Precision Engineering 45 (2016) 203–208

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Effects of molding conditions on injection molded direct joining using a metal with nano-structured surface

Fuminobu Kimura*, Shotaro Kadoya, Yusuke Kajihara

Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan

ARTICLE INFO

Article history:
Received 14 December 2015
Received in revised form 5 February 2016
Accepted 16 February 2016
Available online 3 March 2016

Keywords:
Metal-plastic direct joining
Injection molding
Nano-structures
Tensile shear strength

ABSTRACT

Injection molded direct joining (IMDJ) is one of the metal-plastic direct joining processes and is based on a combination of a special surface treatment of a metal piece and an insert molding. This study employed a chemical processing as the special surface treatment to form nano-structures on the metal piece. We investigated relationship between joining strengths and molding conditions; we focused on pressure of a mold cavity and injection speed as molding conditions in this work. To evaluate the IMDJ samples processed under various molding conditions, we carried out tensile-shear tests. Then we compared the results of the tests to discuss how much each condition variation affected the joining strength. From the discussion, we found an interesting effect of the injection speed, which is unique to the IMDJ using a metal piece with nano-structures. The findings of this study will promote a better understanding of the IMDJ.

1. Introduction

Joining metal and plastic structures is one of the imperative techniques for modern manufacturing fields. These dissimilar material structures are usually joined by using adhesives or mechanical joint such as bolt screws and rivets [1,2]. Meanwhile, a novel technique that directly joins metal and plastic structures without such extra parts has attracted attentions recently [3]. The direct joining technique has many advantages against the typical joining; for example it can reduce weight, can simplify manufacturing processes, and can ease designing restrictions. Some research groups, therefore, have tried to realize the direct joining by using various means.

The joining means are roughly categorized into two groups by methods forming plastic structures. One is that the plastic structure is formed previously and then the plastic and metal structures are joined (a separated type). The other is that the forming plastic structure and joining are processed simultaneously (an in-situ type). For the separated type, a plastic base and a metal base are put to contact each other and are joined by various types of local heating; for example, a laser-induced local heating [4–8], a friction spot joining [9], a friction lap welding [10], and an ultrasonic welding [11]. The local heating melts the plastic base or the metal base at contacted area; and then the bases are joined after cooling and hardening. This type, however, has some limitations about materials or shape/size of the joint structures since thermal energy caused by the local heating must reach on the interface.

The in-situ type that forms a plastic structure and joins it to a metal base simultaneously utilizes an injection molding with inserting a special metal piece. In this study this type method is called an injection molded direct joining (IMDJ). To join the plastic to the metal in a mold, a special treatment is processed on a surface of the metal piece. The proposed surface treatments have been various types; e.g. chemical coupling layer coating [12–14] or micro/nano-structure forming [15–21]. Regarding the chemical coupling layer coating, a surface of a molded plastic is chemically bound with the metal via the coated layer. This type, however, has material limitation caused by affinities between the layer and the materials. By contrast, the micro/nano-structure forming type is based mainly on mechanical interlocking between the surface structures and the molded plastic. The proposed forming methods use abrasive blasting [15,16], laser processing [17–19] and chemical processing [20,21]. In comparison with chemical coupling layer coating type, the micro/nano-structure forming type has few limitations since the base materials are joined structurally.

The IMDJ using micro/nano-structure forming has not been well applied to real industries because of some remaining challenges; nevertheless the IMDJ is a quite promising process. The challenges for industrial applications are as follows: (i) Actual joining mechanism has not been revealed. (ii) Relationships between processing conditions and product characteristics have not been investigated enough. (iii) The processing conditions have not been

---

* Corresponding author. Tel.: +81 3 5452 6466.
E-mail address: fuminobu@iis.u-tokyo.ac.jp (F. Kimura).

http://dx.doi.org/10.1016/j.precisioneng.2016.02.013

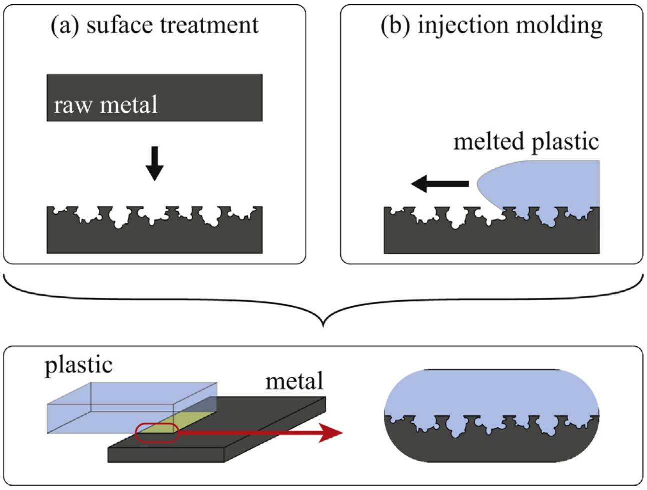

Fig. 1. Process overview of the injection molded direct joining. The process is composed of two key production processes; (a) surface treatment and (b) insert injection molding.

optimized. Possible approaches to solve the challenges are to reiterate mechanical tests, analyses, and observations of boundaries for each joining sample processed under various conditions. Some previous studies [15–18,20] have investigated effects of the processing conditions. However the investigations have been rarely conducted in the case that size of surface structures of the metal piece is nanometer scale.

