Çukurova Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi, 31(ÖS 1), ss. ÖS 51-ÖS 60, Ağustos 2016
Çukurova University Journal of the Faculty of Engineering and Architecture, 31(ÖS 1), pp. SI 51-SI 60, August 2016

Microstructure and Mechanical Properties of High Velocity Oxygen Fuel (HVOF) Sprayed Nickel Powder Coating on Welding Regions of Aluminum Alloy AA5754 and DP600 Welded Steel Plates with the Friction Stir Spot Welding Process

Mesut ÖZER[1], HasanKAYA[2], EgemenAVCU[3], Abdullah DEMİR[4], Mehmet UÇAR[1], Ramazan SAMUR[*5]

[1]*Department of Automotive Engineering, Faculty of Technology, Kocaeli University, Kocaeli*
[2]*Department of Machine and Metal Technology, Asim Kocabiyik Vocational School of Higher Education, Kocaeli University, Kocaeli*
[3]*Department of Machine and Metal Technology, Ford Otosan Vocational School of Automotive, Kocaeli University, Kocaeli*
[4]*Department of Mechanical Engineering, Faculty of Technology, Marmara University, Istanbul,*
5Department of Materials and Metallurgy, Faculty of Technology, Marmara University, Istanbul

Geliş tarihi: 30.12.2015 Kabul tarihi: 30.03.2016

Abstract

In this study, it is aimed to investigate microstructural and mechanical properties of friction stir spot welding joints coated with nickel powder by using high velocity oxygen fuel method HVOF. The welding surfaces of AA5754 alloy was coated with nickel powder with a thickness of 200 μm by using HVOF. Friction Stir spot welding tool was designed and manufactured from hot worked tool steel by machining. Metallographic specimens were cut from welding samples by using abrasive water jet. Specimens were metallo graphically prepared and Vickers hardness of base metal, welding zone and heat affected zones were measured. Microstructure of the specimens investigated by using scanning electron microscope (SEM), energy dispersive spectroscopy (EDS) and optical microscope analysis. The results of experimental studies were interpreted in order to analyze microstructural and mechanical properties of welding joints.

Keywords: Friction stir spot welding process, High velocity oxygen fuel nickel powder spraying (HVOF), DP600 steel

[*]Sorumlu yazar (Corresponding author): Ramazan SAMUR, *Department of Materials and Metallurgy, Faculty of Technology, Marmara University, Istanbul, rsamur@marmara.edu.tr*

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Yüksek Hızlı Oksijen Yakıtlı Alev Toz Püskürtme Yöntemiyle Nikel Kaplanmış AA5754 Alüminyum Alaşımı ve DP600 Galvanizli Çeliğin Sürtünme Karıştırma Nokta Kaynağı ile Birleştirilmesinde Mikroyapı ve Mekanik Özelliklerin İncelenmesi

Özet

Bu çalışmada, sürtünme karıştırma nokta kaynağının yüksek hızlı oksijen yakıtlı alev toz püskürtme yöntemiyle nikel kaplanmış malzemelerdeki mikroyapı ve mekanik özelliklerinin incelenmesi amaçlanmıştır. AA5754 alüminyum alaşımı kaynak yüzeyleri HVOF metodu kullanılarak 200 µm kalınlığında nikel ile kaplanmıştır. Sürtünme karıştırma nokta kaynağı takımı sıcak işlem çeliğinden tasarlanmış ve imal edilmiştir. Metalografik numuneler abrasif su jeti ile kaynaklı parçalardan kesilmiştir. Numuneler Metalografik olarak hazırlanmış ve temel metal, kaynak bölgesi ve ısıdan etkilenen bölge Vickers sertliğinde ölçülmüştür. Numunelerin mikro yapısı taramalı elektron mikroskobu, EDS analizi ve optik mikroskop görüntüleme ile incelenmiştir. Deneysel çalışma sonuçları, mikroyapı ve kaynaklı birleştirmenin mekanik özellikleri analizi için yorumlanmıştır.

