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Fusion and friction stir welding of X6Cr17 stainless steel

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Materials

ABSTRACT

Purpose: The σ-phase is the most serious of these secondary phases due to its impact on the mechanical properties, corrosion resistance or weldability of stainless steels among other properties. The purpose of this study is getting free σ-phase welding joints by using very novel welding method such a called friction stir welding.

Design/methodology/approach: Both of fusion welding methods (MIG and TIG) and friction stir welding method were used to compare microstructure analysis of AISI 430 ferritic stainless steels. After welding, the formation of σ-phase was investigated by mechanical, chemical and micro structure analyses of welded joints.

Findings: As a result, the formation of σ-phase have not been observed in FSW processes while compared to traditional fusion welding processes. Not only σ-phase have not been observed in metallurgical investigations but also micro hardness of all specimen have not been over 400HV on friction stir welded joints.

Research limitations/implications: It is very difficult to be constant vertical force during friction stir welding. For keeping constant this force, hydraulic controlled welding machines could be used in further researches.

Practical implications: This paper and its' results shown that the friction stir welding could be used for joining of ferritic stainless steels, when you select suitable welding parameters.

Originality/value: This study was performed in the frame of the Pamukkale University Scientific Research Projects Coordination Unit project no 2009FBE022 "The research of the factors affecting the friction stir weldability of ferritic stainless steels".

Keywords: Friction stir welding; Ferritic Stainless steel; σ-phase; X6Cr17; AISI 430

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1. Introduction

Sigma phase (σ-phase) in classical fusion welding techniques of ferritic stainless steels is an undesirable intermetallical phase. σ-phase may occur when stainless steels are exposed to 650-850°C for a period of time [1]. The nucleation of σ-phase generally occours in the grain boundaries [2-7]. Sigma precipitation can drastically decrease the toughness properties [8,9].

To prevent the σ-phase, stainless steels must not be preheated over 400°C, and after welding stainless steels must be cooled very quickly [9-10]. ElSawy [11] investigated the characterization of gas tungsten arc welding (GTAW) fusion line phases for super ferritic stainless steel weldments. He found σ-phase on the broken tensile sample.

Park and et al [12] investigated the microstructural evolution in a 304 stainless steel weld during friction stir welding. They observed that the microstructural observation revealed that σ-phase including the numerous stacking faults was formed at the advancing side of the stir zone. They suggested that the rapid formation of the σ-phase is related to the transformation of austenite to delta-ferrite in the stir zone, from introduction of high strain and dynamic recrystallization during FSW.

Silva and et al [13] investigated the microstructural characterization of the heat affected zone (HAZ) in AISI 444 ferritic stainless steel welds. They used shielded metal arc welding (SMAW) process and observed that σ-phase precipitation at the ferrite grain boundaries.

Brózda and Madej [14] were searched the σ-phase precipitation in austenitic steel welded joints. They found that the main reason of cracking is the σ-phase formation in welded joints, with its effect of embrittlement, with the crack initiation on stress concentrating welding defects.

Kim and et al [15] investigated the effect of sigma phases formation depending on Cr/Ni equivalent ratio in AISI 316L weldments. They found that that the main reason of cracking is the σ-phase formation in welded joints, with its effect of embrittlement, with the crack initiation on stress concentrating welding defects.

Ahn and et al [16] investigated the microstructures and properties of friction stir welded 409L stainless steel. They observed that any precipitates, such as Cr-carbide (Cr_xC_y), were not observed in the stir zone (SZ) and HAZ. They also observed that the mechanical properties in the weld were similar to that of the base material (BM). They suggested that FSW is a proper welding process for 409L stainless steel.

Sakthivel and et al [17] searched the comparison of creep rupture behaviour of type 316L(N) austenitic stainless steel joints welded by multi pass tungsten inert gas (TIG) and activated TIG welding processes. They observed that weld metal showed the extensive formation of σ-phase along the boundaries in multi pass TIG joint, which were less prevalent in the activated TIG joint.

