Application of friction stir welding for several plastic materials

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Abstract

Application of friction stir welding (FSW) known as a low heat input process to plastic materials was studied. Several plastic materials such as high density polyethylene (HDPE), polyamide 6 (PA6) and polyvinyl chloride (PVC) were selected in order to investigate effect of difference in physical properties of the materials on weldable condition and joining strength. The revolution pitch for the weldable condition in each material increased with decreasing of melt viscosity. Moreover, traverse speed in the weldable conditions of the plastic materials was lower compared with that of metallic material, such as aluminum alloys. Stir zone showed lower hardness value compared to the base material and the hardness reduction ratio depended on the materials. In the each plastic material, joining strength increased with decrease of the revolution pitch. Voids formed at the retreating side and played as a fracture origin. Therefore, it is considered that the joining strength depends on both the degradation of mechanical property and the voids formed at the welded area. The maximum joint efficiency of HDPE, PVC and PA6 were about 70%, 45% and 35%, respectively.

Keywords: Friction Stir Welding, HDPE, PA6, PVC, Weldable condition, Process parameters, Revolution pitch, Joint efficiency

1. Introduction

Recently, lightweight materials have been widely applied in order to reduce the greenhouse gas emissions[1] for transportation industries. Plastic materials as one of the lightweight materials are used for many applications in industries due to its advantages in good productivity, chemical resistance and electrical property, etc. However, joining technologies are often required for components made of plastic material with large scale and complex shape. Mechanical joining and adhesive bonding are used as conventional joining methods for plastic materials. In addition, welding methods such as hot plate welding[2], die slide injection (DSI)[3] and vibration welding[4] are also known as joining methods for plastic materials. However, the mechanical joining and the adhesive bonding have disadvantage on recyclability and productivity because which need other machining process or time for joining. Moreover, there is a problem in welding too, thermal degradation easily occurs in generally by excessive heating during the process. Therefore, joining technology with high productivity and reliability is required for plastic materials.

On the other hand, much attention has been paid to friction stir welding (FSW). FSW is based on generation of frictional heat between a rotating welding tool and a material, and known as a solid state welding method which means low heat input process compared with conventional welding methods. FSW has been applied to practical use mainly focused on aluminum alloys[5),6),7),8)] in current.

On the other hand, recently, some friction stir technologies for plastic materials have been reported[9),10),11),12)]. However, application of friction stir technology to plastic materials is still limited compared to that to metallic materials.

In this study, FSW was applied to several plastic materials to investigate the weldability and evaluate the joining strength.

2. Experimental procedure

In this research work, high density polyethylene (HDPE), polyamide 6 (PA6) and polyvinyl chloride (PVC) were selected in order to investigate effect of difference in physical properties on FSW process, weldable condition and joining strength. Table 1 shows

Table 1 Physical and mechanical properties of plastic materials used.

	Young's modulus, GPa*	Tensile strength, MPa*	Thermal conductivity, W/m・k	Glass transition temperature, ℃	Melting temperature, ℃	Crystallinity, %	Melt viscosity, Pa・s (Shear velocity $10^2 s^{-1}$)
HDPE	1.18	31.9	0.24	-90	137	70	8×10^2 (140℃)
PA6	2.63	67.1	0.21	50	225	20-25	2×10 (230℃)
PVC	3.28	66.5	0.16-0.17	87	212	0.14	6×10^3 (210℃)

* at crosshead speed; 1.0mm/min.

physical and mechanical properties in each plastic material. FSW was carried out to butt joint configuration by using a specimen with dimension of L100×W40×T5 mm.

Pin of a rotating tool has M10 right-hand screw made of SCM435 with 4.8mm in length. Shoulder of the tool was 20mm in diameter and made of SUS304.

In the present study, the FSW tool rotated in a counterclockwise direction without tilt angle and was traversed along interface. The plunging depth was 4.7mm which means 0.1mm gap between the shoulder and bottom surface of the specimen as shown in Fig.1. The welding experiment was carried out with changing rotation speed and traverse speed of the tool in each material in order to investigate effect of process parameters on weldable conditions.

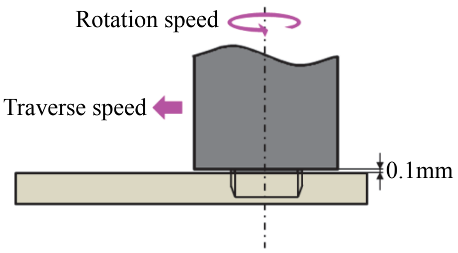


Fig.1 Schematic illustration of the welding experiment.