Anahtar Kelimeler: Sürtünme karıştırma nokta kaynağı, Yüksek hızda oksijen yakıtlı yüksek hızlı alev toz püskürtme yöntemiyle nikel kaplama, DP600 çelik

1. INTRODUCTION

Friction stir spot welding method, was invented by the Kawasaki Heavy Companies in 2000 as a derivation of the stir welding method [l]. The two most important parameters in friction stir spot welding; is the rotational speed and dwell time of the tool. These parameters form a welding geometry with the material flow around the pin during the formation of welding spot and heat is generated. Moreover, they also determine the mechanical properties of the welding spot A review of recent studies by several researchers reveal a big surge in the number of studies on the effect of the rotation speed and dwell time on physical and mechanical properties of the welding spots created during the joining of A1 and Mg alloys using the friction stir spot welding method. However, only a very few researchers are studying the joining of different materials, such as aluminum and steel with the friction stir spot welding method [2]. Initially, there were only a limited choice of suitable steel tool materials that could withstand high temperatures during friction stir spot welding (FSSW) of aluminum alloys. However, with the development of new tool materials the friction stir spot welding (FSSW) can now be applied to steel [3]. Friction stir spot welding method have become a quiet popular topic among researchers due to its excellent mechanical properties, low distortion, ease of use, low cost and clean and un-messy operation. The plunge of the tool into the material and the dwell time is the main factors that generate heat in the friction stir spot welding method. Furthermore, as the plastic deformation of the material around the pin determines the welding geometry, it also determines the mechanical properties of welded joints [4]. The 5xxx series aluminum alloys containing significant amounts of Mg, can be used in the construction of aircraft and naval vessels due to their processing characteristics offering usability from room temperature to high temperatures. Ultrasonic welding of these alloys continues to be a subject of interest for many researchers. Welding of aluminum alloys with the friction stir welding method was invented by the Welding Institute UK (TWI) in 1991, [5]. Particularly, the 5XXX series containing Mg in solid solution, or Al_3Mg_2 particles dispersed in a random matrix, have good corrosion resistance properties. Friction stir welding (FSW) is a solid state joining process involving different areas of heating and cooling than conventional fusion welding method. Therefore, it is possible to say that formation of different microstructures provides uniformity in itself. Therefore such an homogeneity can be the driving force that can suppress stress corrosion cracking (SCC) and intergranular corrosion cracking (IGC). The tool which is rotating at a high speed plunges into material and provides softening without melting the materials during friction stir. Furthermore, the tool advancing along the welding axis by rubbing on the material in front of it during friction stirring causes a heterogeneous chemical change in the initial material pushing it toward the rear of the tool. Because no additive material is used, welding joints have the same chemical composition with the main material. This should reduce the corrosion sensitivity observed in joints with two factors [7]. Due to their low weight aluminum and its alloys can be considered as a building material in advanced applications for energy-saving purposes. Aside from corrosion resistance, their weight ratio and other superior characteristics make this material and its alloys more attractive for transportation industries such as automobiles, trains and aircraft [8]. When the different chemical composition and mechanical properties of base materials are taken into account, it can be said that the results from the friction stir welding of different materials have become comparable to that of similar materials. Because fusion welding of dissimilar aluminum is problematic, friction stir welding process (FSW) are widely used with success in the welding of different materials that do not form a secondary phase, as the temperature in this method is below the melting temperature of the base material [9]. Some studies (FSW) focused on the corrosion behavior of welding seams of aluminum alloys have shown that friction stir welding zones (AA2024, AA5454, AA5456, AA7050, AA7075) are locally more sensitive to corrosion compared to base metals. Only a few authors have shown the electrochemical surface reactivity change between the various regions of FSW. The highest anode reaction in regions where the potential for failure is measured was detected in the 5456 FSW welding seam nugget [10]. As the double-layered sheets both have the desired properties, they can have unique features such as wear resistance, improved mechanical and physical properties. For example, in the two-layered Al-Cu structure, copper provides a 50% reduction in the aluminum mass because it has equivalent conductivity features with A1 [13]. High-velocity oxy-fuel thermal spraying (HVOF), is a conventional thermal spray technique used in coating base materials for high temperature applications. One of the unique features of this technology are the high impact velocity formed during the powder injection molding process. During spraying of dust particles to sub-layers at high-speed powder is melted through acceleration and dense and non-porous coatings are created. High velocity oxy-fuel-spraying (HVOF) method should particularly be used in order to obtain dense and homogenous microstructures formed by plastic deformation of sprayed powder. Because, HVOF spray systems operate at atmospheric pressure, investment and operating costs are much lower than other thermal spray processes operated at vacuum [15].

