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Fatigue Behavior of Dissimilar Welded Monel400 and SS316 by FSW

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Abstract**—**In the present work, the dissimilar Monel400 and SS316 were joined by Friction Stir Welding (FSW). The applied rotating speed was 400 rpm, whereas the traverse speed varied between 50 and 150 mm/min. At a constant rotating speed, the sound welds were obtained at the welding speeds of 50 mm/min and 100 mm/min. However, a groove-like defect was formed when the welding speed exceeded 100 mm/min. The mechanical properties of the joints were evaluated using tensile and fatigue tests. The fatigue strength of dissimilar FSWed specimens was higher than that of both Monel400 and SS316. To study the failure behavior of FSWed specimens, the fracture surfaces were analyzed using a Scanning Electron Microscope (SEM). The failure analysis indicates that different mechanisms may contribute to the fracture of welds. This was attributed to the dissimilar characteristics of dissimilar materials exhibiting different failure behaviors.

Keywords**—**Frictions stir welding, FSW, stainless steel, Monel400, mechanical properties.

I. Introduction

MONEL400 is one of the most important nickel-copper alloys exhibiting very high corrosion resistance. The corrosion resistance along with sufficient ductility and cold workability makes Monel400 very attractive for utilizing in a wide range of industrial applications. For example, Monel400 is widely used in reducing and oxidizing environments, marine industry, power and chemical plants etc. [1]. As for the stainless steels, they are widely used as structural materials in a large number of applications such as pressure vessels, power and chemical plants, pipes and marine structures [2]. These unique properties are due to the good corrosion resistance and toughness of these steels. In terms of present work, there are many situations in industrial applications which dissimilar materials are joined and used. Generally speaking, the joining of dissimilar materials enhances the effectiveness of parts. Another aim of joining dissimilar materials is to attain the certain properties for especial applications. However, in order to take advantage of different properties of different materials, the main concern is to produce high quality joints of dissimilar materials. Meeting this demand requires new methods for joining the dissimilar materials. In this regard, FSW is among the new techniques to produce the welds of high quality [3], [4].

On the other hand, fatigue is the main cause of failure regarding the welded components and structures [5]-[7]. There are many works regarding the effect of FSW parameters on the properties of similar materials joined by FSW. Song et al. [8] studied the effect of welding speed on the microstructural evolutions and mechanical properties of FSWed Inconel600. Also, Zhou et al. [9] investigated the effect of rotating speed on the properties of Ti–6Al–4V joined by FSW. Jafarzadegan et al. [10] applied the FSW technique to join the st37 and SS304. Then, the microstructural evolutions of dissimilar joint of SS304 and st37 steel were studied [10]. They reported that in the stir zone of the SS304, the refined grains were formed via dynamic recrystallization process. The fatigue behavior of FSWed parts was investigated by Zhou et al. [11]. They reported that the defects such as root flaws were observed in the stir zone of welds. These defects exhibit detrimental effects on the fatigue behavior of FS joints. However, the root flaws cannot be detected easily comparing to other defects formed during the FS welds [12]. The fatigue behavior of welded Al–Mg alloys as a function of welding speed was studied by James et al. [13]. Ericsson and Sandstrom studied the effect of welding speed on the fatigue life of FSWed AA6082 [14]; their results were then compared with those obtained by conventional fusion welding technique [14].

Therefore, the aim of present work was to join the dissimilar alloys of Monel400 and SS316 via FSW as well as to study the fatigue behavior of the produced weld. The properties of FSWed specimens were then compared with those of base materials.

II. Materials and Experimental Procedure

The dissimilar materials used in this study were 3.5 mm thick SS316 and Monel400. The compositions of studied SS316 and Monel400 are given in Tables I and II, respectively. Table III presents the mechanical properties of both materials.

TABLE I
CHEMICAL COMPOSITION OF SS316 (WT%)

Fe	Ni	Cr	C	Mn	Mo	others
65.3	10.1	20.2	0.05	1.87	2.31	0.71

TABLE II
CHEMICAL COMPOSITION OF MONEL400 (WT%)

Ni	Cu	Fe	Mn	Mg	Co	others
65.5	29.7	1.36	1.23	1.1	0.57	0.57

TABLE III
MECHANICAL PROPERTIES OF MONEL400 AND SS316

Ultimate tensile strength of Monel400 (MPa)	Yield strength of Monel400 (0.2% offset) (MPa)	Ultimate tensile strength of SS316 (MPa)	Yield strength of SS316 (0.2% offset) (MPa)
570	283	430	270

