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Mold temperature control for injection molded direct joining to improve plastic infiltration and joint strength

Fuminobu Kimura[1)], Takayuki Hiramoto[2)], Takeshi Murakami[2)], Yusuke Kajihara[1)]

[1]Institute of Industrial Science, The University of Tokyo, 4-6-1, Komaba, Meguro-ku,Tokyo, 153-8505, Japan
[2]NSK ltd., 1-5-50 Kugenumashinmei, Fujisawa-shi, Kanagawa, 251-8501, Japan

fuminobu@iis.u-tokyo.ac.jp

Abstract

Injection molded direct joining (IMDJ) is a direct joining process between metal and plastic parts. IMDJ consists of two basic processes, a surface treatment for a metal part and an injection molding process for a plastic part. The surface treatment produces a microstructure on the metal surface. After the treated metal part is placed in a mold, plastic melt is injected into the mold cavity. As the plastic part solidifies, the two materials are joined simultaneously. Plastic infiltration into the microstructure plays a role of an anchor at the interface, achieving the joining. In this study, we investigated a special temperature control method for IMDJ between laser processed aluminum plates and injection molded polypropylene (PP). The laser processing as a surface treatment formed micro dimple arrays on the aluminum plates. The temperature of mold was dynamically controlled to keep high temperature during the melt plastic flowing in the mold cavity and low temperature during plastic solidification. We assumed that the higher temperature makes higher fluidity of the melt plastic and higher infiltration into the micro dimple arrays, which could provide stronger joints. To evaluate the infiltration, we dissolved the aluminum plates of the joint specimens to expose the plastic surfaces at the joint areas. The micro protrusions replicated by the micro dimples on the exposed plastic surfaces were measured to statistically determine their heights. By comparing the results of joint strength and protrusion heights in each temperature condition, we found that not only the protrusion height affects the joint strength. The height of the protrusion is only the depth of the infiltration, but does not represent the infiltration volume, which would be a key factor affecting joint strength.

Plastic–metal direct joining, Injection molding, Mold temperature, Joining strength, Plastic infiltration

1. Introduction

Vehicle lightweighting is one of the most interesting issues today. Using plastic-metal hybrid parts is an effective approach to lightweighting; therefore, a variety of hybrid manufacturing methods have been studied and developed. Injection molded direct joining (IMDJ) is one of the methods expected to be of practical use [1, 2]. IMDJ consists of two basic processing techniques, a surface treatment for a metal part and an injection molding process for a plastic part (Fig. 1). A metal part is surface treated to form a microstructure on its surface and then is placed in a mold. By injection molding, melted plastic infiltrates into the microstructure. Then both materials are directly joined after plastic solidification. The infiltration of the plastic provides interlocking between the materials.

The previous studies [2-4] investigated the effects of injection molding parameters on joining performance such as joining strength. The parameters affect physical states of melted plastic flowing in a mold, which can determine the joining performance. Temperature is one of the most effective physical states; however, its effect is not simple. The higher temperature causes the higher fluidity and the better infiltration, which is a positive perspective. Whereas, the high temperature also causes negative points such as long cooling time and thermal degradation of plastics. To avoid such contradictory effects, we have proposed a special temperature control method, dynamic control of mold temperature, in the previous study [5]. Using this method, the temperature of the mold was controlled to keep high while the melted plastic was flowing and to keep low while the plastic was solidifying. However, the result showed some unexpected phenomena that we could not give a proper interpretation [5].

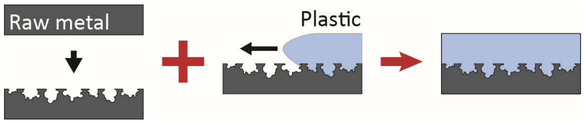

Figure 1. Process overview of injection molded direct joining.

To understand the effect of the dynamic control of mold temperature, we investigated the relationship between temperature condition, joining strength, and plastic infiltration in the present study. To avoid the unknown factors, we used the regular microstructure, micro dimple array, and a simple plastic material, homopolymer polypropylene (PP). The infiltration of plastic was evaluated by laser microscopy that measured the 3D geometry of the micro protrusions on the exposed plastic surfaces. Analysis using a histogram representing the distribution of height values of the 3D data provided the equivalent height numerically. From the investigation results, we found that the dynamic control achieved the higher joining strength and the higher efficiency of the process than the normal process. The equivalent height of the micro protrusions became higher by the dynamic control. However, we also found the height of the micro protrusions is not the only factor affecting joining performance.