In this study, the friction stir spot welding FSSW technique was used for the dissimilar welding of a 2mm-thick AA5754 Aluminum alloy to a DP600 steel sheet, 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 3.2mm and 3.5mm different pin length. The mechanism of the nickel coated interfacial microstructure formation was analyzed and the effect of the nickel and pin length used in the first step on the final microstructure and mechanical properties of the flattened AA5754/DP600 steel sheet welds was investigated.

2. EXPERIMENTAL

2.1. The Design of the Materials to be Joined by Friction Stir Welding

Chemical and mechanical properties of used materials are shown in Table 1 and 2.

Table 1. Chemical analysis of aluminum and steel 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.
DP600	Remaining	0.10	0.15	-	1.40	%N 0.009		%P0.07	%S 0.008	0.02

Table 2. Mechanical properties of the aluminum and steel materials used in the welding process.

Sample	**Tensile Strength (N/mm^2)**	**% Elongation**	**Hardness (H_V)**
AA5754	232	15	76
DP600	625	25	286

2.2. High Velocity Oxygen Fuel (HVOF) Sprayed Nickel Powder Coating on Welding Regions of AA5754

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 cermets 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 [17]. The HVOF thermal spray method is cost effective and has been applied to Ni-based coatings.

Nickel is often used as the bond strength-enhancing layer. Ni powder coatings deposited by means of HVOF thermal spray, onto AA5754 aluminum alloy substrate. The parameters of the process in this study are listed in Table 3. The morphology and chemical composition of the phases that are present in the coatings were characterized by means of SEM, EDS techniques.

Table 3. High velocity oxygen fuel (HVOF) powder spray parameters

Powder spray Process parameters	**High velocity oxygen fuel 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
Flammable gass pecies	Natural Gas
The coating powder	Nickel

The results show that the nanostructured coating has excellent mechanical properties due to the microstructural homogenization and the well preserved nanostructure characteristic of the ball milled powders. It is shown in Figure 1.

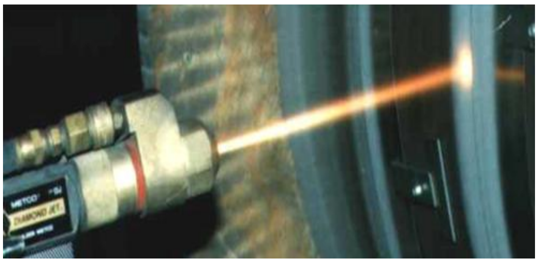


Figure 1. High velocity oxygen fuel nickel powder spraying method (HVOF) [6]

2.3. Tool Tip Geometry, Design of Materials to Manufacturing and Machining Production

HB44UF Carbide tool material is very fine (ultrafine) particles have a structure. Having balanced wear resistance and ductility values HB44UF is an ideal quality. It is especially ideal for high speed tool with a quality that can be processed hardened steels up to 64 HRC.