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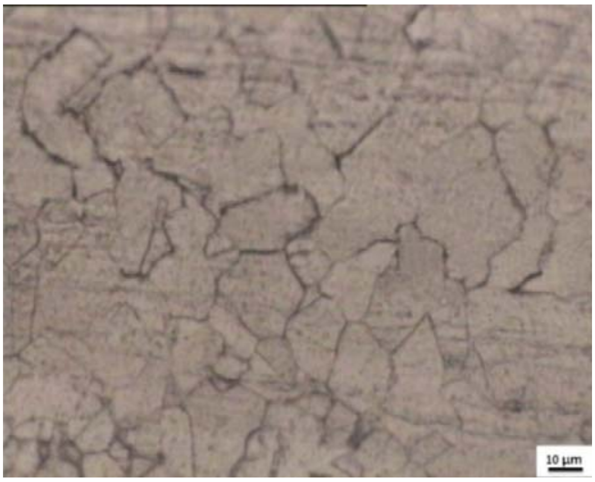
The initial microstructure of SS316 featured coarse austenite grains, whereas Monel400 exhibited a structure composed of fine equiaxed grains (as depicted in Fig. 1). The welding tool employed for FSW was constructed from WC (tungsten carbide) and featured a shoulder with a diameter of 16 mm. Additionally, the tapered pin had a length of 3.2 mm, as illustrated in Fig. 2. To prevent oxidation, pure argon gas was used as a shielding gas during the FSW process.



(a)

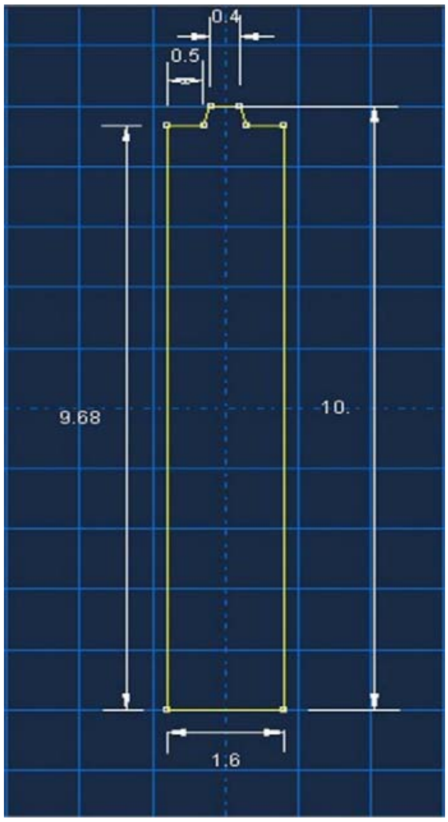
(b)

Fig. 1 (a) Initial microstructures of Monel400, and (b) SS316

The applied rotating speed was 400 rpm, whereas the traverse speeds of 50 mm/min, 63 mm/min, 80 mm/min, 100 mm/min and 150 mm/min were employed. During the FSW, the tilt angle and plunge depth were 3° and 3 mm, respectively.

The specimens for tensile testing were cut perpendicular to the welding direction. The fatigue specimens were also machined perpendicular to the weld line having a gauge length of 20 mm. The fatigue tests were carried out at the stress ratio and frequency of R = 0.1 and 62.5 Hz, respectively. The fracture appearance of tensile and fatigue specimens was characterized using SEM.

(a)



(b)

(c)

Fig. 2 The tool used for FSW (a), and (b) (all dimensions are in cm), are schematic of tool and (c) is picture of tool

III. Results and Discussion

A. Tensile Strength

Fig. 3 presents the results of tensile tests regarding the dissimilar joints obtained at different traverse speeds. Obviously, all the joints exhibited lower tensile strength than the starting Monel400. However, this was not the case for the

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specimen welded at the welding speed of 100 mm/min. At a constant rotating speed, the tensile strength of the joints increases with increasing the welding speed. The maximum tensile strength was obtained at the welding speed of 100 mm/min. When the welding speed exceeds 100 mm/min, the heat input is not sufficient for joining the present high-melting point materials. As a result, a groove-like defect was observed when the traverse speed exceeded 100 mm/min.

B. Fatigue Behavior

The S-N curves regarding the Monel400-SS316 welds are shown in Fig. 4. The samples were produced at the rotating and traverse speeds of 400 rpm and 100 mm/min. For comparison, the S-N curves regarding the Monel400 and SS316 are also presented in Fig. 4.

