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# Microstructure and Mechanical Properties of High Velocity Oxygen Fuel (HVOF) Sprayed Titanium Powder Coating on Welding Regions of Aluminum Alloy AA5754 Welded Plates With The Friction Stir Spot Welding Process

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## Abstract

In this study, it is aimed to investigate microstructural and mechanical properties of friction stir spot welding (FSSW) joints coated with titanium powder by using high velocity oxygen fuel method (HVOF). The welding regions of AA5754 aluminum alloy was coated with titanium powder with a thickness of 70µm by using HVOF. FSSW tool was designed and manufactured from cold work tool steel material by machining. Specimens were metallographically prepared and Vickers hardness of base metal, welding zone and heat affected zones were measured. Microstructure and fracture surface of the specimens investigated by using scanning electron microscope (SEM), energy dispersive spectroscopy (EDS) and optical microscope analysis. Due to titanium coating interface and ductile joint formation in the welded region during FSSW process. The results of experimental studies were evaluated in order to analyze microstructural and mechanical properties of welding joints.

**Key words:** Friction stir spot welding process, high velocity oxygen fuel, titanium powder spraying

## 1. Introduction

High-strength aluminum alloys have been increasingly employed in welding of large aerospace structures, such as fuel tanks of launch vehicle, space shuttles and space ships. The welded structures usually experience a complex internal/external pressure and structure torque during the service which requires the high-standard welds. With the advancement of manned spacecraft and deep space exploration projects, however, conventional fusion welding technique is no longer competitive to fulfill the requirement of rocket fuel tanks with high reliability and high efficiency production. As soon as the FSW technique was invented, it drew extensive interests from aerospace industry owing to its exceptional advantages including less defects, low distortion and excellent joint performance [1]. FSSW is a modification of the FSW process that can effectively replace the resistance spot welding (RSW) technique abundant in the automotive industry. FSSW exhibits several advantages in welding dissimilar materials [2]. No melting is involved in this process, thus, many problems are eliminated or reduced, such as porosity, shrinkage and distortion which are often found in conventional friction stir welding [3]. High strength 7000 series aluminum alloys are widely used in critical condition in aircraft and aerospace structures. Along with 2000 series aluminum alloys, it is considered relatively difficult to weld using fusion welding techniques because of the crack sensitivity and severe mechanical property decrease [4]. In this study, the

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friction stir spot welding FSSW technique was used for the welding of a 2mm-thick AA5754 Aluminum alloy sheets, which are the most common materials used in the car industry. The welding processes were carried out with same welding parameters but with the rotating tools having 3.4 mm, 3.5 mm and 3.8 mm different pin length. The mechanism of the titanium powder coated interfacial microstructure formation was analyzed and the effect of the titanium powder coating and pin length used in the first step on the final microstructure and mechanical properties of the flattened AA5754 alloy sheets welds was investigated [5].

## 2. Materials and Method

### *2.1. The design of the materials to be joined by FSSW*

**Table 1.** Chemical analysis and mechanical properties of aluminum materials used in the welding process.

| Material | % Fe | %C | % Si | %Cu | %Mn | % Mg | % Zn | %Ti | %Cr | %Al |
|---|---|---|---|---|---|---|---|---|---|---|
| AA5754 | 0,312 | - | 0,23 | 0,024 | 0,34 | 3,2 | 0,16 | 0,098 | 0,26 | Remain. |
| | Tensile Strength (N/mm2) | | | | % Elongation | | | Hardness (HV) | | |
| | 232 | | | | 15 | | | 76 | | |

### *2.2. HVOF sprayed Titanium powder coating on welding regions of AA5754 Aluminum alloy sheets*

Thermal spraying is a well established means of forming relatively thick coatings. In particular, high velocity oxy fuel (HVOF) spraying has been developed into a reliable technique to apply hard, tribologically superior and well adherent metallic and composite cermet's coatings to a great variety of metallic surfaces. Among the thermal spraying techniques, HVOF is effectively used to prepare coatings with dense structure at a particle velocity of above 700 m/s [6, 7]. The HVOF thermal spray method is cost effective and has been applied to Titanium-based coatings.

