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Metal-polymer direct joining: effect of polymer injection speed on joint strength

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Abstract

This work experimentally investigates the effect of injection speed on the joint strength of metal-polymer direct joining. The joint products were processed by the Injection Molded Direct Joining (IMDJ) method. In IMDJ, micro/nano structures are formed on metal surfaces prior to injection molding process to join metal and polymer directly. In this work, we focused on two parameters: size of metal surface structures and polymer injection speed. We used two different chemical etching methods to form different structures. Using treated metal pieces, we processed joint products under different injection speed conditions and measured the joint shear strength. The tensile test results show that the effects of injection speed are different according to the surface structure size. We discuss this difference from the viewpoint of the replication ratio, the viscosity and the viscous resistance of melted polymer.

Keywords: direct joining, insert molding, metal surface treatment, injection speed

1. Introduction

Metal-polymer direct joining is receiving attention in various industrial fields such as automobiles, airplanes, or mobile devices due to its advantages: light weight and high productivity. Various types of direct joining methods have been proposed: using laser welding [1, 2], chemical bonding [3, 4], and micro/nano anchor effect [5-8]. However, these methods have not been applied to industries so much mainly because the reliability is not sufficient. For practical application, we need to elucidate the joining mechanism and to optimize the joining conditions. We are aiming to reveal the mechanism through investigations of the relationship between joining conditions and joint strength. In our study, we focus on one method, which uses metal surface roughening and injection molding, called Injection Molded Direct Joining (IMDJ) process. In IMDJ, melted polymer flows into metal surface structures, then metal and polymer are joined directly in the mold mainly by anchor effect. In comparison to other methods, IMDJ has some merits in productivity and material selectivity.

Our previous work [9] revealed that the polymer injection speed was an important factor to produce strong joint. In this work, we investigate how the injection speed affects the joint strength. We prepared two types of roughened metal, whose surface structure sizes were different (several 10 nm and several 10 µm), and measured tensile-shear strengths of the samples produced with different injection speed. The tensile test results show that the effect of the injection speed differs according to the size of surface structure. We discuss this difference with the polymer temperature and polymer flowing speed which are related to polymer replication ratio.

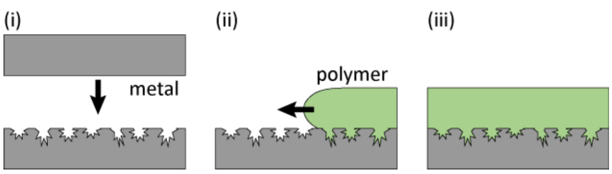

Figure 1. IMDJ process overview.

2. Injection Molded Direct Joining

Figure 1 shows the schematic illustration of IMDJ process. IMDJ is divided into three steps: (i) roughening metal surface, (ii) insert molding, and (iii) after treatment. First, micro/nano structures are formed on metal surfaces by some methods: e.g. laser processing or chemical etching. In this study we utilized chemical etching process, which can treat complex and large area at once. Second, polymer is molded with a treated metal piece by injection molding. Melted polymer flows into metal surface structures. Metal and polymer are joined directly after cooling. Finally, the joint product is annealed and extra parts such as sprue and runner are removed.

3. Experiment

3.1. Materials and Metal surface treatment methods

We investigated the joint between aluminum alloy A5052 and PBT (Toraycon 1101G-X54, Toray). A5052 pieces were chemically etched by two different methods: NMT process (Taiseiplas) [7] and Amalpha process (MEC) [8]. Figure 2 shows SEM images of the treated surface. NMT makes porous structures on the surface. The porous size is approximately 20 nm. Contrariwise, Amalpha makes several 10 µm structures.

3.2. Processing of joint samples

To investigate the joint shear strength, we processed single lap joints as shown in Fig. 3. Metal and polymer are joined at 10 mm × 5 mm area. For insert molding process we used a commercial injection molding machine (ROBOSHOT α-S100iA, FANUC). A pressure sensor (6158A, Kistler Japan) and a temperature sensor (EPSSZT-04, Futaba Corporation) were installed on the mold to measure cavity conditions during the molding process.

The molding conditions were shown in Table 1. Note that the mold temperature (140 °C) is higher than the glass transition temperature of PBT (about 30 °C). We processed the joint samples under six injection speed conditions (10, 30, 50, 100, 200, 300 mm/s). Injection speed is the moving speed of injection screw, and it can be controlled easily by a common injection molding machine.