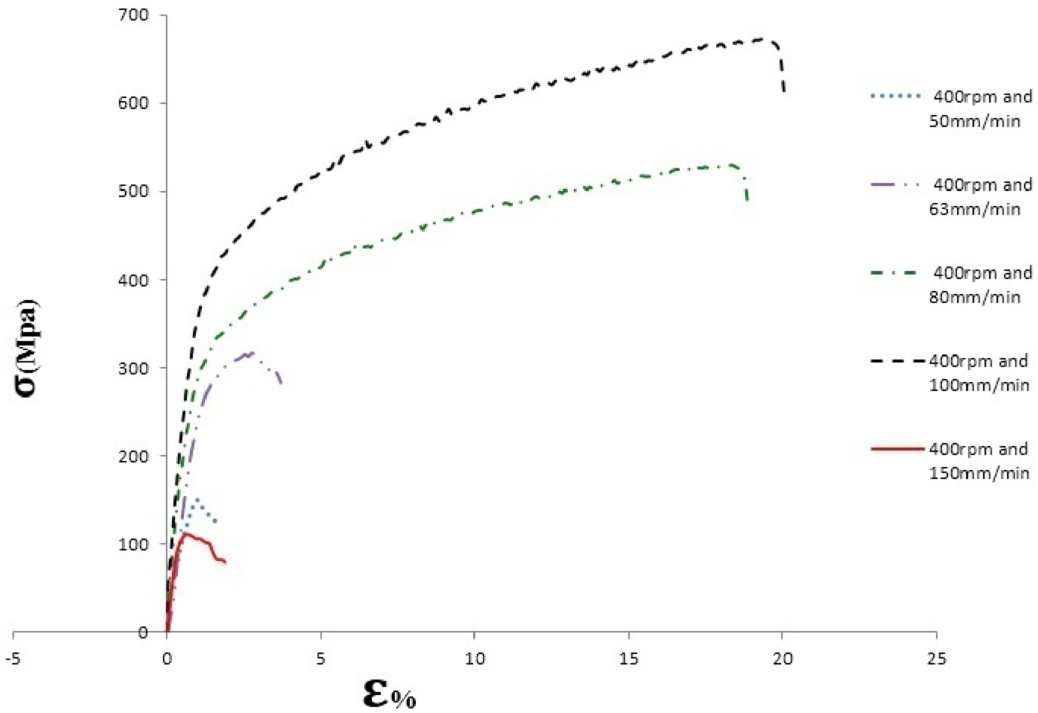

Fig. 3 The tensile properties of the FS Weld specimens joined at different rotating and traverse speeds; the best quality was obtained with the rotating speed of 400 rpm and welding speed of 100 mm/min

According to Fig. 4, the fatigue strength of the dissimilar FSW specimen is higher than those of both starting materials, i.e., Monel400 and SS316. This can be attributed to the lower tensile residual stress generated during FSW comparing to other conventional welding techniques. It is well known that the fatigue strength of welded structures is influenced by residual stress. Comparing to conventional fusion welding, there is less heat input during FSW which can lead to lower tensile residual tensile stress in the FSW case. On the other hand, as even extrusion process occurs during FSW, there can be higher compressive residual stresses in the FSW specimens which have a positive effect on their fatigue life [15]. In addition, as FSW is a kind of thermomechanical treatment, i.e., applying severe plastic deformation at high temperatures, a defect-free weld can be attained. Therefore, it is possible that not only the defects such as coarse/dendritic microstructure, but also the porosities existed in the structure of starting materials are removed during such thermomechanical treatment. The grain refining and therefore structure modification during the solid-state welding of FSW can lead to enhanced properties including fatigue resistance. All of these can be responsible for higher fatigue resistance of FSWed specimens in comparison with the base materials, though the contribution of each requires more detailed studies.

The fatigue specimens of FSWed Monel400 and SS316 were failed due to the cracks that were initiated in the root area of the welding zone. Generally speaking, weld root is more susceptible to crack initiation due to the lack of sufficient stir processing. This is also because of the constraint stresses that lead to hot cracking as well. As the studied alloys have high strength, the weld defects may be more pronounced if the welding speed is high, i.e., higher than 100 mm/min here. In other words, the higher the strength, the lower the traverse speed should be. That is because the lower traverse speed provides higher heat input as well as more time for stirring which results in stronger joints. As fatigue resistance is very sensitive to weld discontinuities, the presence of such defects can significantly decrease the fatigue life of welds.