**Table 2.** High velocity oxygen fuel (HVOF) titanium powder spray parameters

| Powder spray process parameters | HVOF spray |
|---|---|
| Spray Gun Type | Metco Diomont Jet |
| Spray distance | 330 mm |
| Spraying rate | 5.7 kg/h |
| oxygen pressure | 9.35 atm |
| Nitrogen pressure | 3.2 atm |
| The coating powder | Titanium |

The morphology and chemical composition of the phases that are present in the coatings were characterized by means of SEM, EDS techniques. The results show that the nanostructured coating has excellent mechanical properties due to the microstructural homogenization and the well preserved nanostructure characteristic of the Titanium powders.

### *2.3. Tool tip geometry, design of materials to manufacturing and machining production*

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Cold work tool steel material is fine particles have a structure. having balanced wear resistance and ductility values cold work tool steel is an ideal quality that can be processed hardened steels up to 60 HRC.

**Table 3.** Tool profile and the experimental parameters used in friction stir spot welding

| FSSW Sheets | Titanium powder coating deposited thickness | FSSW Tool tip Profile | Tool Rotational Speed (rpm) | Dwell Time (s) | Tool tip Penetration Depth (mm) |
|---|---|---|---|---|---|
| AA5754/Ti/ AA5754 | 70μm | Conical | 2000 | 5 | 3.4 |
| AA5754/Ti/ AA5754 | 70μm | Conical | 2000 | 7 | 3.5 |
| AA5754/Ti/ AA5754 | 70μm | Conical | 2000 | 9 | 3.8 |

### *2.4. The design of steel mould used in friction stir spot welding FSSW and machining process to manufacturing production and use on milling machines*

**Figure 1.** The milling machine used AA5754/Ti/ AA5754 Aluminum alloy sheets for friction stir spot welding process

### *2.5. Metallographic sample preparation and mechanical testing after the welding*

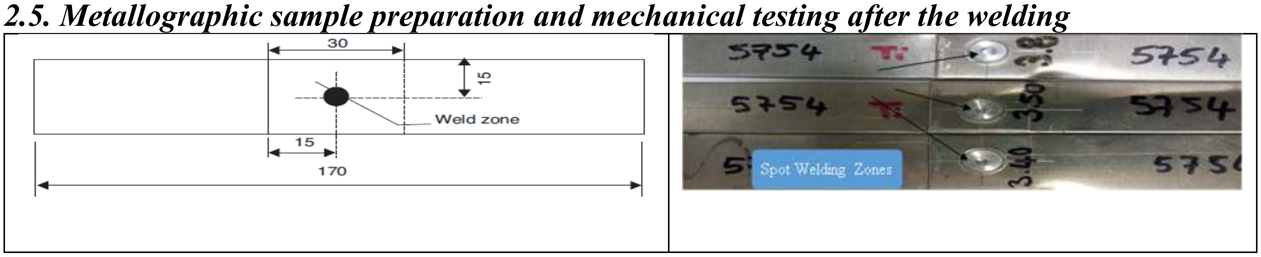


**Figure 2.** Scheme of the dimensions measured on the spot weld cross-section [9] and HVOF sprayed titanium powder coating on welding regions of AA5754/Ti/ AA5754 aluminum alloy welded sheets with the FSSW

The shear tensile tests of the welds were carried out using an Instron-type testing machine with a crosshead speed of 1mm/min, according to the ASTM E8M-04 standard.

