Materials Research Proceedings **32** (2023) 95-102 https://doi.org/10.21741/9781644902615-10

Effect of friction stir forming parameters on mechanical properties and plastic flow of material in the mechanical interlocking of optical fiber and SP-700 superplastic titanium alloy

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Keywords: Friction Stir Welding, Friction Stir Forming, Titanium Alloy, Superplasticity, SP-700, Optical Fiber, Mechanical Interlock, Dissimilar Material Joining

Abstract. The present study discusses the fluidity of titanium alloy during friction stir forming (FSF) and investigates the effect of process parameters on the mechanical properties of titanium alloy in the mechanical interlocking of optical fiber and SP-700 superplastic titanium alloy. In this study, a guide slit is provided in a titanium alloy plate, an optical fiber is placed inside the slit, and FSF is performed on the surface of the titanium alloy. By performing FSF, titanium softens and material plastically deforms inside the slit, which results in mechanically joining optical fiber and titanium alloy. Experimental results of evaluating the mechanical properties after FSF revealed that the hardness value of the material that flowed into the slit was significantly higher than that of the base material, which confirms that the stirring zone has flowed into the slit around the fiber. It was also confirmed that the temperature becomes unstable during the process for a travel speed of 50 mm/min or less, also above 800 mm/min. This resulted in insufficient material flow. As a result, inhomogeneous structures were confirmed. Tensile test results after FSF showed that the strength was lower than that of the base metal (67% to 55% of the base metal) for most process parameters. Although no significant changes in strength were observed by changing the travel speed, it was confirmed that the strength has an increasing tendency as the rotation speed increases, which is considered to be related to the grain refinement of the material. It was also concluded that the limitations in the present study such as insufficient material flow and reduced strength and also damage to the embedded optical fiber can be improved by pre-heating the workpiece and controlling the FSF process parameters which require further experiments and temperature measurements during FSF. In this study, the developed composite can give us hope for embedding FBG sensors inside high melting point alloys to simultaneously measure deformation, strain, pressure, and temperature and create new functional smart materials.

Introduction

Recently, a new metal forming method using the principles of Friction Stir Welding (FSW) [1] called "Friction Stir Forming (FSF)" [2] has gained attention in the field of dissimilar material joining [3-7]. Prof. Tadashi Nishihara of Kokushikan University, the developer of this method, proposed placing the workpiece on the mold and applying friction stir on the backside of the workpiece to transfer the mold shape onto the workpiece, as shown in Fig. 1.

The development of Fiber Bragg Grating (FBG) sensors is essential for achieving lightweight smart parts in aircraft and intelligent aviation control. The development of FBG sensors requires the embedding of fiber optic sensors (FOS) into the substrate of components. However, embedding fibers flawlessly into high-melting-point alloys like titanium-based materials is challenging. As aircraft systems become more complex and high-performance, the need for aircraft lightweighting and fuel efficiency continues to rise. Consequently, the development of innovative technologies to improve the quality, reliability, and health monitoring capability of aircraft systems has become crucial. However, research on embedding FOS into metals is very limited. High-melting-point metals like titanium can protect sensors in harsh environments, but the embedding process into metals involves stringent conditions, and methods like casting or hot pressing cannot be easily employed [3]. Our previous study has proposed a novel method for joining dissimilar materials, titanium alloys, and optical fibers, using friction stir forming and aimed to experimentally investigate the development of novel composite material with embedded optical fibers inside titanium alloy using FSF without compromising the fiber's characteristics which opens possibilities for the development of new functional materials [3]. By introducing this novel composite material as the base material for smart structures, it is expected to function as a sensor for detecting the internal state (temperature and strain) of the host titanium. In previous research, the authors demonstrated the potential of embedding optical fibers inside titanium alloys and discussed the fluidity of titanium during friction stir forming.

In the present study, further investigation is conducted on the material's fluidity during the process, aiming to examine the influence of process parameters in friction stir forming on the mechanical properties of titanium alloys.

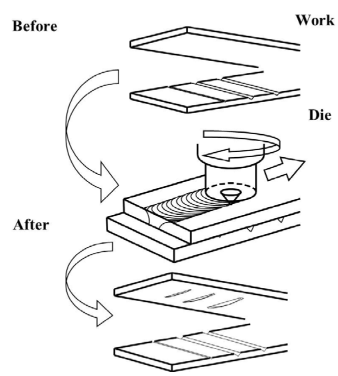

Fig. 1 Schematic Drawing of FSF [2]

Experimental Procedure

The methodology employed in this study is similar to previous research [3]. As shown in Fig. 2, a guide slit is created in an SP-700 titanium alloy plate, and optical fibers are placed within it. Ti-4.5Al-3V-2Mo-2Fe (commercially known as SP-700) is a beta-rich superplastic titanium alloy with fine structures developed for the aerospace industry [9]. Using the tool depicted in Fig. 1 (c) which was made of pure tungsten, friction stir forming (FSF) is performed on the titanium alloy's surface. FSF induces a plastic flow of the material within the slit, mechanically joining the optical fibers inside the titanium alloy.