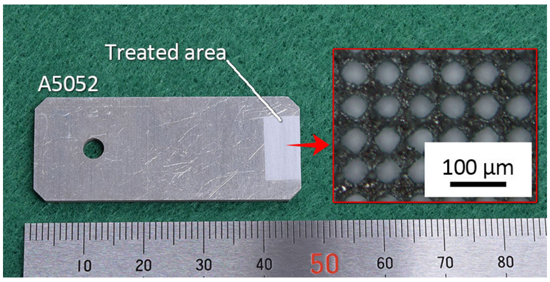

Figure 2. Laser processed metal plate. A micro-dimple array was formed.

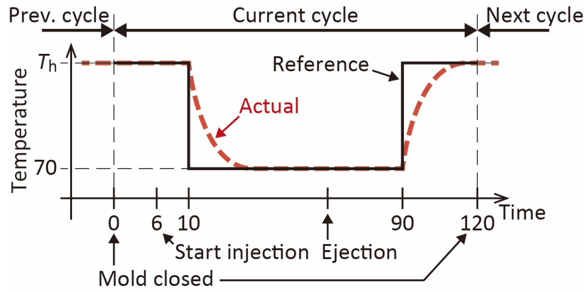

Figure 4. Time-course variation of temperature for dynamic control of mold temperature in one cycle of injection molding.

Table 1. Molding condition.

Injection speed [mm/s]	Polymer temperature [°C]	Packing pressure [MPa]	Holding pressure [MPa]
10, 100, 200	250	60	50

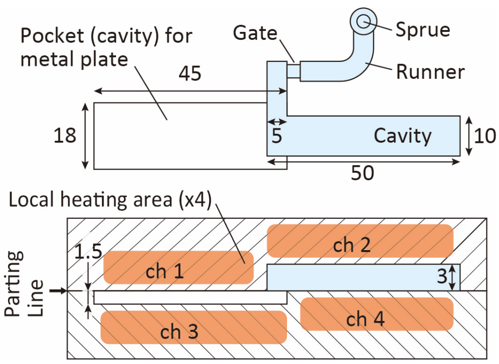

Figure 3. Schematic of mold (top view and front view).

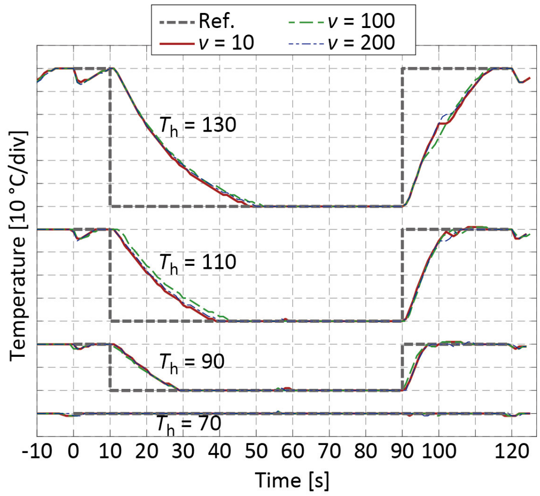

Figure 5. Examples of time-course measurements of mold temperature under different conditions. For high visibility, the measured values under different T_h conditions were vertically shifted by different amounts.

2. Preparation of joining samples

2.1. Surface treatment for metal plates

The material of the metal plates was AA5052 aluminum alloy. The geometry of the plates was 45 mm width, 18 mm height, and 1.5 mm thickness. Parts of the surfaces were surface-treated by short-pulse laser processing to fabricate micro-dimple arrays [6]. The condition of the laser (FLS-IRM-50, IPG photonics) was as follows; power: 0.375 mJ; wavelength: 1 064 µm; pulse width: 100 ns. Figure 2 shows the photo of a treated plate and the microscope image of a micro-dimple array. Each dimple had approximately 47 µm diameter and 108 µm depth. The pitch of dimples was 60 µm.

2.2. Injection molding

The treated metal plate was inserted into a mold; then the plastic part was injection-molded using an electric injection molding machine (α-S100iA, Fanuc) with a 22 mm diameter cylinder. The material of the plastic was homopolymer polypropylene (PP. J105G, Prime Polymer), which is the most basic grade of PP. To reduce the unknown influences, we used this simple grade of PP. The molding condition was shown in Table 1. The injection speed parameter, v, had three levels, but other parameters were constant.

2.3 Mold temperature control

Figure 3 shows a schematic of the mold that produces a single lap joint following ISO19095. The geometry of the plastic part was 50 mm width, 10 mm height, and 3 mm thickness, and joint area, which is overlapped area between the materials, was 50 mm^2 (5 × 10).

