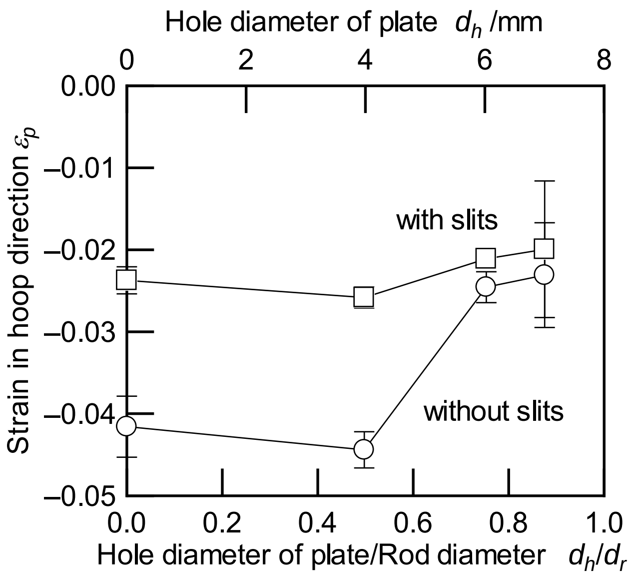

Fig. 12 Elastic recovery strain of plate in hoop direction after pullout test.

4. Discussions on joining mechanism

4.1. Residual strain

Since the Young's modulus of polycarbonate (2.25 GPa) is about 1/30 of that of aluminum (70 GPa) and the yield strength of polycarbonate (σ_{Yp} = 64 MPa) is about 2/3 of that of aluminum (JIS: A1050-H16, 100 MPa), the elastic strain of polycarbonate (0.03) is much larger than that of aluminum (0.002). The elastic strain affects to the clamping force of the plate in indentation plastic joining of steel rod and polycarbonate plate because the indented rod was clamped by the residual stress of the plate as described in Section 3.2.

The strain distribution of the plate during indentation plastic joining was calculated by a commercial elastic-plastic finite element analysis code, Simufact Forming ver. 15.0 (MSC Software Company). In the analysis, the elastic-plastic deformation of the polycarbonate plate was calculated with two-dimensional axisymmetric analysis. Temperature change and crack initiation in the plate were not considered in the analysis. The rod and dies were assumed to be rigid bodies. The indentation conditions such as the dimension, geometry and velocity were identical to the experimental conditions as shown in Figure 2. The flow stress curve of polycarbonate measured by the upsettability test at room temperature shown as **Figure 13** was used in the analysis. The coefficient of friction at the rod–plate interface was assumed to be fixed at 0.1.

Figure 14 shows the calculated elastic strains of the plate in indentation plastic joining. The elastic strains of radial and hoop directions were compressive in the plate near the indented rod, and the compressive elastic strains in the plate with $d_h/d_r = 0$ were larger than those in the plate with $d_h/d_r = 0.88$. This indicates that the clamping force of the indented rod by the residual stress of the plate with $d_h/d_r = 0$ was larger than that of the plate with $d_h/d_r = 0.88$. Therefore the shear bonding stress and the pullout energy in the indented rod–plate with $d_h/d_r = 0$ were sharply dropped by preparing the slits in the plate in Figure 11.

On the other hand, shrink fitting of die insert by shrink ring is well-known technique to impose compressive hoop pre-stress on the die insert. Shrink fitting is widely applied in the dies for cold forging to improve the die life. In shrink fitting of the die insert, Lange (1985) mentioned the interference between the die insert and the shrink ring was critical at 0.4% of the outer radius of the die. Following to this mention, Eyercioglu et al. (2009) and Lee et al. (2009) investigated the stress state in the shrink fitted die for cold forging. The compressive hoop strain and relative stress (stress/yield strength) were roughly estimated to be less than 0.004 and 0.5 from the stress states in these research works, respectively, whereas these were approximately 0.02–0.04 and 0.2–0.7 in Figures 12 and 14. Very high value of the compressive hoop strain in the indentation plastic joining was due to high elastic limit characteristic of polycarbonate. From comparison between these values in indentation plastic joining and shrink fitting, it is concluded that appropriate amount of the clamping force was generated in indentation plastic joining.