Previous research results have revealed that during FSF, the material flows more on the retreating side compared to the advancing side. Therefore, in this experiment, the probe center was offset by 2 mm from the center of the slit and offset towards the advancing side while performing FSF. When the probe center was placed directly above the slit and FSF was performed, the optical fiber became brittle and tended to break due to the effect of heat input [1].

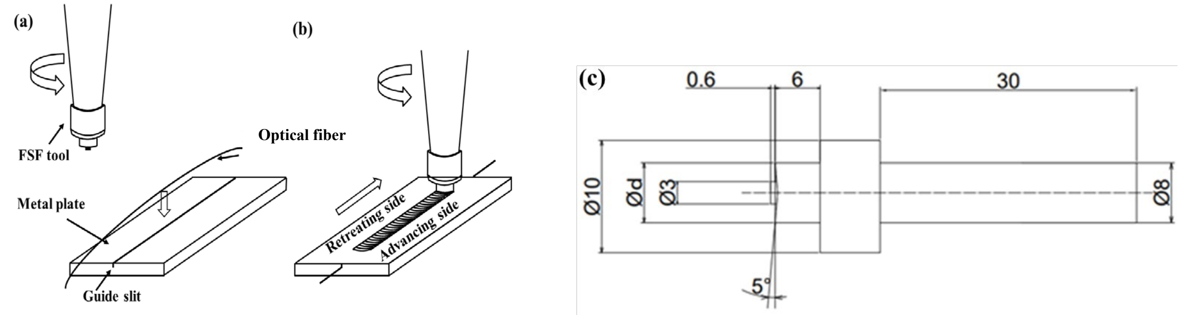

Fig. 2 Schematic of the experimental procedure (a) rotating tool is plunged into the workpiece, (b) tool is traversed along the guide slit to mechanically interlock titanium and optical fiber [1], (c) Dimension of FSF tool (d= 8, 10, 12 mm)

Experimental Results

Material flow and hardness distribution around the optical fiber. It was confirmed in previous studies that as the feed rate increases, the heat input decreases, and especially at speeds of 200 and 400 mm/min, it was confirmed that the frictional heat does not reach the back of the test specimen. However, it was also confirmed that the material was sufficiently filled within the slit even at high feed rate parameters. It is believed that the material flow during FSF is influenced not only by heat input but also by pressure. With higher feed rates, the pressure increases, which is expected to affect the material flow. Additionally, it was observed that burrs are more likely to occur and the surface becomes rough when the feed rate is low at 50 mm/min or high at 800 mm/min [1].

To investigate the change in material flow, FSF was conducted by changing the tool shoulder diameter. Due to the instability of temperature during FSF caused by process parameters, the specimens were cut into four sections after FSF, and cross-sectional microstructure observations were conducted using a metallographic microscope.

As observed in Figure 3 (a), the optical fiber remained intact without damage, but voids were observed, indicating that the material did not flow completely around the optical fiber. Additionally, at the beginning of the process, insufficient heating resulted in insufficient material flow, leaving slits.

Furthermore, hardness tests were conducted, revealing that the hardness value near the stirred region adjacent to the optical fiber was significantly higher than that of the base material. The hardness value of the base material near the optical fiber was found to be equivalent to the original base material hardness. This result suggests that the stirred region flows within the slit, while regions other than the stirred region are not affected by the heat during FSF. In Figures 3 (b)-(d), a uniform material flow can be observed, and there is no significant change in hardness values. This is attributed to the stable heating during the process.

However, it was observed that the temperature becomes unstable during the process at feed rates below 50 mm/min and above 800 mm/min, resulting in heterogeneous material flow. Figure 4 shows the hardness values around the fiber when using a tool shoulder diameter of 8 mm in the FSF experiment, and compared to a tool shoulder diameter of 10 mm, no significant changes were observed. However, it was confirmed that reducing the shoulder diameter reduces the size of the thermomechanically affected zone (TMAZ) and heat-affected zone (HAZ), leading to minimal changes in the structure below the shoulder.