However, according to the aforementioned mechanisms, it is believed that if the FSW specimen is tested in the High Cycle Fatigue (HCF) region, the S-N curve will drop most likely lower than the base materials. That is because, in the HCF region, the crack initiation does not make sense since there are discontinuities in case of welds comparing to base. Thus, this can be attributed to the presence of pre-existing cracks in welded joints, which tend to propagate more easily, leading to a reduced fatigue life for the welded parts. This holds true even for ductile materials that are typically suitable for the HCF region, as cracks are readily initiated but have a more challenging time propagating.

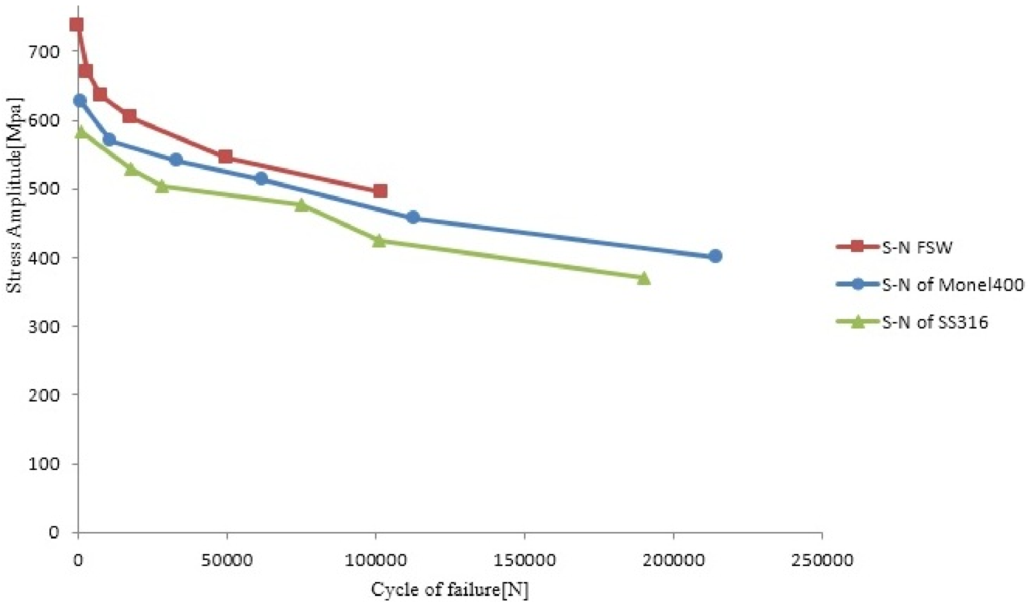

Fig. 4 Fatigue endurance curve of the studied joint for rotating and welding speed, 400rpm and 100mm/min, the fatigue strength of dissimilar FSWed specimen is higher than those of both starting materials of Monel400 to SS316

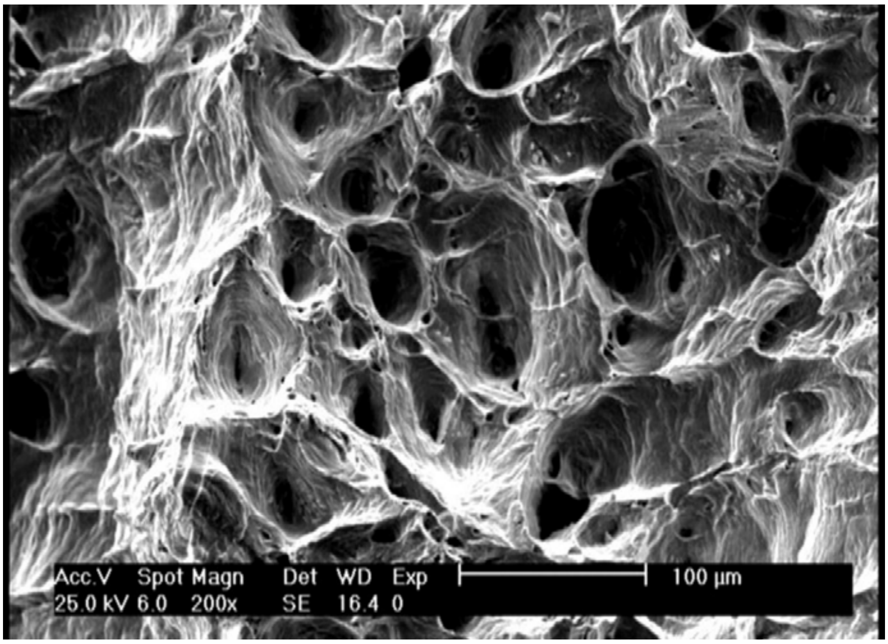

Fig. 5 Fracture surfaces of the fatigue specimen welded at the speed of 100 mm/min, that illustrating a combination of both dimple and striations