Badji and et al [18] investigated the effect of solution treatment temperature on the precipitation kinetic of σ-phase in 2205 duplex stainless steel welds. They found that increasing thesolution treatment temperature from 1050 to 1250 °C delaysthe σ-phase formation. They suggested that the results indicate a marked sensitivity of the σ-phase precipitation kinetic to the solution treatment temperature. They also suggested that high precipitation rate corresponds to a fine grained structure with ferrite enriched in σ forming elements.

Roychowdhury and et al [19] investigated the σ-phase induced embrittlement in titanium containing austenitic stainless steel tie-bars in a condenser. They suggested that chromium equivalent parameter indicated the bar material and the weld fusion zone were prone to precipitation of σ-phase.

Lakshminarayanan and et al [20] was investigated effect of welding processes on tensile and impact properties, dardness and microstructure of AISI 409M ferritic stainless joints fabricated by duplex stainless steel filler metal. They found that gas tungsten arc welded joints of ferritic stainless steel have more mechanical properties with shielded metal arc and gas metal arc welded joints and this is most probably reason of the presence of finer grains in welding zone.

Meran and Canyurt [21] was investigated friction stir weldability of austenitic stainless steels. They found that when the selecting proper welding parameters, AISI 304 stainless steel can be obtain high quality joints.

Bilgin and Meran [22] investigated the effect of tool rotational and traverse speed on friction stir weldability of AISI 430 ferritic stainless steels. They suggested that the σ-phase could not determine in welding zone and HAZ. It can be found many studies on friction stir welding of metals and composites [23-26].

2. Experimental procedures

Both of fusion welding methods (metal inert gas MIG, TIG) and friction stir welding methods were used to compare microstructure analysis of AISI 430 ferritic stainless steels. In the study AISI 430 (X6Cr17) ferritic stainless steel sheets were used. Two sheets with dimensions of 3x100x200 mm were joined in butt position. Properties of AISI 430 are shown in Tables 1 and 2.

All tensile tests were performed with a Zwick/Roell Z100 servo-hydraulic tensile test machine with a load capacity of 100 kN. The stress-control mode was chosen over stroke or strain modes due to the convenience and smoothness of the operation. The impact tests were performed with a Wolpert PW30 notch impact testing machine with a capacity of 300 J. Microstructural examinations were performed in order to check for weld defects such as porosity, coarse dendrites, poor penetration of the weld bead, and grain structure of the HAZ. The etchant used for microanalyses was a mix of 50 ml hydrochloric acid and 50 ml distilled water. Vilella's reagent (a mixture of 1 g picric acid, 5 ml hydrochloric acid, and 95 ml ethyl alcohol) was the etchant used for microscopic microanalyses.

Table 1.
Chemical composition of the AISI 430 stainless steel (mass. %)

C	Mn	Si	Cr	P	S
0.1	1	1	16-18	0.04	0.03

Table 2.
Properties of the AISI 430 stainless steel

Density (g cm^{-3})	Young's Modulus *E* (GPa)	Tensile Strength R_m (MPa)	Yield Strength $R_{p0,2}$ (MPa)	Elongation to Failure *A* (%)	Hardness Rockwell B (HRB)
7.8	200	468	323	22	85