Figure 2 and Table 4 represent friction stir spot welding tools, tools profile and the experimental parameters

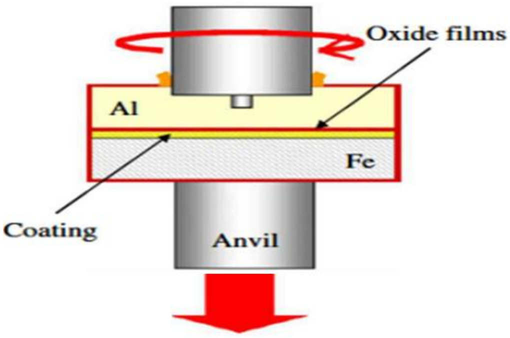
Figure 2. Tapered pin having 3.2 mm and 3.5 mm length of friction stir spot welding tool

Table 4. Tool profile and the experimental parameters used in friction stir spot welding

Friction Stir Spot Welding Sheets	AA5754/ DP600	AA5754/ DP600
Friction Stir Spot Welding Tool Profile	Conical	Conical
Tool Rotational Speed (rpm)	1600	1600
Tool Penetration Depth Rate (mm/min)	12,5	12,5
Dwell Time (s)	5	8
Tool Penetration Depth (mm)	3,2	3,5

2.4. The Design of Steel Mold Used in Welding and Machining Process to Manufacturing Production and Use on Milling Machines

Overlapped sheets were placed on the steel mold on the milling machine table. The number of revolution of milling machine spindle is adjusted. However the spot places are marked on the sheet metals. The stages of the process are demonstrated in Figure 3, the milling machine and its apparatus are shown in Figure 4.



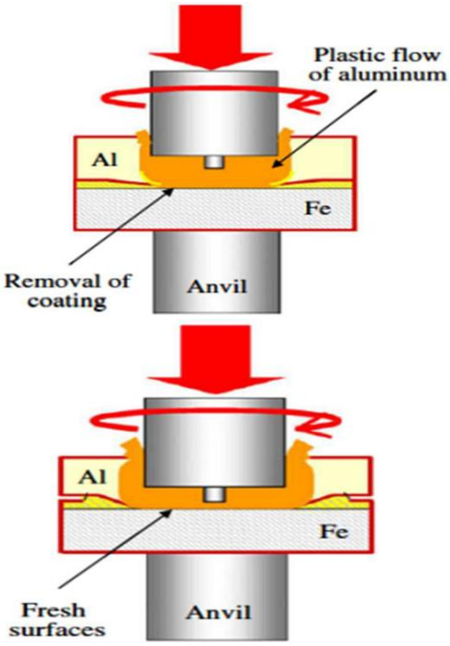


Figure 3. A schematic illustration of the friction stir spot welding FSSW process steps for joining Aluminum with Galvanized steel [11]

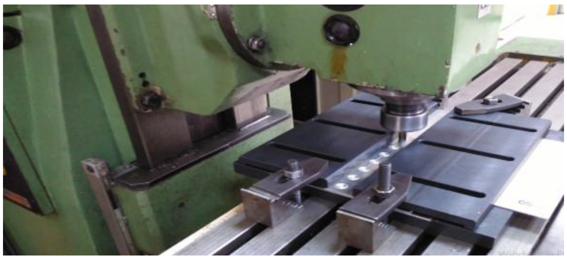


Figure 4. The milling machine used for friction stir stop welding process

2.5. Metallographic Sample Preparation and Mechanical Testing After the Welding

After a succesfull friction stir stop welding process, specimens were cut by waterjet cutting as shown figure 5 dimensions. After cutting operations, the specimens are prepared for the metallographic scanning (Figure 6-7). As the mechanical testing, tensile lap-shear test was applied, appearance and cross-sectional macrostructure of the fractured specimen are investigated (Figure 8).