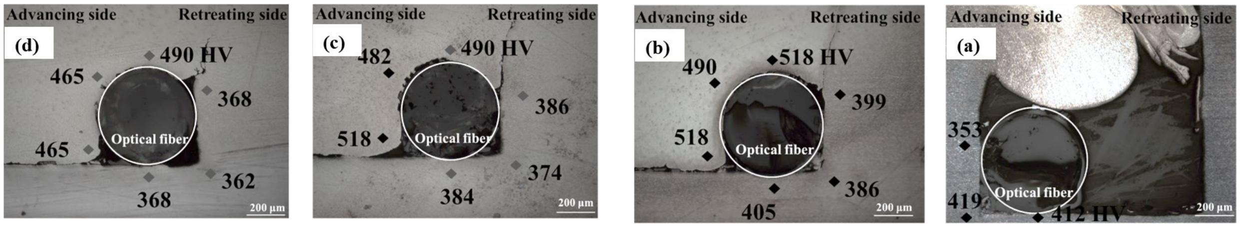

Fig. 3 Cross section of embedded fiber for (a) starting region, (b) and (c) middle region, (d) finishing region (Tool shoulder diameter: 10 mm)

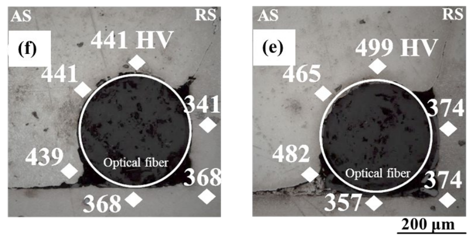

Fig. 4 Cross-section observation of embedded fiber within the middle zone (Tool shoulder diameter: 8 mm)

Evaluation of tensile strength after FSF. In experiments where FSF was performed with an optical fiber installed inside a slit with a width of 1.0 mm and a depth of 1.7 mm, the tensile strength perpendicular to the feed direction may decrease due to insufficient material flow. Therefore, rectangular tensile test specimens perpendicular to the feed direction were created after FSF, by varying the process parameters of the tool and subjected to tensile testing. The creation of the tensile test specimens referred to ASTM E 646-98. The results are shown in Figure 11. In all parameters, lower strengths (ranging from 55% to 67% of the base material strength) were obtained compared to the base material strength, and as confirmed in Figure 5, fracture occurred near the guide slit. It is believed that this can be improved by performing multipass, but further investigation is necessary.

Furthermore, as shown in Figure 5 (right), it was observed that the FSF tool was damaged and the probe section wore out under conditions of high heat input.

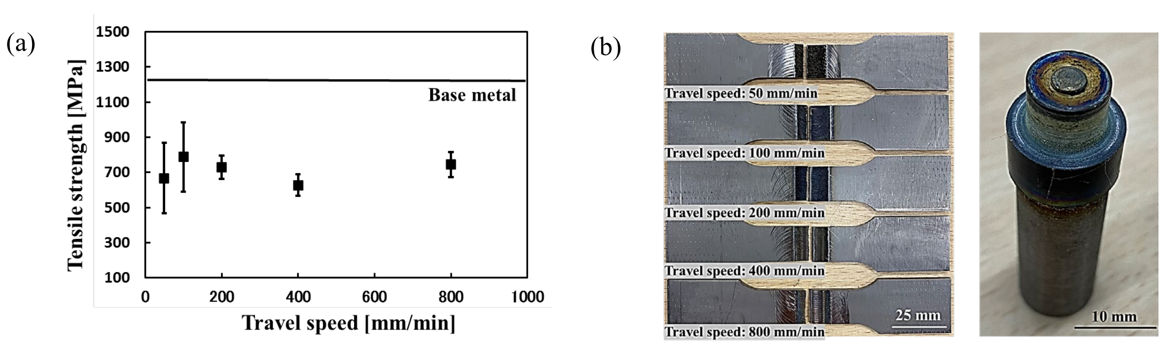

Fig. 5 (a) Relation between tensile strength and FSF tool travel speed (Perpendicular to the direction of processing) (b) Fig. 12 Tensile tested specimens (left) and tungsten tool after FSF (right)

Fig. 6 (a) shows the relationship between tensile strength and tool rotation speed (tensile test results perpendicular to the FSF process direction). As can be seen from the graph, an increasing trend in tensile strength was observed with an increase in rotation speed. This is believed to be related to the heat input during FSF. When the rotation speed is low, the material flow is insufficient, resulting in voids remaining in the slit, which is thought to lead to a decrease in tensile strength.