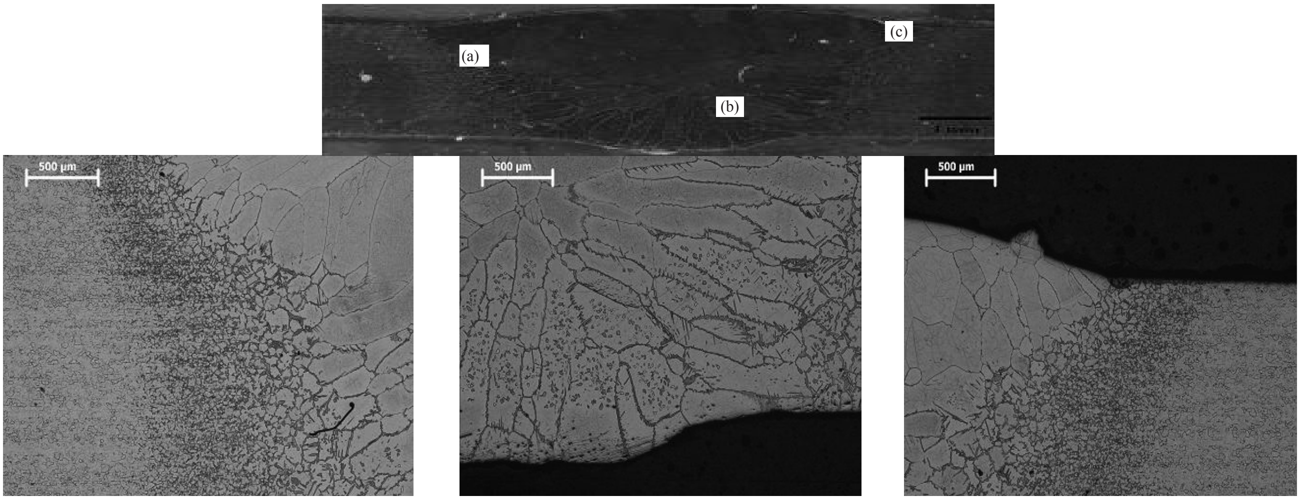
3. Results and discussion

The microstructure of TIG welding has shown in Figure 1. It can be seen that the structure of the transition metal deterioration of the weld metal grains in the weld metal to solidify in a transition zone and the transition began; solidified particles are directed towards the center of the weld.

Similar situation described above can also be seen in Metal Inert Gas (MIG) welding. Because of higher heat input, excessive grain growth is higher than TIG. The microstructure of MIG welding has shown in Figure 2.

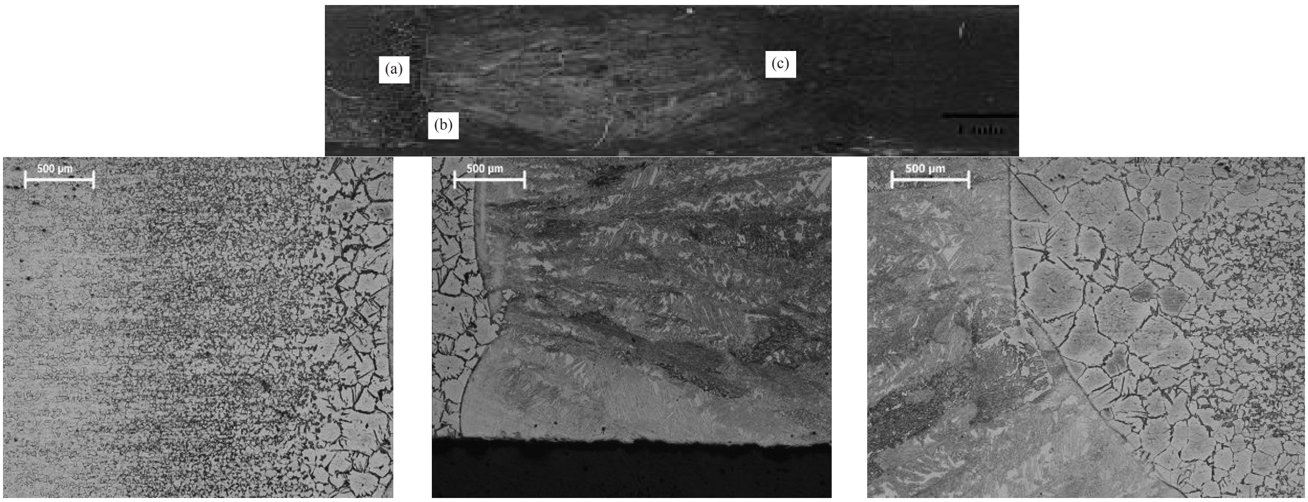
The excessive grain growth can also be seen for MIG welding in the Figure 3. Different from TIG welding, a dentritic structure formed in MIG welding. As the excessive grain growth can be seen clearly on the Figure 3 from base metal to HAZ, and welding zone after TIG welding. Size of the grains increased twice for all regions.