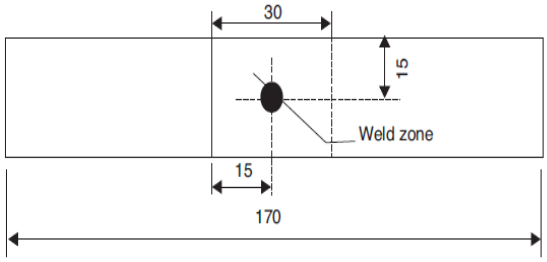


Figure 5. Dimensions of lap-shear tensile specimen [3]

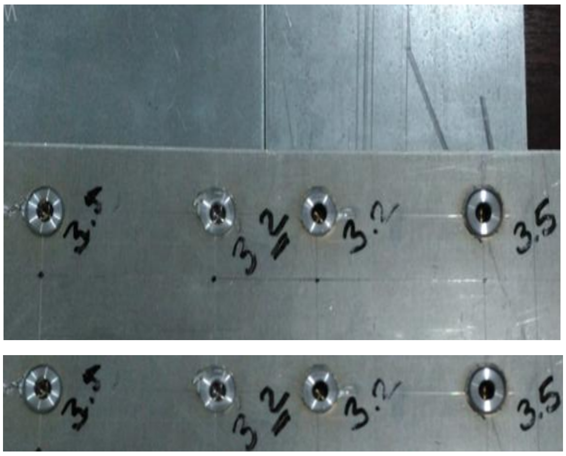


Figure 6. High velocity oxygen fuel (HVOF) sprayed nickel powder coating on welding regions of aluminum alloy AA5754 and DP600 welded steel plates with the friction stir spot welding

Figure 7. Metallographic specimens

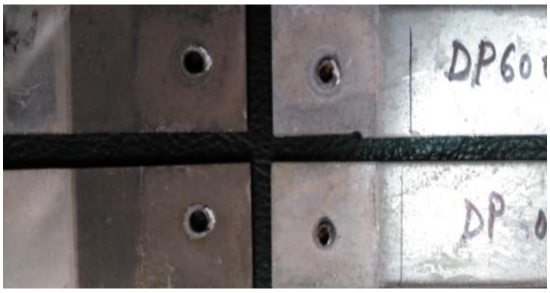


Figure 8. Appearance and cross-sectional macrostructure of the fractured specimen after shear tensile tests with Interfacial mode

2.6. Performing Tensile Testing After Welding

Lap-shear test data obtained from welding inserts (Figure 9), made with friction stir spot welding (FSSW) method shows the tensile load and deformation rate. Data obtained from wielding joints, created with plunge depths of 3.2 mm and 3.5 mm in very short periods of time, which are respectively 2.169 kN, 2.387 kN, demonstrate that they have sufficient tensile strength. Fracture type, can be described as rupture from the interface with low tensile strength, .With the addition of nickel to the microstructure, the tensile strength increased slightly compared to joining with nickel-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 steel, was obtained. These results can be explained with the presence of nickel on the nickel-plated AA5754 aluminum sheet, and the formation of a strong metallurgical bonding between the DP600 steel plate and the corresponding interface. The shear tensile tests of the welds were carried out using an Instron-type testing machine with a crosshead speed of 3mm/min, according to the ASTM E8M-04 standard. The relationships between tensile-shear strength and tool dwell time are shown in (Table 5) and (Table 6). The tensile-shear strength is strongly affected by shoulder plunge depth. The tensile-shear strength increases with increasing shoulder plunge depth. The tensile-shear strengths are the highest (2387,66 N) at the pin plunge depth of 3.5 mm. Pin penetration depth increases, the tool dwell time is increasing in parallel.

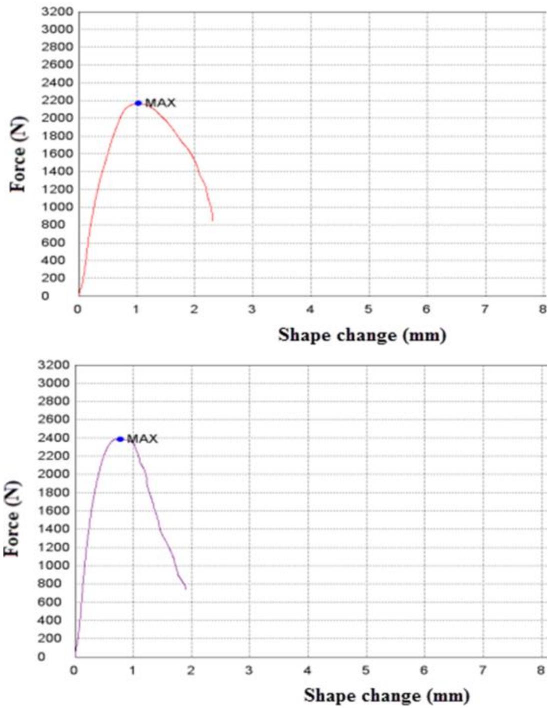


Figure 9. Tensile strength and strain graph of pin penetration depth and dwell time