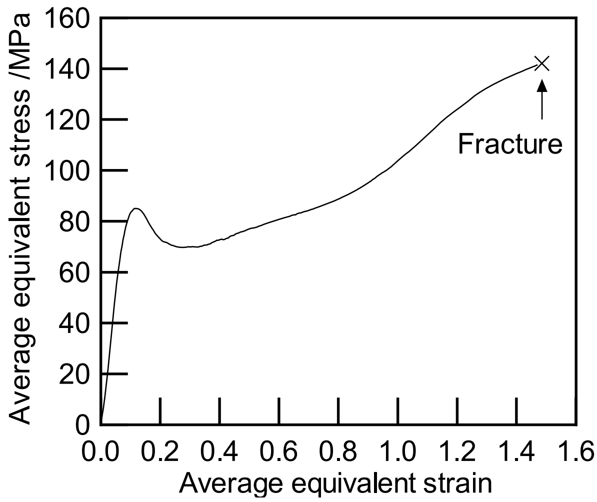

Fig. 13 Average equivalent stress–equivalent strain curves of polycarbonate measured by the upsettability test at room temperature.

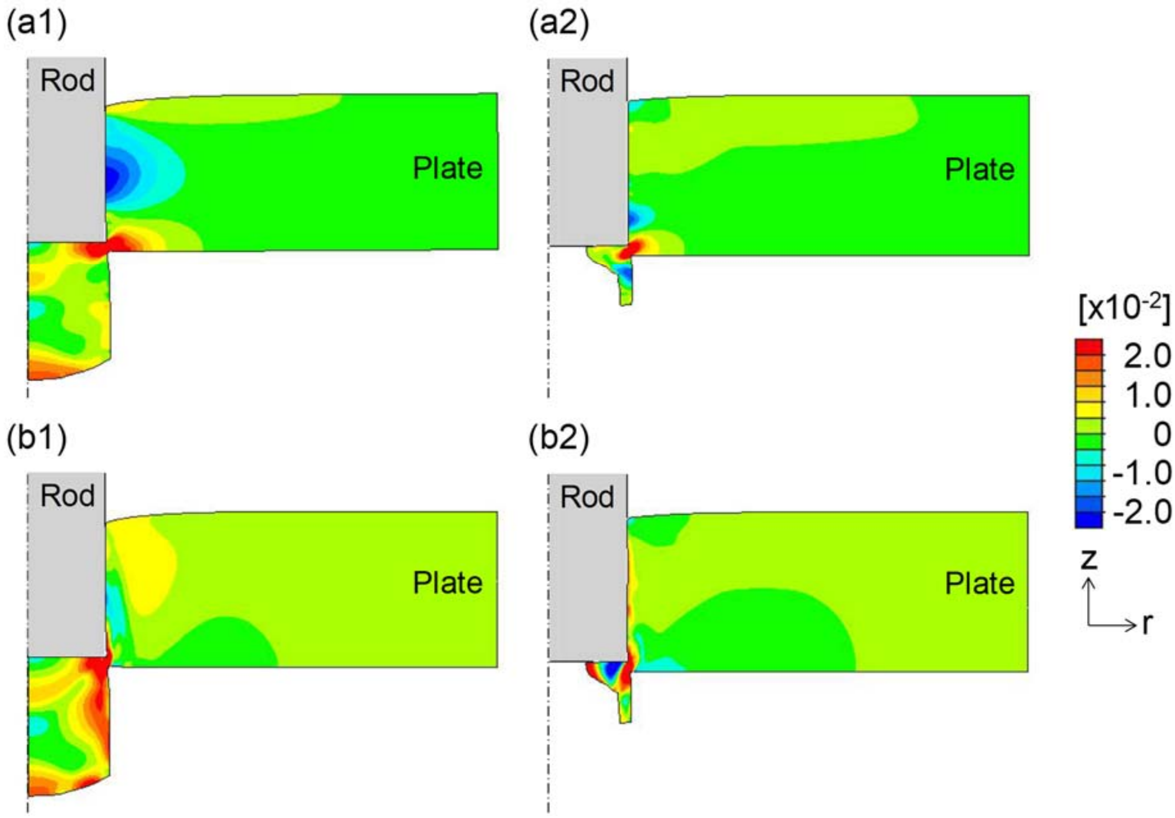

Fig. 14 Calculated elastic strains of plate in indentation plastic joining with an indentation stroke of 7.5 mm: (a1) radial direction, $d_h/d_r = 0$, (a2) radial direction, $d_h/d_r = 0.88$, (b1) hoop direction, $d_h/d_r = 0$, (b2) hoop direction, $d_h/d_r = 0.88$.

4.2. Comparsion with indentation plastic joining of steel rod and aluminum plate

To clarify the characteristics of indentation plastic joining of the steel rod and the polycarbonate plate, indentation plastic joining of the steel rod and commercially pure aluminum (JIS: A1050-F, 40 Hv0.2) plate was demonstrated. **Figure 15** shows the maximum shear bonding stress of the indented rod and the aluminum plate in pullout test. The shear bonding stress in joining with d_h/d_r = 0 and 0.88 was almost constant P_D/k_p = 0.60, and it hardly decreased by the slits in the plate. The clamping force by the residual stress was hardly generated in the interface of the indented rod and the aluminum plate, while seizure of aluminum was observed at the indented part of the indented rod in **Figure 16**.