In literature, it has been mentioned σ-phase formation was observed for TIG and MIG welding of stainless steels, Figure 4. Undesirable σ-phase formation can be prevent with Friction Stir Welding (FSW). Because it has been observed that grain size becomes smaller from base metal to welding zone. Half of grain size has obtained from base metal to HAZ, and half of grain size has obtained from HAZ to welding zone. It has been determined that the average grain size in stirring zone is about 6.5 µm, in HAZ 15 µm and in BM 30 µm. The grain size of stir zone is finer than base material. The fine-grained microstructure in the SZ is due to the dynamic recrystallization induced by severe shear deformation and the significant amount of heat generated during FSW.



a) Base materials b) Welding zone c) Heat affected zone

Fig. 1. The macro and the microstructure of a specimen welded with TIG



a) Base materials b) Welding zone c) Heat affected zone

Fig. 2. The macro and the microstructure of a specimen welded with MIG

The macroscopic and microscopic appearances of the friction stir welded joints are shown in Figure 5.

The EDX of base metal was investigated and rates of 16.25% Cr, 0.62% Si, 1.14% Mn, 0.32% P, 0.32% S and 81.35% Fe were found, as shown in Figure 6. These rates are proper for AISI 430 ferritic stainless steels. The EDX of HAZ was investigated and rates of 15.27% Cr, 0.51% Si, 1.46% Mn, 0.11% P, 0.19% S and 82.46% Fe were found, as shown in Figure 6. And also the EDX of welding zone was investigated and rates of 15.13% Cr, 0.52% Si, 0.83% Mn, 0.30% P, 0.21% S and 83.01% Fe were found, as shown in Figure 6.

The SEM result of friction stir welded sample was given in Fig. 7. As seen SEM results, the grain boundary structure is not similar to structure included σ phase which given Figure 4. Furthermore it was seen some uncertain matrix structures similar to σ-phase during SEM investigation. In addition to three zones mentioned Figure 6, EDX analysis of a matrix structure was investigated and rates of 15.46% Cr, 0.69% Si, 0.74% Mn, 0.44% P, 0.28% S and 82.42% Fe were found, as shown in Figure 7. The EDX analysis of the matrix structure has no difference from base metal, HAZ and welding zone rates. All values seem normal values. Of course, the plastic flow of the material during mixing as a result of some small amounts of alloying elements may vary depending on the concentration of some of the data points are taken. But in general all rates about zones have resemblance with each other.

a) TIG welded

b) MIG welded

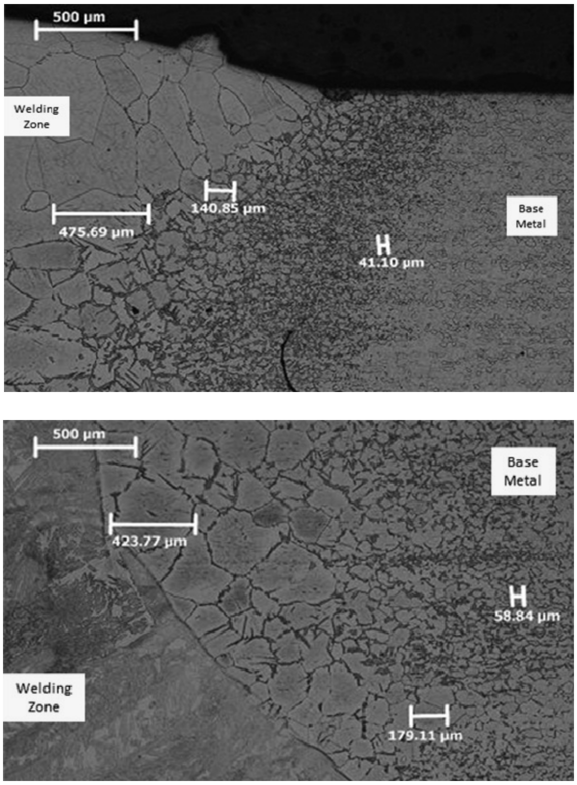


Fig. 3. The microstructure of grain sizes of the TIG (a) and MIG (b) welded specimens