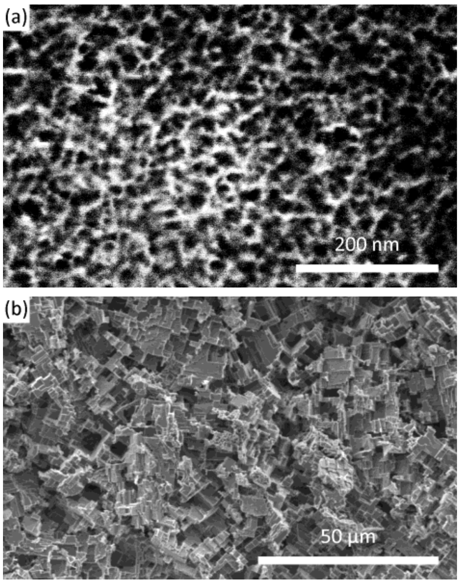

Figure 2. SEM images of treated metal surface: (a) NMT, (b) Amalpha.

3.3. Tensile-shear test

We carried out the tensile-shear test with original tensile tester [10]. This original tester is optimized to test lap joints, with which we can measure the proper shear strength. The joint sample was pulled with a speed of 1 mm/minute so as to apply shear stress on the joint surface. We recorded the maximum force before the sample was broken as the joint strength.

4. Results and Discussions

Figure 4 shows the tensile test results. The markers and error bars mean values and standard deviations of the strength, respectively. The circle and square markers mean the results of nano holes (NMT) and micro structures (Amalpha), respectively. From the results, we get two findings. First, as for micro structures, the higher speed caused the higher joint strength. Oppositely, as for nano porous, the injection speed and the joint strength have a strong negative correlation.

The reason of positive correlation of micro structures is expected as following; with high injection speed, polymer flows into the cavity before getting cold. With high temperature, the polymer viscosity is also high and melted polymer flows into metal surface structures more deeply, which increases the anchor effect between metal and polymer. In the case of general injection molding such as emboss processing, it is known that the higher injection speed causes the higher replication ratio.

On the other hand, as for nano porous, the injection speed and the joint strength show negative correlation. To explain this result, we consider two interpretations. First, the polymer viscous resistance affects the strength. The viscous resistance is one of the forces hindering melted polymer deforming and flowing into metal surface structures. As the viscous resistance is calculated by the product of the flowing speed and the viscosity, the anchor effect becomes lower when polymer is molded in high injection speed. With the condition of certain size metal surface structures (such as nano scale), the viscous resistance may be more dominant than viscosity. Second interpretation is the effect of polymer slipping on cavity surface. In general injection molding process, it is expected that melted polymer slips at nanoscale on cavity surface when it flows into cavity. If this slipping phenomenon really occur, the nanoscale anchor on the metal-polymer interface is easily destroyed and the joint strength becomes lower. To verify the interpretations, analysis on the cross-section of joint interface is necessary. For future work, we will investigate the replication ratio with TEM analysis.

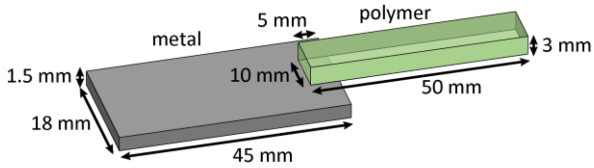

Figure 3. Schematic illustration of lap joint.

Table 1. Molding conditions.

Injection speed (Injection rate)	10, 30, 50, 100, 200, 300 mm/s (3.78, 11.4, 19.0, 38.0, 76.0, 114 cm^3/s)
Cylinder temp.	250 °C
Mold temp.	140 °C (constant)
Pack pressure	90 MPa
Holding pressure	60 MPa
Cycle / cooling time	2.5 min / 70 s

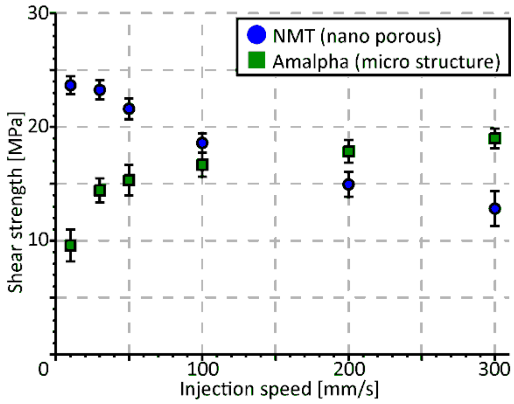

Figure 4. Tensile test results.

5. Summary

This work experimentally investigate the effect of the injection speed on the joint strength. The findings of this work are listed as follows:

(a) With micro scale structures, the higher injection speed causes the higher joint strength.

(b) As for nano structures, the injection speed and the joint strength show negative correlation.

The above difference is considered to occur due to the effect of the viscous resistance and the slipping phenomena on cavity surface. To confirm our consideration, we will carry out TEM analysis of joint surface.

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