The relationship between the shear bonding stress and the indentation pressure in indentation plastic joining is plotted into **Figure 17**. Linear relationship was obtained in indentation plastic joining of the polycarbonate plate because the clamping force by the residual stress increased with increasing indentation pressure. On the other hand, the shear bonding stress was almost constant with indentation pressure in indentation plastic joining of the aluminum plate because seizure of the aluminum plate was dominant in the joining strength.

From above comparison of the joining characteristics, owing to large elastic recovery characteristic of polycarbonate, the steel rod was confirmed to be fixed to the polycarbonate plate with the same level of the shear yield strength of polycarbonate at room temperature in indentation plastic joining of steel rod and polycarbonate plate.

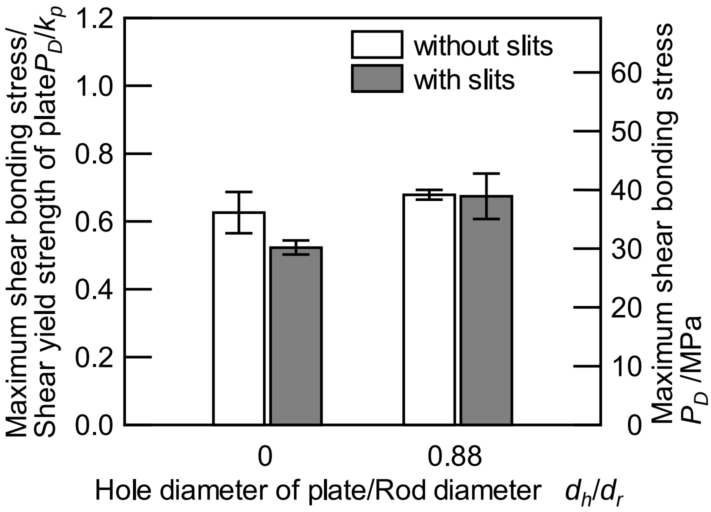

Fig. 15 Maximum shear bonding stress of indented rod and aluminum plate in pullout test.