In order to investigate temperature history during FSW process, temperature measurement was carried out by using a thermocouple and a tool with slip ring as shown in Fig.2. K-type thermocouple was located at 1.0mm from the bottom of the pin as shown in the figure.

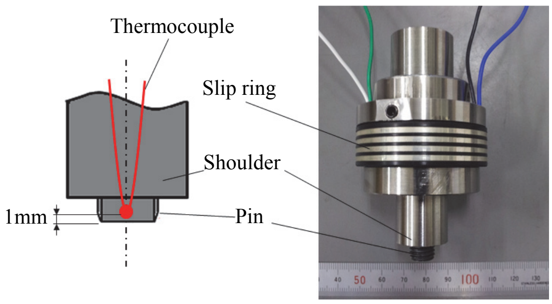


Fig.2 Tool for temperature measurement.

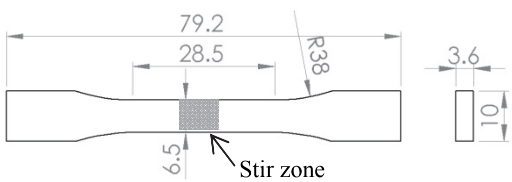


Fig.3 Dimension of tensile specimen (in mm).

Joining strength of FSWed specimens was evaluated by tensile test. Dimension of the specimen was determined as a half size of the specimen defined in ASTM standard D638[13], as shown in Fig.3. Tensile test was carried out at room temperature with crosshead speed of 1mm/min by using Shimadzu Autograph DSS-10 T-S.

3. Results and discussion

3.1. Weldable conditions

Weldable conditions obtained in each material were different as shown in Fig.4. In higher heat input conditions, burr and thermal deformation occurred since excessive heat input and significant material flow. Therefore, welding condition which can weld a joint without occurrence of burr was defined as a weldable condition in the present experiment.

As shown in Fig.4, it is thought that weldable conditions in each plastic material depend on the material properties. Moreover, traverse speed in weldable conditions of the plastic materials was lower compared with that of metallic material, such as aluminum alloys[5),6),8)]. Plastic materials are difficult to warm up extensive area since that have lower thermal conductivity compared to metallic materials. Material flow and softening in plastic material are not easy to occur with higher traverse speed. It is speculated that the rotation speed should increase significantly in order to get the high traverse speed.

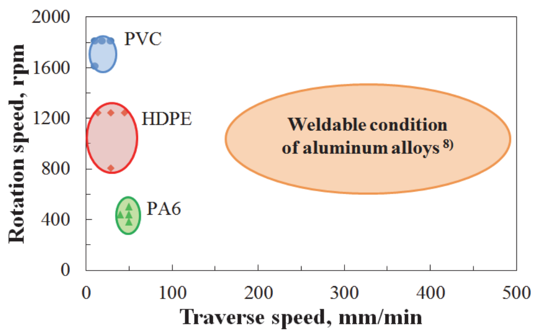


Fig.4 Weldable conditions in plastic materials used.

Revolution pitch which has been used as an indication of heat input during FSW process was calculated from Eq.(1)[14),15)].

$$\text{Revolution pitch}, mm/rev = {}^{T, mm/\min}\!\big/_{R, rpm} \qquad (1)$$

where, T and R represent traverse speed and rotation speed, respectively.

Fig.5 shows relationship between the revolution pitch and melt viscosity. As can be seen from the figure, weldable conditions mainly depend on the melt viscosity. It is surmised that material flow will be able to occur easily at lower heat input condition in PA6 because its melt viscosity is lower than melt viscosity of other plastic materials tested.

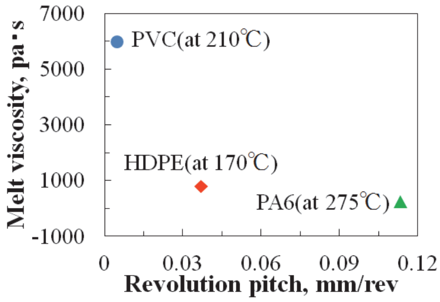


Fig.5 Relationship between melt viscosity and the revolution pitch in different plastic materials (Shear velocity;$10^2 s^{-1}$).

In the following section, process parameters in weldable conditions as shown in Table 2 were used for the joining.

Table 2 Process parameters for the welding in each material.

