

# Fundamental Study of Direct Joining between Ceramic and Engineering Plastic Using Lasers<sup>†</sup>

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## Abstract

*Dissimilar-material welding or joining are necessary and important from a manufacturing viewpoint. Therefore, the authors have developed a laser direct joining method between metals and plastics with using a metal oxide film. In this study, the laser direct joining was applied to join ceramic of Si<sub>3</sub>N<sub>4</sub> to engineering plastic of polyethylene terephthalate (PET), although the metal was replaced by the ceramic. Since, the ceramic is similar to metal oxide or nitride in elemental composition. The shear strength of the joints of 30 mm in width was over 3000 N, which was strong enough to elongate the base plates of 2 mm in thickness. It was confirmed that the laser direct joining process has the potential to directly produce a strong dissimilar material in a joint of a ceramic and an engineering plastic.*

**KEY WORDS: (Dissimilar-Material Welding), (Direct Joining), (Ceramic), (Engineering Plastic), (Lasers)**

## 1. Introduction

Metals, plastics and ceramics have been widely used in several industrial applications such as automobiles, aircrafts and electronic devices. Welding or joining of these dissimilar materials are necessary and important from a manufacturing viewpoint. The features of metals include high strength, high toughness, high heat conductivity and high heat resistance. On the other hand, plastics are characterized by lightweight, high corrosion resistance and excellent formability. PET is known as a typical engineering plastic and commercially available in bottle form. Moreover, ceramics are used owing to their high hardness and/or good heat resistance. Silicon nitride ceramic is utilized as a bearing of engine or a rotor blade of turbine.

Joining of these dissimilar materials have been conventionally performed using adhesive bonds (glues) or mechanical tools such as bolts and rivets. However, these joining processes have some problems in terms of environmental restriction of volatile organic compound (VOC) emission and mass production. Therefore, the authors have developed a new laser direct joining method between metals and plastics [1-5].

The laser direct joints between the engineering plastic PET and stainless steel SUS304 before and after the tensile shear test are shown in **Fig. 1**. The top surface of PET was not damaged to be as smooth as what it had been before the laser irradiation. However, many bubbles

of sub-millimeter sizes were formed inside the plastic near the joint. The shear load of the joint was about 3000 N, and the base PET was elongated sufficiently as shown in the lower photo of **Fig. 1**. Such strong joints were produced by the laser direct joining process with many small bubbles.

The laser direct joints were observed with transmission electron microscopes (TEM), and these examples are shown in **Fig. 2**. The TEM image demonstrates that the metal and the plastic are tightly bonded on the atomic or molecular sized level. The base metal and the intermediate layer were identified to be fcc gamma ( $\gamma$ ) phase and 5 nm-thick Cr-oxide film from these diffraction patterns, respectively. It was therefore revealed that the strong joint could be produced by atomic, nanostructural or molecular bonding of the metal and the plastic through the oxide film on the metal plate surface. Not only the anchor (mechanical bonding) effect but also Van der Waals interaction force and chemical bonding were considered as bonding mechanisms of the laser direct joining.

Recently it has been reported that the laser direct joining between several metals and engineering plastics could produce sufficiently strong joints, as shown in **Table 1** [1-5]. The joints between PET and some kinds of metals demonstrated so strong a strength that the PET base plastic was elongated over 3000 N in shear tensile test. The joints between practically-used PA with fibers

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Transactions of JWRI is published by Joining and Welding Research Institute, Osaka University, Ibaraki, Osaka 567-0047, Japan

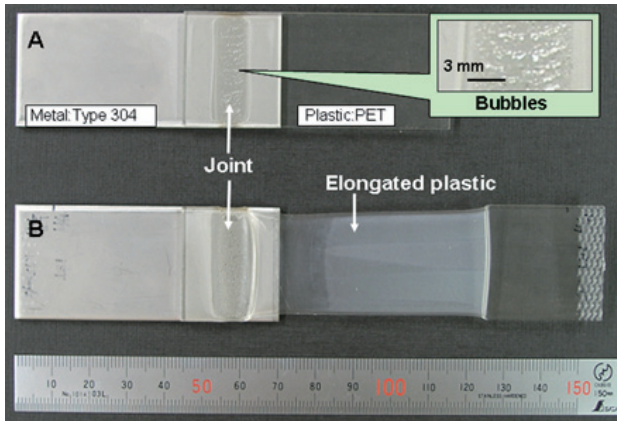


Fig. 1 LAMP joints before and after tensile shear test.