This study investigated the effects of molding conditions on strength of the IMDJ samples, of which metal pieces had surface nano-structures. Although there are many controllable molding conditions, target conditions of this work were mold cavity pressure and injection speed. We formed the nano-structures on the metal piece by a chemical processing. Then we produced IMDJ samples, of which shape is a single lap joint geometry, to measure shear strength of joining by a tensile shear test. From measured strength, we discussed effects of molding conditions.

2. Experimental procedure

2.1. Joining process

Fig. 1 shows an overview of the production process. The IMDJ process is composed of two key processes: (a) a surface treatment of a metal piece and (b) an insert injection molding using the surface-treated metal piece. Combination of these processes enables the direct joining of metal and plastic structures. Details of each process and processing conditions used in this work are described in the following.

2.1.1. Surface treatment

Some means of surface treatments have been proposed for the IMDJ [15–21]. Since it is difficult to form the surface structures in nanometer scale by using abrasive blasting [15,16] or laser processing [17–19], we utilized a chemical processing. We applied one of the chemical processing (Nano Molding Technology, Taiseiplas [21]) to the forming of nano-structures on surfaces of A5052 aluminum alloy pieces for the joining experiments.

Fig. 2 shows an image of a surface of the treated metal (30° tilted view) taken by a scanning electron microscope (SEM). From the SEM image, we can see a porous structure with pore diameters of approximately 20 nm. The structure consisted of not a simple array of (vertical) holes but a three-dimensionally foam network such as a sponge foam. The aluminum alloy pieces were treated under the same condition for whole joining experiments since we focused on only the effects of molding conditions but not on the effects of surface structures in this study.

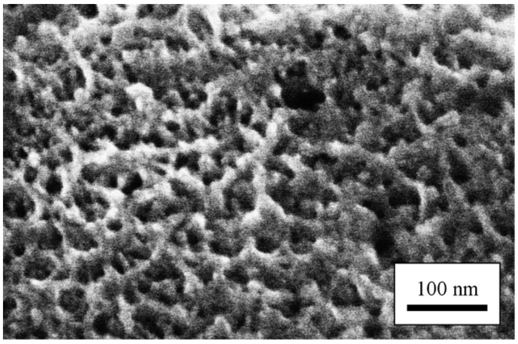

Fig. 2. SEM image of a surface treated metal piece (30° tilt). Porous structures were formed on the metal surface. The size of each pore was approximately 20 nm.

2.1.2. Molding

In this study, we utilized a commercial injection molding machine (ROBOSHOT α-100iA Linear, FANUC) and an original mold. Fig. 3 shows a shape of the mold (cavity) for a single-lap joint sample. The size of the main cavity (plastic body) and of the metal insert were 10 mm × 50 mm × 3 mm and 18 mm × l_{metal} × 1.5 mm (width × length × thickness), respectively. The length of the metal insert, l_{metal}, is selectable from two sizes: 45 mm (short type) or 50 mm (long type). Along with the selection, length of overlap between the plastic body and the metal piece was changed as 5 mm or 10 mm, and thus the joint area was 5 mm × 10 mm or 10 mm × 10 mm, respectively. However strength of the IMDJ sample processed by the long type mold was too large to be evaluated because of too large joint area, which is twice as large as the short type. We, then, used only the short type for the evaluation and analyses. The detail of the evaluation problem is given in Section 3.1.

A unique point of this mold is that a pressure sensor (6158A, Kistler Japan) and a temperature sensor (EPSSZT-04.0×030, Futaba Corporation) were installed to monitor cavity states. To estimate the pressure on the boundary surface, the pressure sensor was located near the joint area as shown in Fig. 3. This is because the pressure on the boundary surface would be one of the most effective factors for plastic replication to the nano-structures and resultant joining strength. The melted plastic would flow into the nano-structures more easily under higher pressure on the boundary surface. By monitoring the cavity states with the sensors, we controlled the molding conditions.

Process states of one cycle of the injection molding are as follows [22]; (I) queueing, (II) packing, (III) holding, (IV) cooling, and (V) ejecting. We can know the state during the molding by the cavity monitoring (especially monitoring pressure behavior). Fig. 4 shows an example of time-course measurements of cavity pressure (upper) and temperature (lower). Pressure variations represent the molding states I to IV as shown in Fig. 4. At the packing state (state II), the pressure rises rapidly, reaches a peak point, and sinks down rapidly as well. Then the cavity state changes to the holding state (state III), where the pressure keeps approximately steady value. Finally, the pressure decreases gradually since the plastic cools and hardens at the cooling state (state IV). The peak value at the state II and the steady value at the state III of the pressure are pack pressure, P_p, and holding pressure, P_h, respectively (Fig. 4). These two types of the pressure values are the investigation objects of this study. Methods of controlling the pressure values are given in the following paragraphs.

Table 1 shows molding conditions. Among them, this study focused on the pack pressure, P_p, the holding pressure, P_h, and the