C. Fractography

Although the fatigue specimens failed from the weld root, the failure of tensile specimens occurred adjacent to the weld line. The failure location corresponds to the transition zone placed between the thermo-mechanically affected zone (TMAZ) and the heat affected zone (HAZ) of SS316. As already discussed, in addition to the interface between different zones of FSW, the weld root can act as a common defect or discontinuity in the welds produced by FSW. In fact, when the root flaws are already present, the first stage or fatigue crack nucleation is ignored, resulting in a significant decrease in fatigue life. In such a case, the fatigue life of welds is determined only by the crack propagation rate [16]. Fig. 5 presents the fracture surface of the fatigue specimen illustrating a combination of both

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dimple and striations. This image is taken from the stir zone adjacent to SS316. Failure occurred in this area probably because two dissimilar materials are not well stirred/mixed to form a uniform structure or a solid stir zone. This figure shows an especial feature of fracture appearance including the striations along with the voids of different sizes. It is of interest that the voids are separated by striations indicating the changes in fracture behavior mostly because of dissimilar materials. However, there are some flat regions located between the dimples. As the difference between the mechanical properties and microstructure of parent materials is noticeable, this kind of behavior may imply that in case of dissimilar materials when the first material is in the second stage of fatigue process, the second one can be in the third stage. The former behavior is termed growth stage characterize by striations, whereas the latter is known as final rupture stage occurred in a ductile manner due to the overload.

By increasing the traverse and rotating speed, the material is extruded too fast due to the high strain rate imposed during FSW. On the other hand, the higher the strain rate, the shorter time is provided for optimum mixing of the dissimilar materials in the stir zone.

The fracture appearance concerning the specimen welded at the traverse speed of 150 mm/min is presented in Fig. 6. This image is regarding the stir zone where there is a proper and desirable stirring/mixing of dissimilar materials. In such a case, a solid and uniform stir zone is formed. It is clear that two different types of fracture behavior are observed, indicating again a mixed mode of fracture mechanisms due to mixing of dissimilar materials with different behaviors. The striations are observed within the flat regions separated by dimples. Such a fracture appearance resembles also the cleavage planes with river patterns. On the other hand, the wavy/rough appearance of regions rather than their flat appearance indicate the ductile behavior of material. Just next to the striation, there are different sizes of dimples distributed on the fracture surface. Both striations and dimples indicate the ductile behavior through different mechanisms. However, the difference in the flow of dissimilar materials can result in localized-deformation zones which act as the preferential sites for crack initiation and eventually final failure.

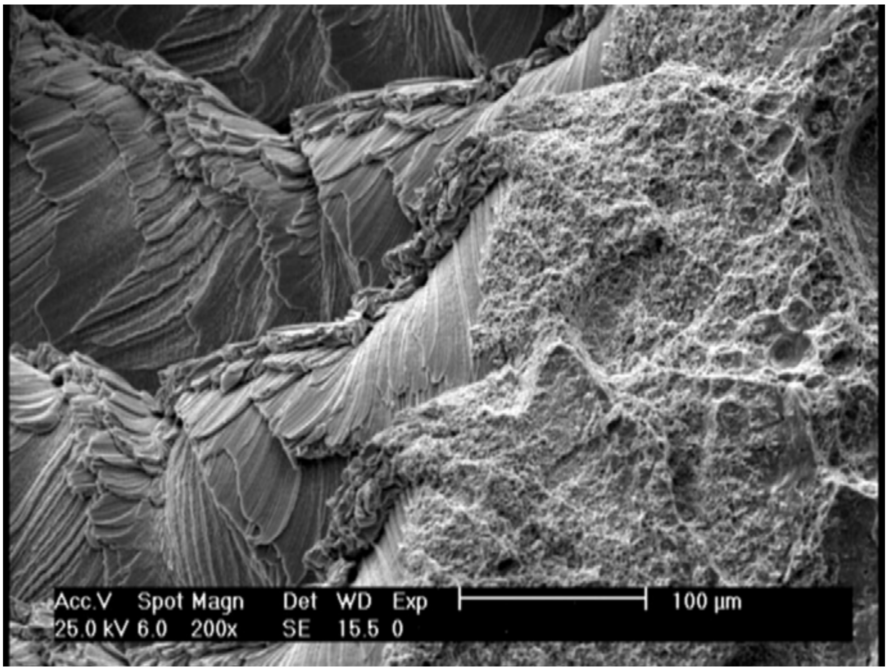

Fig. 6 Fracture appearance of the fatigue specimens welded at 150 mm/min, this is regarding the stir zone where there is a proper and desirable stirring/mixing of dissimilar materials