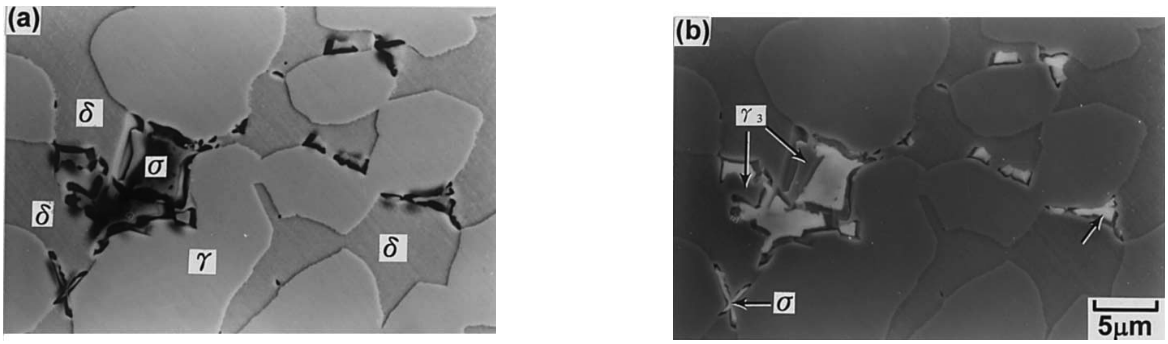
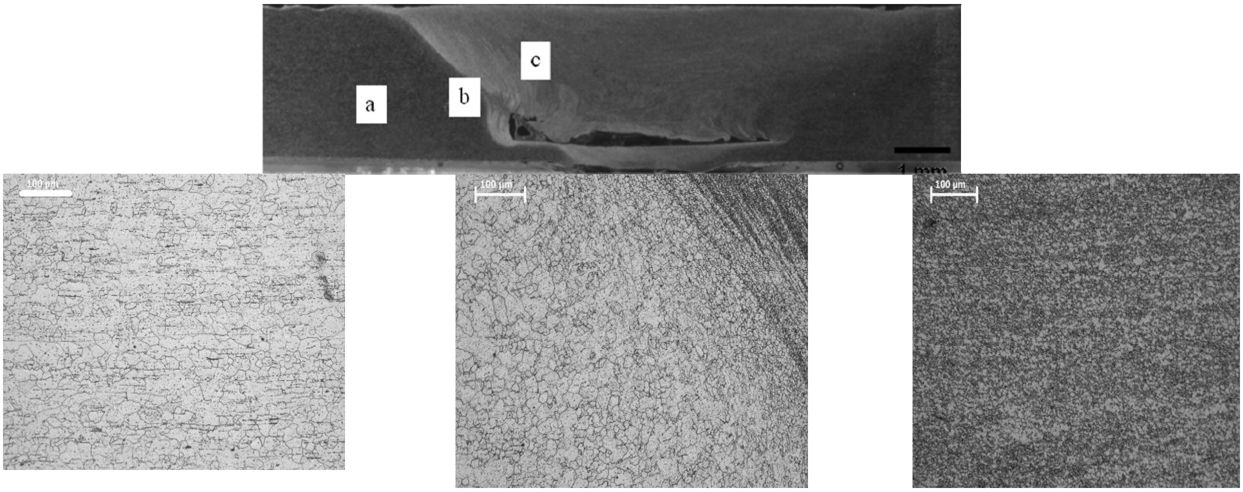