HDPE	Rotation speed, rpm	Traverse speed, mm/min	Revolution pitch, mm/rev
HDPE-1	1240	15	0.0121
HDPE-2	1240	30	0.0242
HDPE-3	1240	45	0.0363
HDPE-4	800	30	0.0375
PA6			
PA6-1	440	40	0.0909
PA6-2	500	50	0.100
PA6-3	440	50	0.114
PA6-4	380	50	0.132
PVC			
PVC-1	1800	10	0.00556
PVC-2	1600	10	0.00625
PVC-3	1800	20	0.0111
PVC-4	1800	30	0.0167

3.2. Temperature history during FSW

Fig.6 shows an example of temperature history during FSW in PA6 welded with the lowest revolution pitch condition. The maximum temperature was measured at 15sec, and then steady state in temperature was observed. Furthermore, Table 3 shows the maximum temperature during FSW in each material welded with the lowest revolution pitch condition. From these results, it is thought that the maximum temperature observed within weldable conditions was below the melting temperature for each material. Namely, solid state welding was performed for plastic materials in the present experiment. It was also speculated that thermal degradation in the stir zone did not occur.

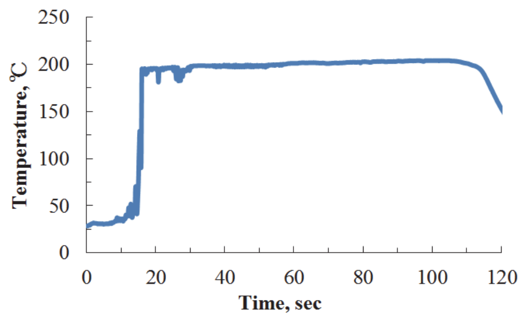


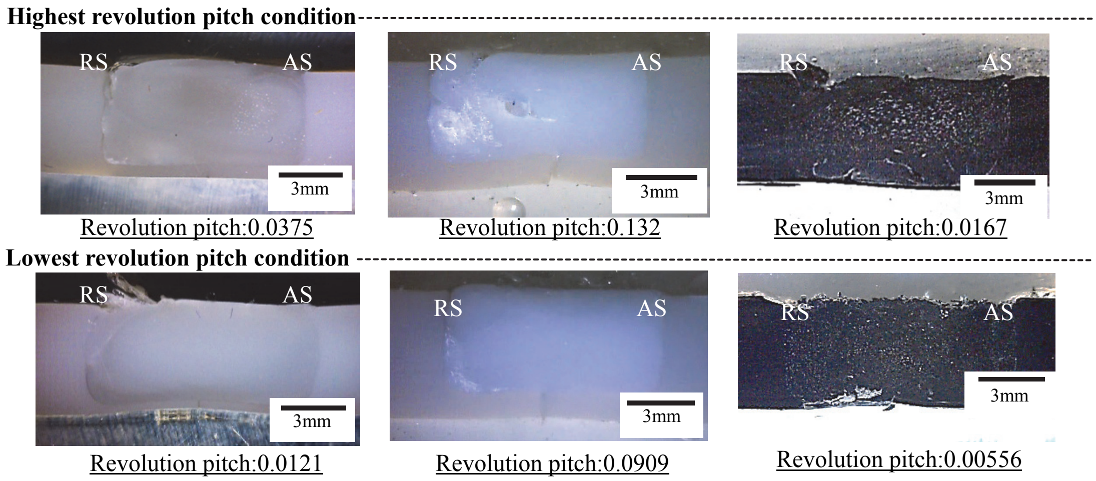
Fig.6 An example of temperature history during FSW in PA6 welded with the lowest revolution pitch condition.

Table 3 Maximum temperatures measured during FSW in HDPE, PA6 and PVC.

	HDPE	PA6	PVC
Maximum temperature, °C	122.6	206.1	181.2
Melting temperature, °C	137	225	212

3.3 Cross sectional observation

Fig.7 shows examples of cross section of the joints welded with the highest and the lowest revolution pitch condition in each material. As can be seen from



(a) HDPE (b) PA6 (c) PVC

Fig.7 Observation of cross section in welded region of each material joint welded with different conditions (see Table 2).

the figure, welding defect was not significantly observed in the cross section of HDPE joint. Nevertheless, voids were clearly observed in the retreating side in cases of PA6 and PVC joints and that amount increased with increase in revolution pitch. However, it is considered that not only heat input but also other factors can affect formation of the voids.