Therefore, in case of dissimilar materials, the failure occurs according to dissimilar mechanisms which depend on the characteristics of each material. Another point is that at traverse speeds higher than 100 mm/min, the less heat input can cause boundary weakening of the recrystallized grains which can enhance the premature fracture.

Fig. 7 illustrates the fracture appearance regarding the SS316 side of FSWed specimen after tensile testing. This figure clearly shows the formation of dimples and voids which are known as the characteristics of ductile fracture. Referring to Fig. 7, the left side is close to the stir zone (SZ), while by getting away from the SZ and approaching the base material, the dimples get not only larger but also clearer. In fact, by getting away from the interface, the regions are mostly affected by the heat rather than by the mechanical work which are defined as the HAZ and TMAZ, respectively. Consequently, the grains get coarser by getting away from the interface. It is well known that the regions with coarse grains are softer than regions having finer grains. As a result, the dimples in the softer zones, which have coarse grains (i.e., low-strength zones), are larger than the dimples formed in the regions having fine grains (i.e., high-strength zones). To clarify this point, the aforementioned zones are marked in Fig. 7. Generally speaking, the fine grains are formed in the stir zone via the occurrence of dynamic recrystallization, whereas the coarse ones are formed in the HAZ.

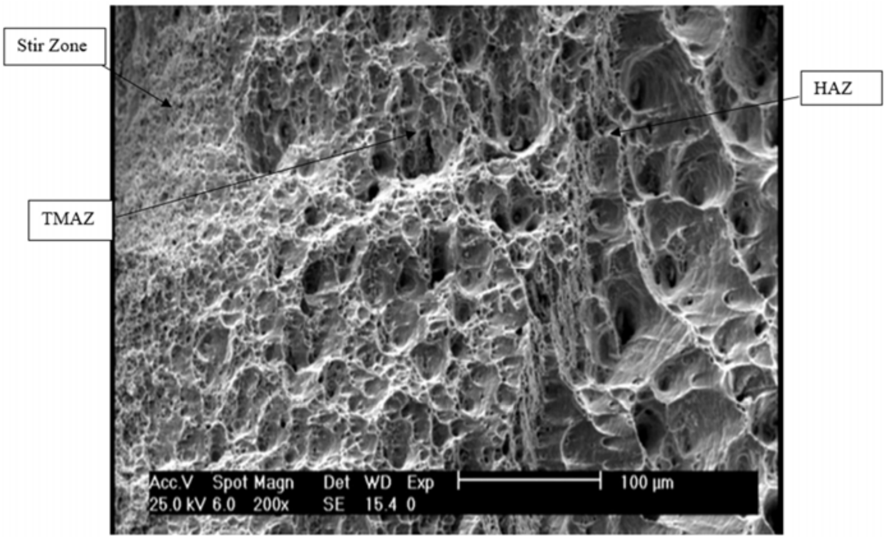

Fig. 7 Fracture appearance regarding the SS316 side of FSWed specimen after tensile testing. The left side is close to stir zone

IV. Conclusions

The effect of traverse speed on the fatigue and fracture appearance of dissimilar friction stir welding of Monel400 and SS316 was investigated. When this speed exceeds 100 mm/min, the heat input is not sufficient for joining the present high-melting point materials. As a result, the joint was not sound and a groove like defect was observed. Such defects exhibit detrimental effects on the fatigue performance of the friction-stir welds. In terms of fatigue, two different fracture behaviors are observed, indicating a mixed mode of fracture behavior due to mixing of dissimilar materials. The striations are observed within the flat regions separated by dimples. Just next to the striation-included planes, there are dimples with different sizes which are distributed on the fracture surface. Both striations and dimples point out to the ductile behavior via different mechanisms. However, such difference in the material flow of dissimilar materials can result in localized-deformation zones which act as the preferential sites for crack initiation and eventually final failure.

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