Table 5. Tensile strength change with tool penetration depth

Welded Materials	Tool Penetration Depth (mm)	Force (N)
5754/DP600	3,2	2169,53

Table 6. Tensile strength change with tool penetration depth

Welded Materials	Tool Penetration Depth (mm)	Force (N)
5754/DP600	3,5	2387,66

2.7. Scanning Electron Microscope (SEM) Macro and Microstructure Analysis

When the friction stir tool first plunges down to the DP600 steel plate underneath it, the plate close to the pin forces the interface to bend upwards, but this effect is dampened by excessive shear deformation forces around it. The metallurgical bonding process between the AA5754 aluminum and DP600 steel plates which are friction stir spot welded by super-positioning on top of each other takes place at the welding zones. A thin oxide film usually occurs at the surface of the metallic materials facing the atmosphere. At the same time, the upper AA5754 aluminum plate welding interface has a 200 µm thick nickel coating, while the lower DP600 steel plate has a 4 µm thick zinc coating. The oxide film, formed on the plate interface around the pin of the friction stir tool rotating at high speed, the zinc film, and the nickel-coating, are broken into fine particles and spread across the welding metal matrix heterogeneously. The most important feature of the nickel and zinc coating is the minimization of the formation of oxide during the friction stir process. Furthermore it is possible to improve the metallurgical bonding between the plates in this way. While these discontinuous oxide particles formed into an array partially prevent the formation of a metallurgical bond between the superimposed sheets, zinc and nickel particles which exist in the structure can be said to improve the formation of a metallurgical bond. When examined in detail the friction stir spot welding method produces a similar microstructure to friction stir welding method. Agglomerated nickel 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 impact zone, and the nearest neigbouring zone to the base metal as the heat impact zone [14]. (Figure 10-11)

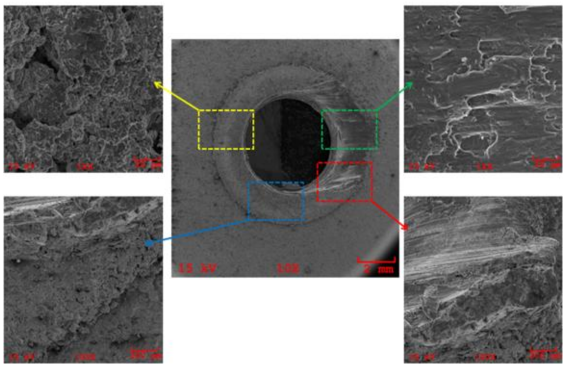


Figure 10. SEM fractograph micrographs regions of AA5754

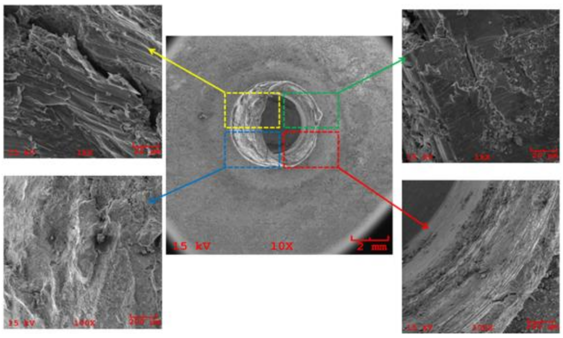


Figure 11. SEM fractograph micrographs regions of DP 600

2.8. Microhardness Distributions Analysis of the Fssw Joint in AA5754 Aluminyum Alloy and Dp600 Steel Sheets

The Vickers hardness tests on the cross-sectional of the welds were carried out using an Vickers hardness testing machine according to the ASTM: E384-11. (Figure 12)