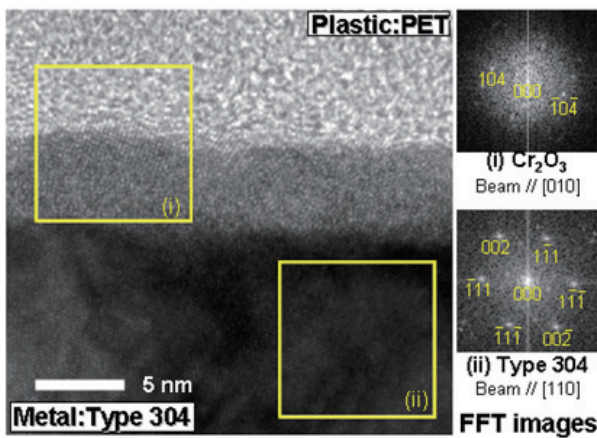


Fig. 2 TEM image and FFT analyses of joints of SUS304 stainless steel and PET plastic.

Table 1 Tensile shear test results of several joints.

| Metal                                      | Plastic        | Tensile shear load [N]<br>* Width: 30 mm |
|--|----------------|--|
| SUS304                                     | PET            | 3000 N (Elongation of base plastic)      |
| A5052                                      | PET            | 3000 N (Elongation of base plastic)      |
| Carbon steel                               | PET            | 3000 N (Elongation of base plastic)      |
| Ti   | PET            | 3000 N (Elongation of base plastic)      |
| Galvanized steel                           | PET            | 2000 N (Fracture of zinc-coated part)    |
| SUS304                                     | Amorphous PA   | 4000 N (Fracture of base plastic)        |
| SUS304                                     | PA with fibers | 4000 N (Fracture of base plastic)        |
| A5052/Carbon steel<br>(sandwich structure) | PET            | 5000 N (Fracture of base plastic)        |

and SUS304 showed good strength over 4000 N. Moreover, the structure PET sandwiched between A5052 and carbon steel had the strong strength of 5000 N over the strength of base plastic in the tensile test, because PET plastic was stressed compressively. Therefore, the joints had sound strength and nanostructural or molecular bonding of the metal and the plastic through the oxide film.

In this research, as the ceramic is similar to metal oxide or nitride in elemental composition, the laser direct joining method with a 3-kW diode laser (LD) was applied to join  $\text{Si}_3\text{N}_4$  ceramic and PET engineering plastic. The joining process was carried out to optimize welding speed. The obtained joints were evaluated by the tensile shear test. Furthermore, the joints were observed in details through TEM in order to investigate the joining structure.

## 2. Materials and Experimental Procedures

The ceramic used was silicon nitride plate. The size is 110 mm x 30 mm with 3 mm thickness. The plastic used was PET plates. The size is 70 mm x 30 mm with 2 mm thickness. PET has the transmissivity property for a laser beam as shown in Table 2. The transmissivity of amorphous PET is high owing to the transparency. PET is decomposed at more than 600 K. On the other hand,  $\text{Si}_3\text{N}_4$  has much higher temperature of decomposition than PET.

This study was performed with the objective of producing strong joints. The joining with an LD beam was carried out in air without shielding gas for cooling the plastic and keeping the clean surface conditions as illustrated in Fig. 3. The LD beam is in the line shape whose major axis is 23 mm. The focused position of the LD beam is on the metal surface. Laser power is 500 W and traveling speed is 4 mm/s to 8 mm/s. To evaluate the mechanical properties of the joints, SHIMAZU AG-10kNE was used as a tensile shear tester.

Table 2 Optical features and decomposition temperature of experimental materials.

| Material                                       | Molecular formula   | Transmissivity<br>(Wavelengths of LD laser) | Decomposition temperature |
|--|---|---|---------------------------|
| PET<br>(Amorphous)                             | $\left[ \text{C}_6\text{H}_4\text{O} - \text{C}(\text{O}) - \text{O} - \text{C}_2\text{H}_4 - \text{O} \right]_n$ | 85 %  | 600 K                     |
| Silicon nitride<br>( $\text{Si}_3\text{N}_4$ ) | —   | 0 %   | 2173 K                    |