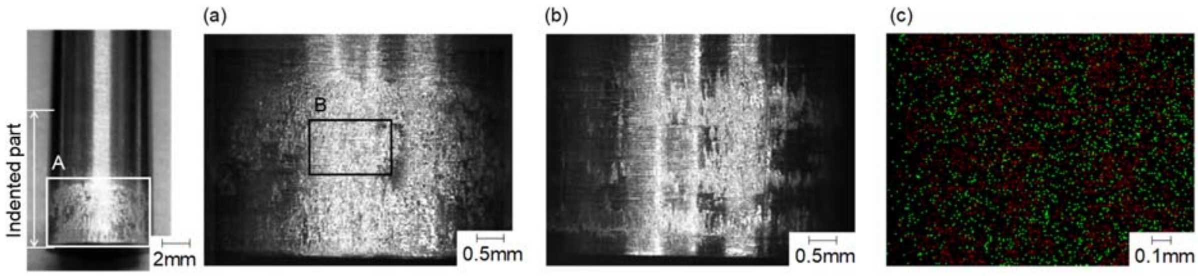

Fig. 16 Photographs of surface of indented rod after indentation plastic joining of aluminum plate: (a) A part in joining with d_h/d_r = 0, (b) A part in joining with d_h/d_r = 0.88, (c) B part in joining with d_h/d_r = 0 (EDX, green: iron, red: aluminum).

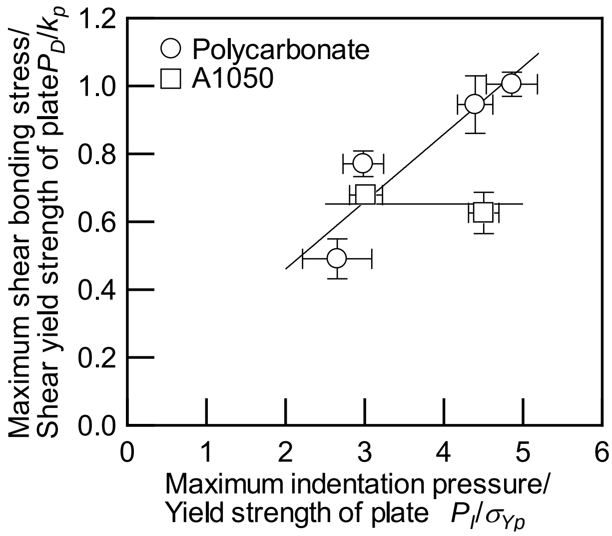

Fig. 17 Relationship between shear bonding stress and indentation pressure in indentation plastic joining.

5. Indentation of rod with a notch

To verify large elastic recovery characteristic of polycarbonate in indentation plastic joining, a SCM435 rod with a notch (see **Figure 18**) was indented to the polycarbonate and aluminum plates. In indentation plastic joining of the rod with the notch, the indented rod was fixed to the plate only by mechanical interlock at the notch part of the rod. Figure 18 shows the maximum shear bonding stress of the indented rod with the notch and the plate and the pullout energy in pullout test. The shear bonding stress of the indented rod with the notch and the polycarbonate plate was higher than the shear yield strength of polycarbonate, and it was also higher than the shear bonding stress with indented rod without the notch (Figure 11). On the other hand, the aluminum plate was not mechanically interlocked with the indented rod with the notch by the gap between the pierced hole of the plate and the notch part of the indented rod. This is because the polycarbonate plate was elastically recovered to the notch part of the indented rod just after piercing by the rod with the notch, while the elastic recovery of the aluminum plate hardly occurred. The photographs of the cross-section of the interface of the indented notch rod–polycarbonate plate were shown in **Figure 19**. The pierced part of the polycarbonate plate was shrank in the radial direction, and the polycarbonate was stuck in the notch part of the indented rod. Thus the polycarbonate plate was mechanically interlocked with the indented notch rod.