Fig. 6 (b) shows the relationship between tensile strength and tool travel speed (tensile test results parallel to the FSF process direction). Comparing it with the tensile test results perpendicular to the process direction shown in Figure 11, a significant increase in tensile strength is observed. The strength variation due to different feed rates is believed to be related to the plastic flow of the material inside the slit and the refinement of the grain structure in the stirred region due to the stirring of the probe during FSF. Additionally, in the tensile tests conducted after FSF of Ti-6Al-4V titanium alloy, relatively lower tensile strength was obtained compared to the SP-700 alloy. This is considered to be due to insufficient plastic flow of the material and inadequate material flow into the slit compared to the SP-700 titanium alloy.

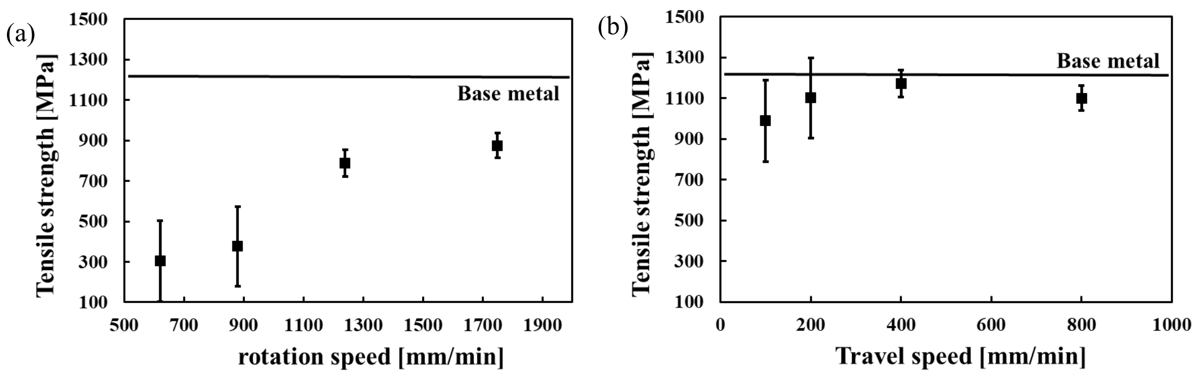

Fig. 6 (a) Relation between tensile strength and FSF tool rotation speed (Perpendicular to the direction of processing), (b) Relation between tensile strength and FSF tool travel speed (Parallel to the direction of processing)

Fig. 7 (a) shows the hardness distribution across the cross-section for different feed rates after FSF. The variation in feed rate causes changes in heat input, which affects the size of the surface grain structure, and this is believed to manifest as changes in hardness values (it is known that hardness increases as grain size decrease due to the Hall-Petch relationship [10-11]).

Furthermore, Fig. 7 (b) presents the hardness distribution across the cross-section for different rotation speeds. As can be seen from the graph, there was no significant change in hardness values due to insufficient stirring at low rotation speeds. At a rotation speed of 1240 rpm, the hardness increased as a result of grain refinement, while at a rotation speed of 1750 rpm, it is believed that the heat input caused coarsening of the grain structure, leading to a decrease in hardness compared to the 1240 rpm rotation speed.

Fig. 8 shows hardness values according to the distance from the surface. As you approach the surface, there is a tendency for the hardness value to increase, which is believed to be related to the differences in crystal grain refinement observed in the micrographs due to stirring.

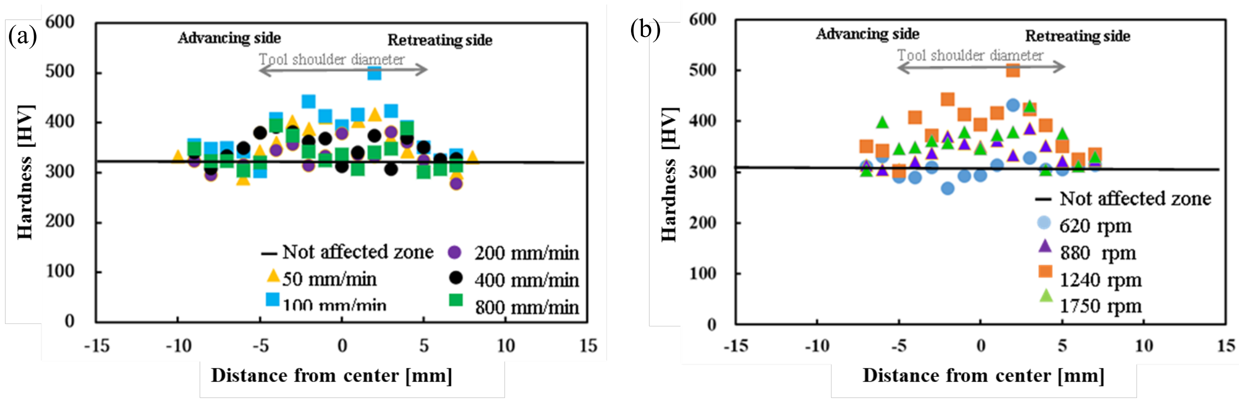

Fig.7 (a) Hardness distribution of cross-section after FSF for different travel speeds (0.5 mm under surface), (b) Hardness distribution of cross-section after FSF for different rotation speeds (0.5 mm under surface)