The temperature of the mold was controlled by Y-HeaT system (Yamashita Electric) that consisted of tiny heaters. The heaters were divided into four groups (channels) that dynamically control the temperature of the local parts of the mold, which is shown as ch 1 to ch 4 in Fig. 3. Figure 4 shows a time-course profile (reference) of the temperature variation in one cycle of injection molding. Time zero (t = 0) was defined as the moment when the mold is closed. To make sure that the temperature was stable, the system waits for 6 s and then starts injection. When the initial injection process is finished (t = 10), the pressure holding process starts, and the mold temperature is changed from the high temperature T_h to the base temperature, which was 70 °C in this study. The injected plastic is cooled and solidifies under the base temperature condition. Then the molded sample, which is joining sample, is ejected from the mold. When the time reaches 90 s, the mold temperature is changed to T_h again to prepare for the next cycle molding. One cycle of the injection molding was 120 s. The high temperature, T_h, had four levels: 70, 90, 110, and 130 °C.

Figure 5 shows examples of time-course measurements of mold temperature under different conditions. The measured area was ch 3. For the high visibility, the measured results under different T_h conditions had vertical shifts in the graph. The measured values had delays but well followed the references. We cannot see the effect of injection speed v on the measured temperature, which means the injection speed control and the mold temperature control were isolated in our system.

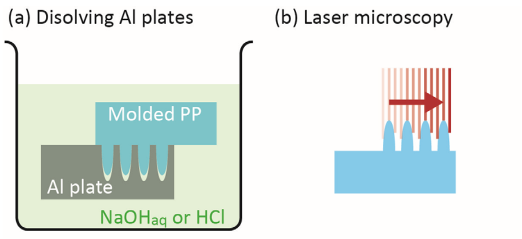

Figure 6. Procedure of evaluation of plastic infiltration. (a) dissolving aluminum plate. (b) laser microscopy of exposed plastic surface.

2.4 Evaluation of joining performance

The joining specimens were evaluated by a tensile shear test. The test applied strain to a specimen with a constant tensile speed of 1 mm/min and measured the applied load. The ultimate load until failure occurred was divided by joining area of 50 mm^2 to obtain tensile shear strength. In each condition, five samples were tested. The testing machine was the one developed in our previous study [7].

2.5 Evaluation of plastic infiltration into micro dimples

The infiltration of molded plastic into the micro dimples was evaluated via the metal dissolving and the laser microscopy. Figure 6 shows an overview of the process.

The joining sample was immersed in 10 wt% sodium hydroxide solution for over 24 hours, then immersed in 10 wt% hydrochloric acid solution for one hour. Since these solutions dissolve aluminum but do not damage PP, the joint interface on PP can be exposed. The exposed PP surfaces have micro protrusions, which have been plastics infiltrating into the micro dimples. We assumed that the height of the micro protrusions is the infiltration depth. Then, the micro protrusion height was measured by a laser microscope (OLS4000, Olympus). The measured area was located at the center of the joint surface and was 256 μm × 256 μm. The *x*-*y* resolution and the number of measured points were 0.25 μm and 1 024 × 1 024, respectively. One sample was evaluated in each condition.

Figure 7 shows examples of results of the laser microscopy: (a) T_h = 70, v = 100, (b) T_h = 90, v = 100, (c) T_h = 110, v = 100. To quantitatively evaluate the height of the micro protrusions, the 3D data were analyzed as follows. First, we made histograms that represent the distribution of height values at the measured points (1 024 × 1 024), which are shown in the bottom side of Fig. 7. There are two peaks in each histogram obtained from the 3D data of the protrusion arrays because similar values of height are distributed around the base plane and the top of the protrusions. Therefore, the interval of the peaks, which is length of the red lines in Fig. 7, could be equivalent to the height of the protrusions. Then, we calculated the intervals under each condition.

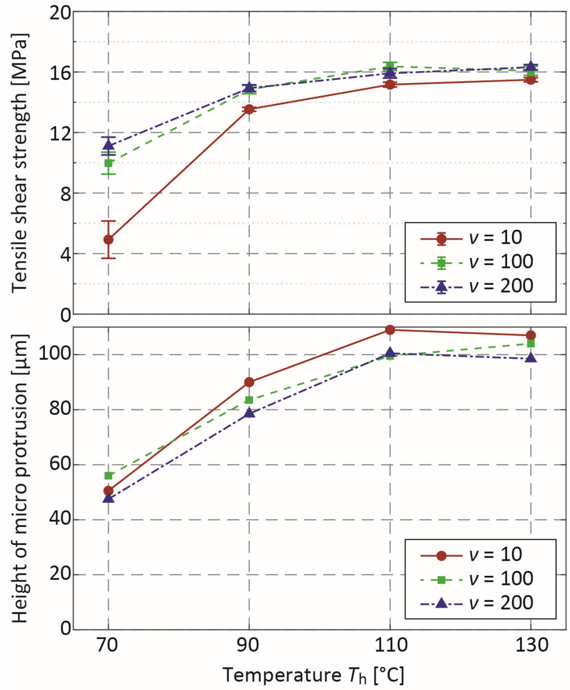

Figure 8. Evaluation results. Relationship between high value of mold temperature T_h and (top) tensile shear strength, (bottom) equivalent height of micro protrusions.