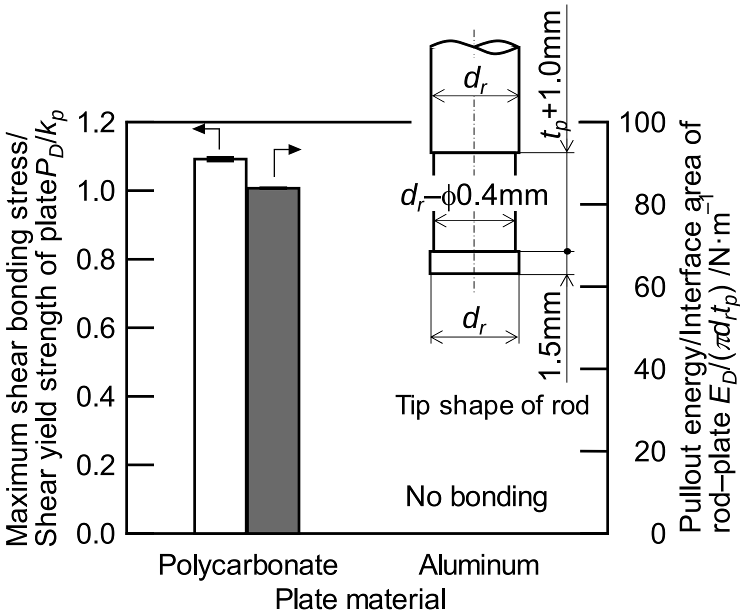

Fig. 18 Maximum shear bonding stress and pullout energy of indented rod with notch and plate in pullout test ($d_h/d_r = 0$).

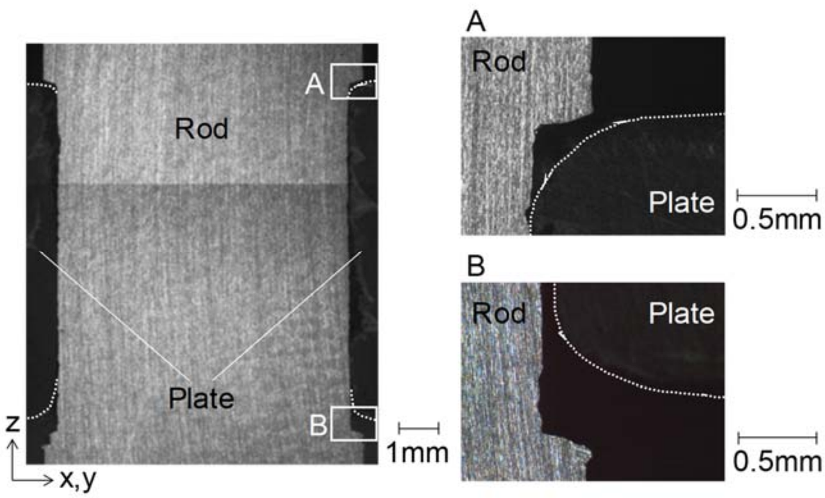

Fig. 19 Photographs of cross-section of interface of indented notch rod–polycarbonate plate ($d_h/d_r = 0$).

6. Conclusions

Indentation plastic joining was applied to join a steel rod and a polycarbonate plate. The joining characteristics were investigated on performing joining and pullout experiments. The joining mechanism was discussed from the points of view of the residual strain and seizure of the plate. Joining of a steel rod and an aluminum plate was demonstrated to verify the unique joining characteristics of the steel rod and the polycarbonate plate. Following conclusions were obtained.

(1) The rod was fixed to the polycarbonate plate by almost the same strength of the shear yield strength of polycarbonate at room temperature (40 MPa) when the diameter ratio of the plate hole to the rod was less than 0.50 in indentation plastic joining.

(2) The clamping associated with piercing of the plate was dominant in the joining strength of the indented rod–polycarbonate plate from the pullout experiment of the indented rod–plate with slits. This was strongly derived from the Young's modulus–yield strength relationship of polycarbonate.

(3) Owing to large elastic recovery characteristic of polycarbonate, the rod with a notch was mechanically interlocked to the polycarbonate plate. The joining strength was higher than the shear yield strength of polycarbonate at room temperature.

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