## 3. Results and Discussion

### *3.1. Fractography of performing tensile testing after welding*

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**Figure 3.** Appearance and cross-sectional macrostructure of the fractured specimen after shear tensile tests with Interfacial mode and ductile fracture mode at this region

**Table 4.** Tensile strength changes with tool penetration depth and dwell time

| Welded Materials | Tool Penetration Depth (mm) | Tool dwell time s | Tensile strength (MPa) |
|---|---|---|---|
| a-AA5754/Ti/AA5754 | 3.4 | 5 | 55.1 |
| b-AA5754/Ti/AA5754 | 3.5 | 7 | 145 |
| c-AA5754/Ti/AA5754 | 3.8 | 9 | 213 |

Lap-shear test data obtained from welding inserts (Fig. 4), made with FSSW method [8] shows the tensile load and deformation rate. Data obtained from welding joints, created with plunge depths of 3.4mm, 3.5mm and 3.8mm in very short periods of 5,7,9s dwell time, which are respectively 55.1MPa, 145MPa and 213MPa demonstrate that they have sufficient tensile strength.

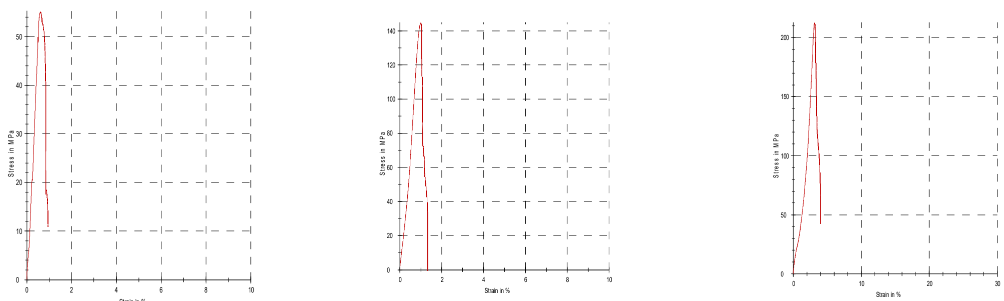

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**Figure 4.** Max.tensile strength (213MPa) and strain graph of 3.8mm pin penetration depth and 9s dwell time with ductile fracture mode at this region

Fracture type, can be described as rupture from the Interfacial mode with low tensile strength. With the addition of titanium to the microstructure, the tensile strength increased slightly compared to joining with titanium-free interface. A higher tensile strength value than would be expected from the joining of two materials with different chemical compositions such as aluminum and titanium, was obtained. These results can be explained with the presence of titanium on the titanium-coated AA5754 aluminum sheet, and the formation of a strong metallurgical bonding between the other sheet and the corresponding titanium-coated interface. The relationships between tensile-shear strength and tool dwell time are shown in (Table. 4). The tensile-shear strength is strongly affected by shoulder plunge depth and dwell time. the tensile-shear strength increases with increasing shoulder plunge depth and dwell time. The tensile-shear strengths are the highest values (145MPa-

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213MPa) at the pin plunge depth of 3.5mm plunge depth, 7s dwell time and 3.8mm plunge depth, 9s dwell time respectively. When examined in detail the friction stir spot welding method produces a similar microstructure to friction stir welding method. Agglomerated titanium particles exist in the dynamic stirring zone where recrystallization takes place from the welding key hole towards the base metal. The zone adjacent to the dynamic stirring zone can be named as thermomechanical affected region, and the nearest neighboring zone to the base metal as the heat affected region [10].

### *3.2. Microhardness distributions analysis of the FSSW joint in AA5754/Ti/AA5754 aluminum alloy sheets*

Microhardness measurements were taken on the specimen's weld key hole weld sides and bottom of the FSSW joint in AA5754/Ti/AA5754 aluminum alloy sheets cross section using Vickers microhardness testing using 200 g load and at 0.5 mm distance between successive indentations according to the ASTM: E384-11.