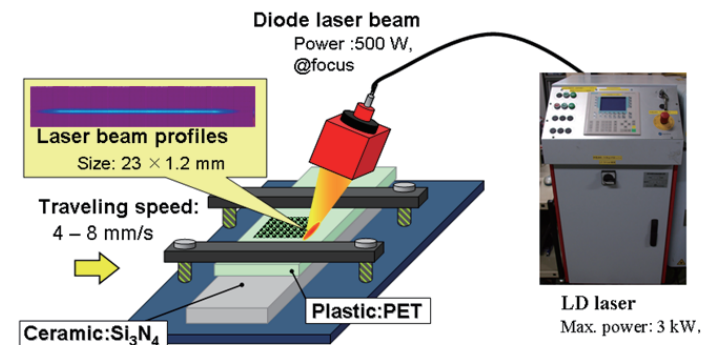


Fig. 3 Schematic experimental set-up of joining of  $\text{Si}_3\text{N}_4$  and PET.

**3. Results and Discussion**

A silicon nitride  $\text{Si}_3\text{N}_4$  plate and a PET plate were overlapped, and then the LD beam was irradiated from the plastic side. The welding speed was changed from 4 mm/s to 8 mm/s at the laser power of 500 W. The typical joining result at 6 mm/s speed is shown in Fig. 4. The top surface of PET was not damaged and smooth as it had been before the laser irradiation as well as the laser direct joining of metals and plastics. The joints were produced at the boundary between the ceramic and the plastic. It was found that many bubbles were formed inside the joints. Figure 5 shows the appearance of the obtained joints at 4 mm/s to 8 mm/s speed. The joining area increased with a decrease in the traveling speed. However, non-bonded areas existed at the speeds of more than 7 mm/s.

From the above results, it was found that the ceramic  $\text{Si}_3\text{N}_4$  and the engineering plastic PET could be jointed directly with LD laser.

The tensile shear strengths of the joints were measured. The tensile shear loads are plotted as a function of welding speed in Fig. 6. The shear loads had a peak at about 6 mm/s, and over 3100 N was achieved. Then the base plastics were elongated. However, at 8 mm/s of travel speed, the joint fractured due to the large non-jointed area. With deceleration of traveling speed from 6 mm/s to 4 mm/s, the shear load decreased to 2500 N. Then the size of bubbles became large.

The joint made at 6 mm/s was observed with TEM. The observation image is shown in Fig. 7. The bright upper part is PET polymer and the dark lower area is  $\text{Si}_3\text{N}_4$ . The TEM image demonstrates that the ceramic and the plastic are tightly bonded on the atomic or molecular sized level. Moreover, it was found that the PET polymer entered at nanoscale hollow formed on the surface of  $\text{Si}_3\text{N}_4$ . It was therefore considered that a strong joint

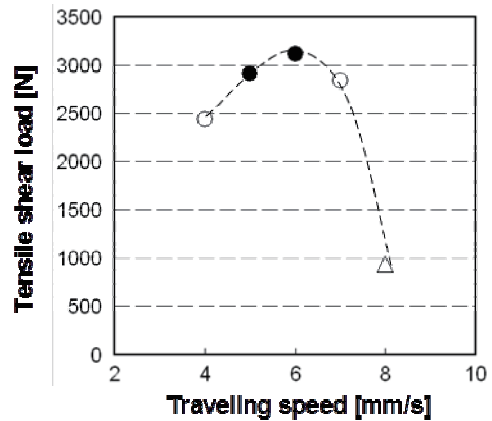


Fig. 6 Tensile shear loads of obtained joints of  $\text{Si}_3\text{N}_4$  and PET made at 500 W laser power, shown as function of welding speed.

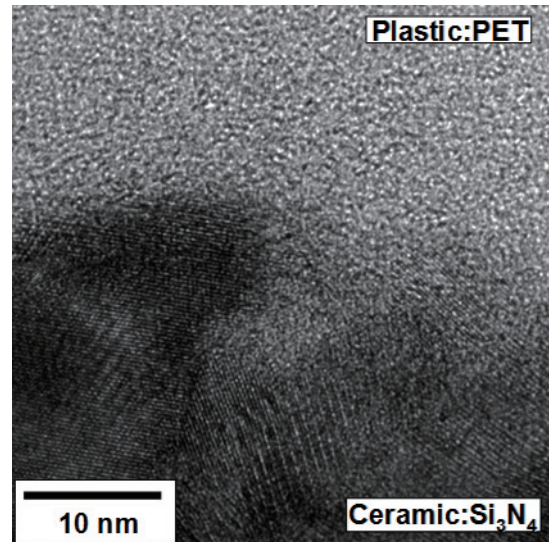


Fig. 7 TEM image of obtained joints of  $\text{Si}_3\text{N}_4$  and PET.