3. Results and discussion

Figure 8 shows evaluation results: (top) tensile shear strength, (bottom) equivalent height of micro protrusions. The horizontal axes show the high temperature T_h. The difference of the marker shape and color represents the difference of injection speed. The errorbars represent standard deviations.

The tensile shear strength increases with increasing of T_h and saturates at T_h = 110. The injection speed also has a positive correlation with the tensile strength; however, the effects

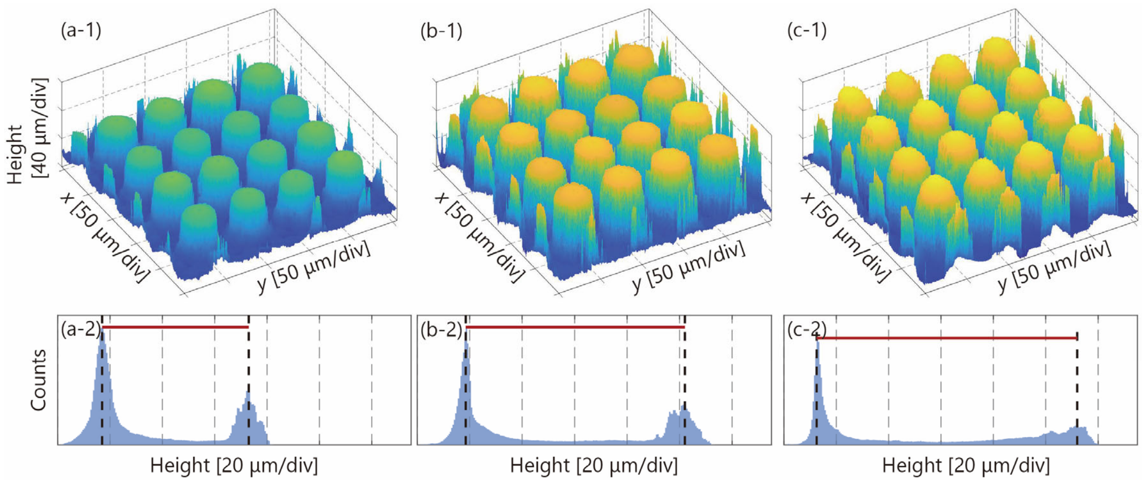

Figure 7. (top) Examples of the 3D data of the micro protrusions measured by the laser microscopy. (bottom) Histograms representing distributions of height values of the measured 3D data. The red lines are equivalent to the height of micro protrusions.

become smaller on the higher T_h conditions. Under the high temperature condition, high injection speed is not necessary for strong joining, which means the dynamic control of mold temperature provides high efficiency for the IMDJ process.

In terms of the height of the micro protrusions, the high temperature value T_h has similar tendency, positive correlation (T_h < 110) and saturation ($T_h \geq 110$). The higher temperature causes the higher fluidity of the melted plastic. Since the melted plastic with high fluidity can easily flow into microstructures, the height of the micro protrusions became higher under the higher temperature conditions. Thus, the reason for the increase of the tensile shear strength may be the increase of the height of the micro protrusions, which corresponds to the infiltration. The higher infiltration provided the higher anchor effect.

However, the injection speed has no effect on the protrusion height, which is different from the tensile shear strength. This indicates that the height of the micro protrusions is not the only effective factor. Other factors, such as width and stiffness of the protrusions, can affect the joining strength and were changed by injection speed. For further understanding, we will investigate the effects of such factors in future work.

4. Conclusion

This study presents the effect of the dynamic control of mold temperature on the joining strength and the plastic infiltration into the micro dimples. The micro dimples were fabricated by the laser processing. The joining process was achieved by injection molding using the surface microstructured metal plates. In the injection molding process, we used a dynamic mold temperature control: the temperature was set to a high value, T_h, while the melted plastics flows, then the temperature was set to a base value while the plastic is solidifying. The joining strength was evaluated by the tensile shear test. The plastic infiltration was evaluated by the laser microscopy that measured the 3D geometry of the micro protrusions on the exposed plastic surfaces. From the evaluation results, we found the following.

- Tensile shear strength has positive correlations with high value of mold temperature and injection speed.
  - The effect of injection speed becomes lower under the dynamic controlling condition.
- Height of micro protrusions can be calculated from 3D data using a histogram that represents a distribution of height values from laser microscopy.
- Height of micro protrusions has a positive correlation with high value of mold temperature but no correlation with injection speed.
  - It is indicated that there are some factors other than the height of micro protrusions that affect joining strength.

In future work, we will find other factors and confirm the mechanism of joining. In addition, other special methods controlling mold temperature, such as temperature distribution control, will be tried using our system to improve joining performance.

Acknowledgment

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