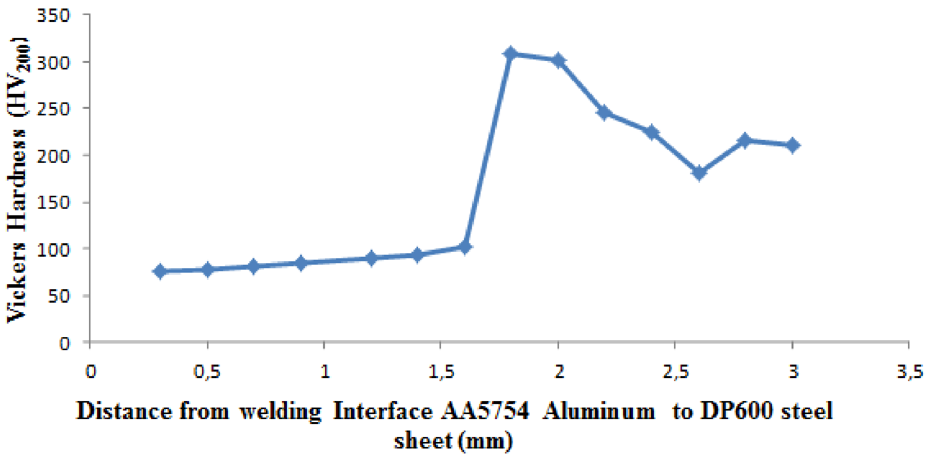


Figure 12. Microhardness distributions of the FSSW joint in AA5754 aluminum alloy and DP600 steel sheets

4. CONCLUSION

1. It was aimed in this study to improve the mechanical strength of the joints of AA5754 medium strength aluminum sheets containing Mg as alloying elements joined with friction stir spot welding by altering the chemical composition of the weld seam. In this context, the plate edges of AA5754 aluminum alloy sheets, were coated with 200 µm nickel using high velocity oxy-fuel thermal powder spraying (HVOF) method.

2. Friction stir spot welding process can quickly be applied to nickel coated AA5754 aluminum alloy which is widely used in the industry and the zinc plated DP600 grade steel sheet.

3. In order to obtain reliable welding joints with sufficient strength in friction stir spot welding applications, it is necessary to work with optimal welding parameters. If the tool rotation speed is low, re-crystallization temperature cannot be achieved particularly at the core section and the tool tip may be worn in a very short time. If the rotational speed of the tool is higher than the desired values, high heat generated due to high rotational speeds may cause alloy elements with low melting temperatures such as zinc and magnesium to be burnt lowering the strength of the welded joint.

4. Friction stir spot welding is a solid state welding process which is applied very quickly. The most important feature of the nickel and zinc coating is the minimization of the formation of oxide during the friction stir process. While inter metallic 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 Fig. 10.

5. In terms of Friction stir spot welding process design, the strength value of the top AA5754 nickel coated aluminum alloy is lower compared to the zinc-coated steel sheet DP600. Since the temperature during the process is at low levels, nickel particles which are agglomerated during friction-plunge are spread to the microstructure. As the temperature is low and the area affected by heat effect is narrower damage is likely to be reduced Fig. 11.

6. In the application of the friction stir spot welding process to the nickel coated AA5754 aluminum alloy and the zinc coated DP600 steel sheet, the aluminum side of the HAZ-TMAZ zones which constitute the joining interfaces of the plates, are the weakest zones. Although this zone has a very diverse 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 occurred mostly in these regions Fig. 11.

5. ACKNOWLEDGEMENTS

Asst. Prof. Dr. SAMUR acknowledges the support by Marmara University, Scientific Research Projects Department (BAPKO), Project FEN-C-YLP-030114-0014.

Note: The responsible translator for English language is Dr. O. Faruk CANTEKİN, School of Foreign Languages, Gazi University, Turkey

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