**Table 5.** Microhardness ($Hv_{200}$) distributions bottom, left side and right side of the FSSW joint in AA5754/Ti/AA5754 aluminum alloy sheets

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bottom | 73 | 75 | 77 | 74 | 72 | 85 | 88 | 98 | 83 | 96 | 85 | 80 | 76 | 74 | 77 | 74 | 75 |
| Left side | 73 | 75 | 87 | 124 | 172 | 185 | 188 | 198 | 208 | 196 | 185 | 180 | 176 | 174 | 177 | 174 | 175 |
| Right side | 73 | 75 | 127 | 184 | 192 | 214 | 209 | 198 | 138 | 196 | 194 | 208 | 198 | 174 | 134 | 74 | 75 |
| Distance from weld interlayer center (mm) | 4 | -3.5 | -3 | -2.5 | -2 | -1.5 | -1 | -0.5 | 0 | 0.5 | 1 | 1.5 | 2 | 2.5 | 3 | 3.5 | 4 |

Micro-hardness distribution for each micro-hardness specimen welding rigions, a total of 32 micro-hardness values were measured at three different layers namely, bottom, right wall and left wall layers along the thickness of the weld at 12 mm distance in NZ and 7 mm distance at other zones. Measured hardness values were compared for welding cases with Al and titanium-coated alloying element and without alloying element. It was observed that the indentation diameters without any alloying element have more size compared to Al and titanium-coated alloying joint. Indentation diameter in case of Al alloying have smaller size because of hard AlTi alloying formation and highest hardness compared to without alloying element and titanium-coated joint specimens. It was observed that micro-hardness of the titanium-coated interlayer is comparatively more than that of bottom regions. Micro-hardness of the titanium-coated interlayer zone is considerably higher compared to TMAZ, HAZ and BM as grains at the titanium-coated interlayer zone became finer due to dynamic recrystallization during the welding process. But in case of FSSW joint with titanium-coated interlayer micro-hardness purely depends on titanium-coating. it is found that

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welding left side wall of the FSSW joint have maximum hardness of 208 $HV_{200}$ due to presence of hard AlTi coating formation at the welding regions.

## Conclusions

In the present study, the influence of 70µm interlayer titanium coated aluminium alloy properties on Al/Ti/Al friction stir spot (FSSW) weldability was analysed in this study for a certain set of welding parameters. Joint surface appearances, cross-sections, microstructure and mechanical properties of the lap joints were mainly studied. The main conclusions can be drawn:

1. Friction stir spot welding method; the aluminum-titanium material was joined with 2000rpm tool rotation speed and 9s max. dwell time parameters. Micro-hardness of the titanium-coated interlayer zone is considerably higher compared to TMAZ, HAZ and BM as grains at the titanium-coated interlayer zone became finer due to dynamic recrystallization during the welding process. It was observed that micro-hardness of the titanium-coated interlayer is comparatively more than that of bottom regions as shown in (Table 5).
2. The tensile-shear strength is strongly affected by shoulder plunge depth and dwell time. the tensile-shear strength increases with increasing shoulder plunge depth and dwell time. The tensile-shear strengths are the highest values (145MPa-213MPa) at the pin plunge depth of 3.5mm plunge depth, 7s dwell time and 3.8mm plunge depth, 9s dwell time respectively.
3. Friction stir spot welding is a solid state welding process which is applied very quickly. The most important feature of the titanium coating is the minimization of the formation of oxide during the friction stir process. While intermetallic composite oxide formation that may occur at the interface is minimized, it is possible to speak of a strong metallurgical bond. Furthermore, thanks to the achieved high strength the structure also features high tensile strength 213MPa (Fig. 4c).
4. Friction stir spot welding process to the titanium coated AA5754 aluminum alloy sheets welding regions of the HAZ-TMAZ zones which create the joining interfaces of the sheets, are the weakest zones (55.1MPa). Although this zone has a many kinds of microstructure, there are formations not completed with the friction stir process which are not recrystallized. In this context the tensile damage during the destructive pull test, ductile-brittle weakest interfacial mode occurred mostly in these regions (Fig. 4a, b).

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