3.4. Hardness distribution

Micro vickers hardness was measured at applied load of 9.8mN with holding time of 15sec in cross section of the joint at 2.5mm from bottom of the specimen. Fig.8 shows the hardness distributions in cross section of the joints welded with different process parameters in each plastic material. Stir zone showed lower hardness value compared to the base material. However, there was almost no difference in hardness at stir zone of the each material joint regardless of difference in process parameter. There is a possibility to change in mechanical properties of the joined area due to changing of molecular weight or crystallinity by friction stirring. Moreover, it is thought that material flow is promoted due to cutting of molecular chain by friction stirring because the melt viscosity decreases in generally with decreasing of the molecular weight. Heat affected zone (HAZ) was defined as the region with lower hardness compared to the base material, as shown in Fig.8. HAZ width increased with decreasing of the revolution pitch and showed different size in each material.

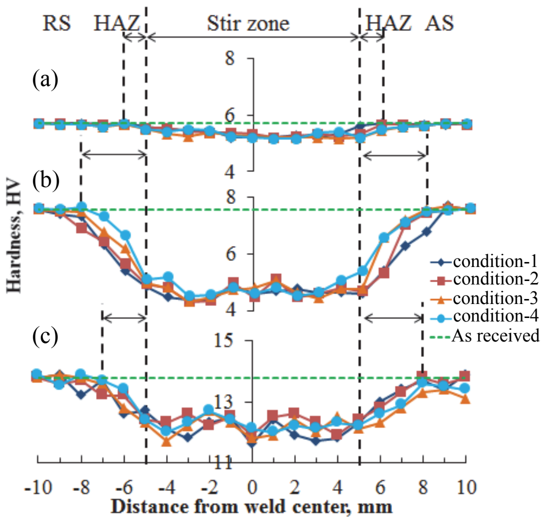


Fig.8 Vickers hardness distributions in welded region of the joints welded with different process parameters (see Table 2), (a)HDPE, (b)PA6, (c)PVC.

Hardness reduction ratio was calculated by using Eq.(2) and result of hardness measurement at weld center of a joint welded with the lowest revolution pitch condition.

$$\text{Hardness reduction ratio,\%} = \left(\text{Base material,HV} - \text{Weld center,HV}\right) \Big/ \text{Base material,HV} \qquad (2)$$

Fig.9 shows the hardness reduction ratio in each material joint. As can be seen from the figure, the hardness reduction ratio depended on the materials. In case of HDPE, the hardness reduction ratio was below 10%. In contrast, in case of PA6, it was considered that mechanical properties changed significantly by friction stirring since hardness reduction ratio of 40%.

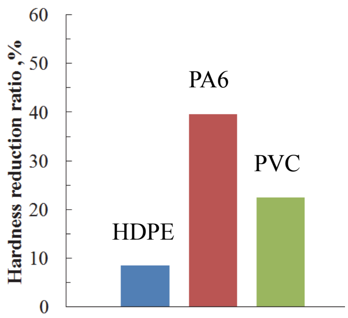


Fig.9 Hardness reduction ratio at weld center of the joints welded with the lowest revolution pitch condition (see Table 2, Fig.8).

3.5. Joining strength

Fig.10 shows strength of joints welded with different process parameters in each material. As can be seen from the figure, joining strength increased with decrease in the revolution pitch in each material.

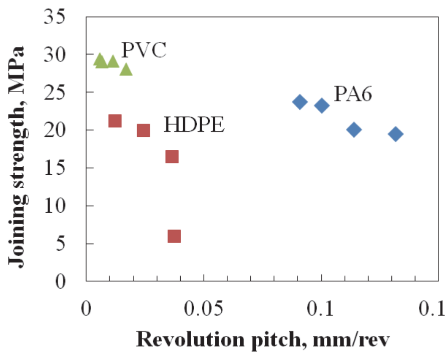


Fig.10 Relationship between joining strength and the revolution pitch in the plastic materials used.

Fig.11 shows the joint efficiency obtained. The maximum joint efficiency of HDPE, PVC and PA6 were about 70%, 45% and 35%, respectively. Fracture occurred in the retreating side for all joints tested as shown in Fig.12.

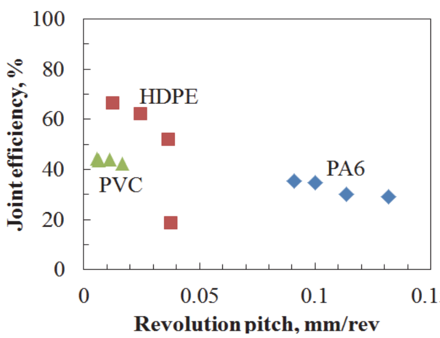


Fig.11 Relationship between joint efficiency and the revolution pitch in the plastic materials used.