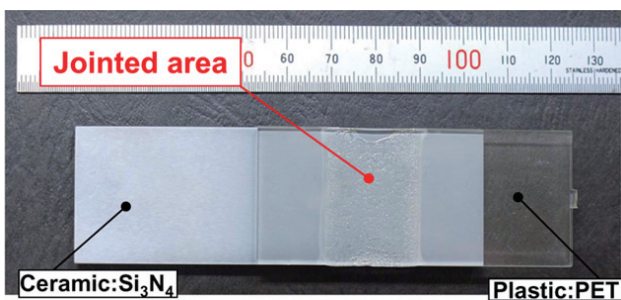


Fig. 4 Surface appearance of joint of  $\text{Si}_3\text{N}_4$  and PET produced at 500 W and 6 mm/s, showing bubbles.

surface, where not only the anchor (mechanical bonding) effect but also Van der Waals interaction force and could be produced by atomic, nanostructural or molecular bonding of the metal and the plastic on the ceramic plate chemical bonding were considered as joining or bonding mechanisms.

| Appearances of LACP joints |        |        |        |        |        |
|----------------------------|--------|--------|--------|--------|--------|
| Traveling speed            | 4 mm/s | 5 mm/s | 6 mm/s | 7 mm/s | 8 mm/s |

Fig. 5 Surface appearances of several magnified joints of  $\text{Si}_3\text{N}_4$  and PET produced at 500 W power and at several traveling speeds of 4 mm/s to 8 mm/s.

#### 4. Conclusions

We had the challenge to produce sound direct joints between the commercially available ceramic  $\text{Si}_3\text{N}_4$  and the engineering plastic PET with a high-power laser beam. The joints produced with a linear shape of diode laser beam were evaluated by the tensile shear test. Furthermore, the joints were observed using TEM in detail in order to investigate the joining structure. The results obtained are as follows:

- i) The best conditions for the joining between  $\text{Si}_3\text{N}_4$  and PET was obtained at 500 W and 6 mm/s, and the joint possessed over 3100 N shear load strength in 30-mm-width plastic samples of 2 mm in thickness. The base plastic was elongated because of the formation of strong joints.
- ii) The TEM image of the joint demonstrates that the ceramic and the plastic are tightly bonded on the atomic or molecular sized level. Moreover, it was also found that the PET polymer entered the nanoscale hollow formed on the surface of  $\text{Si}_3\text{N}_4$ .
- iii) It was considered that the strong joints could be produced by atomic, nanostructural or molecular bonding of the metal and the plastic on the ceramic plate surface, where not only the anchor (mechanical bonding) effect but also Van der Waals interaction force and chemical bonding were considered as

joining and bonding mechanisms.

- iv) The laser direct joining of metals and plastics could be applied to directly join  $\text{Si}_3\text{N}_4$  ceramic and PET engineering plastic

#### References

- [1] Seiji Katayama, Yousuke Kawahito, Akio Tange and Shuji Kubota: "Laser-Assisted Metal and Plastic (LAMP) Joining", Online Proc. of LAMP 2006, JLPS, Kyoto, #06-7, 2006.
- [2] Yousuke Kawahito, Akio Tange, Shuji Kubota and Seiji Katayama: "Development of Direct Laser Joining for Metal and Plastic", Proc. of ICALEO 2006, LIA, Scottsdale, (CD), 2006.
- [3] Yusuke Niwa, Yousuke Kawahito, Shuji Kubota and Seiji Katayama: "Development and improvement in Laser Direct joining of Metal and Plastic", Proc. of ICALEO 2007, LIA, Orlando, (CD), 2007.
- [4] Seiji Katayama, Yousuke Kawahito, Yusuke Niwa and Shuji Kubota: "Laser-Assisted Metal and Plastic Joining", Proc. of the 5th LANE 2007, Erlangen, pp. 41-51, 2007.
- [5] Seiji Katayama and Yousuke Kawahito: "Laser direct joining of metal and plastic" , Scripta Materialia, 59-12,pp.1247- 1250, 2008.