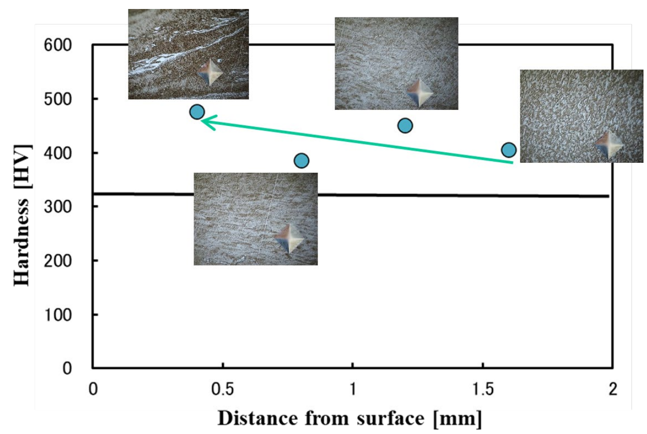

Fig.8 Hardness distribution for different distances from the surface (1240 rpm 100 mm/min)

Temperature measurement during the FSF process. In this experiment, a type K thermocouple was directly installed in the slit (a section with a depth of 1.7 mm) of the test material to create a system that enables temperature measurement inside the material during the FSF process. However, there was a significant variation in the results, and it was not possible to accurately measure the temperature changes with parameter adjustments. The temperature at which the superplasticity of SP-700 titanium alloy occurs is around 1050 K. When the rotational speed was 1240 rpm and the feed rate was 50 mm/min, the maximum temperature measured was 512°C, but it did not meet the temperature indicating the superplastic phenomenon of titanium alloy. By changing the process parameters during the FSF process, it is possible to vary the heat input and control the temperature during the process, which can potentially control material flow and structure. However, further investigation regarding additional temperature measurements is necessary.

Summary

In this study, a mechanical bonding method for optical fibers and titanium alloys using FSF was proposed, and the possibility of forming new functional composite alloys was experimentally investigated. The challenges encountered in this study were insufficient material flow due to the process parameters of FSF and cases where excessive heating resulted in fiber damage. In the future, the development of a system that accurately measures the temperature distribution of the material during FSF will be necessary. However, the potential for smart material development through the mechanical bonding of titanium alloys and optical fibers using FSF has been demonstrated. Furthermore, the relationship between FSF process parameters and the mechanical properties of titanium alloys was examined, and the following findings were obtained:

1. It was revealed that the surface condition, microstructure, and mechanical properties of titanium alloys depend on the process parameters. It was confirmed that feed rates below 50 mm/min and above 800 mm/min lead to temperature instability during the process, resulting in uneven material flow.
2. Hardness tests showed that the hardness value near the stirred region was significantly higher than that of the base material, while the hardness value of the base material near the fiber was comparable to the original base material. This result indicates that the stirred region is undergoing flow within the slit, and areas other than the stirred region are not affected by the heat during FSF.
3. Tensile test results in the feed direction of the tool showed that lower strength values (ranging from 55% to 67% of the base material strength) were obtained in all parameters.
4. Significant changes in strength due to variations in feed rate were not observed, but a decreasing trend in strength was observed as the rotation speed decreased. This is believed to be related to the grain refinement of the material.
5. It is believed that the issue of strength reduction due to insufficient material flow can be improved by performing multipass, but further investigation is needed.
6. The results of material flow at high feed rates suggest that in addition to the effect of heating, pressure and the velocity dependence of superplastic titanium alloys during FSF may also influence material flow, indicating the occurrence of superplasticity during the process.
7. The FSF tool made of pure tungsten was damaged under high heating conditions, particularly because the probe part experienced wear. Therefore, the selection of tool materials for FSF of titanium alloys needs to be considered.

Acknowledgments
Part of his study was conducted with the support of the AMADA Foundation's "Encouragement Research Grant" (Young Researchers Category) (AF-2019044-C2), and we would like to express our gratitude for their support.

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