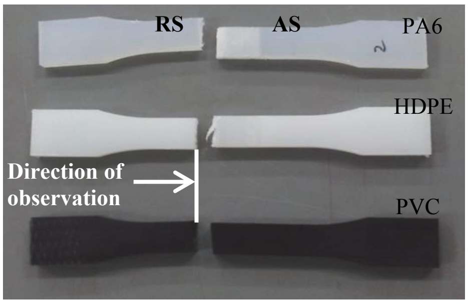


Fig.12 Overview of the specimens broken after tensile test (with the lowest revolution pitch condition).

Fig.13 shows examples of fracture surface of the joint welded with the lowest revolution pitch condition in each material. In case of HDPE, brittle fracture region was mainly observed and almost no voids were found in the fracture surface. On the other hand, the region which has fine roughness was observed in fracture surface of PA6 and PVC as shown in Fig.13(b) and (c). This roughness means that fracture occurred through the voids formed at the retreating side, according to magnified pictures of fracture surface in Fig.13(b) and (c). Previous studies showed that temperature and shear velocity were different between retreating side and advancing side[12),16),17)].

Material flow is not easy to occur at retreating side when that temperature or shear velocity at the side is lower. It is considered that difficulty of the material flow in retreating side might induce formation of the voids as observed in the present study.

According to the hardness reduction ratio as shown in Fig.9, the joining strength in each material showed the same tendency with the hardness reduction ratio, namely, the joining strength increased with decreasing of the hardness reduction ratio. Therefore, it is considered that the joining strength depends on both the degradation of mechanical properties and the voids formed at the welded area.

4. Conclusion

Weldable conditions in each plastic material mainly depended on the melt viscosity. Moreover, traverse speed in weldable conditions of the plastic materials was lower compared with that of metallic material, such as aluminum alloys. In the present experiment, solid state welding was performed for plastic materials using FSW process. The maximum joint efficiency of HDPE, PVC and PA6 were about 70%, 45% and 35%, respectively. Voids were formed significantly at retreating side in PA6 and PVC joint but few in HDPE joint. Amount of the voids increased with increase in the revolution pitch. Stir zone showed lower hardness value compared to the base material in all materials used. Difference in strength of the joint showed the same trend with difference in hardness at the stir zone in comparison of materials used. It was considered that the joining strength depends on both the degradation of mechanical property and the voids formed at the welded area.

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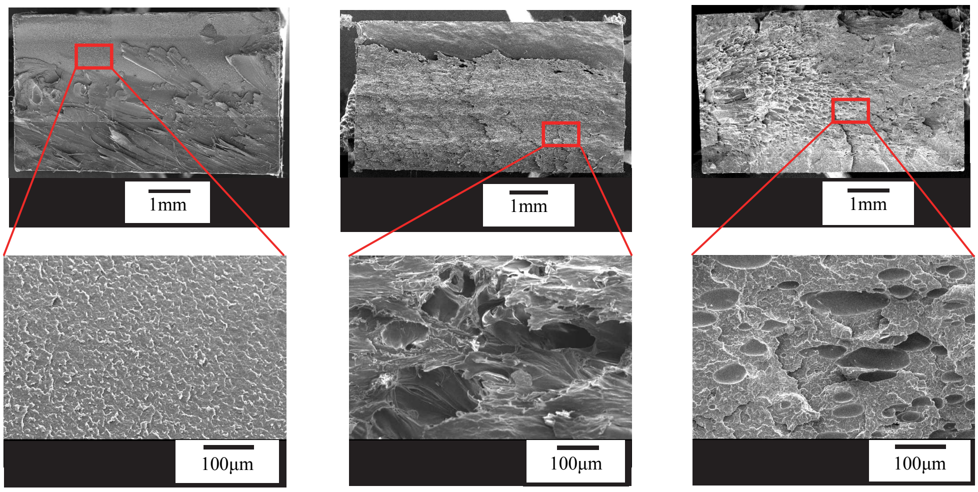

Revolution pitch:0.0121
(a) HDPE

Revolution pitch:0.0909
(b) PA6

Revolution pitch:0.00556
(c) PVC

Fig.13 Observation of fracture surface in each material joint welded with the lowest revolution pitch condition (see Table 2).

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