Fig. 4. Scanning electron micrographs showing σ phase located at the δ/γ-interface, (a) SE and (b) BS images [27]



a) Base materials b) Welding zone c) Heat affected zone

Fig. 5. The macro and the microstructure of a specimen with friction stir welded

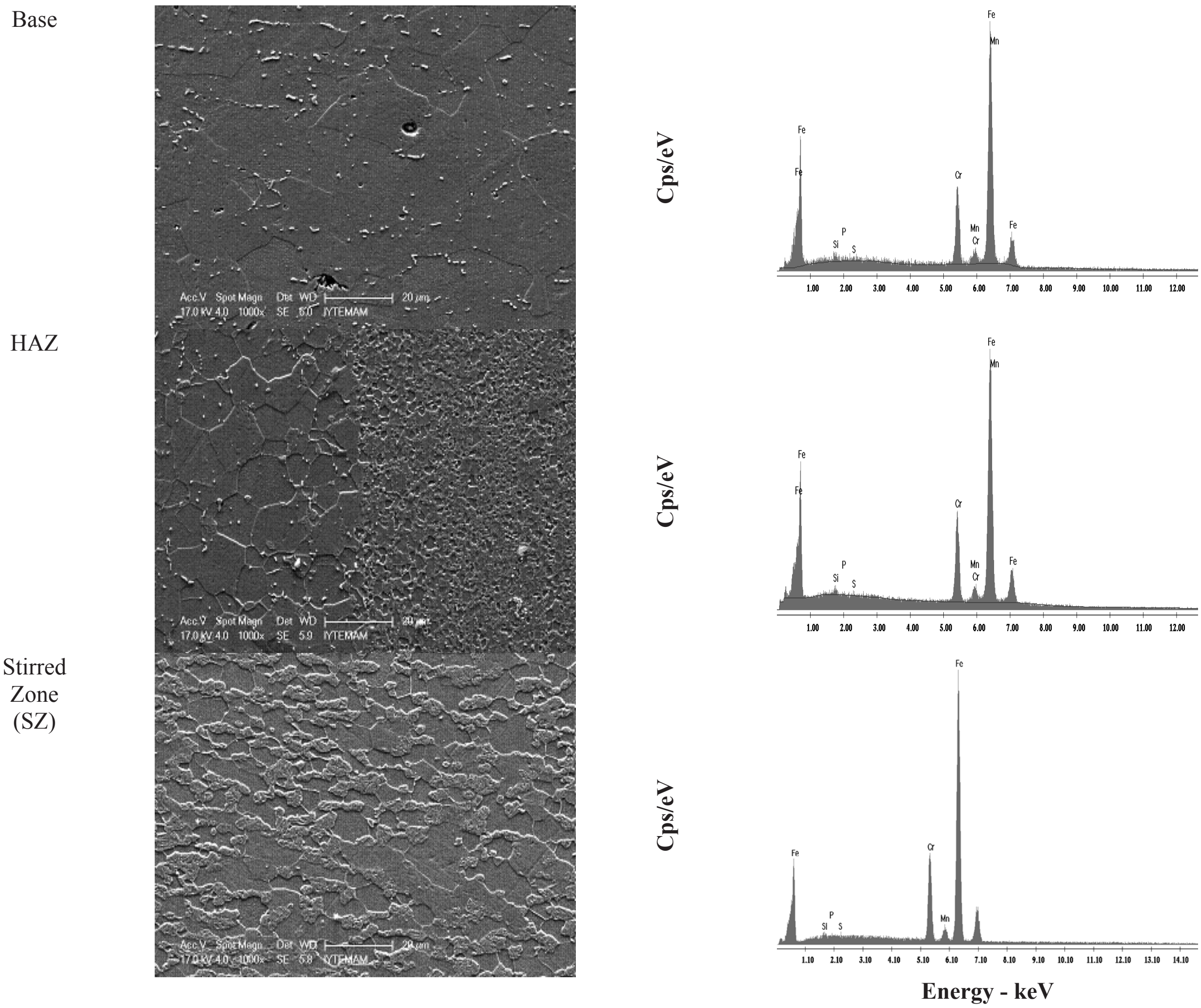


Fig. 6. The EDX analysis of base metal, HAZ, and SZ in friction stir welded samples

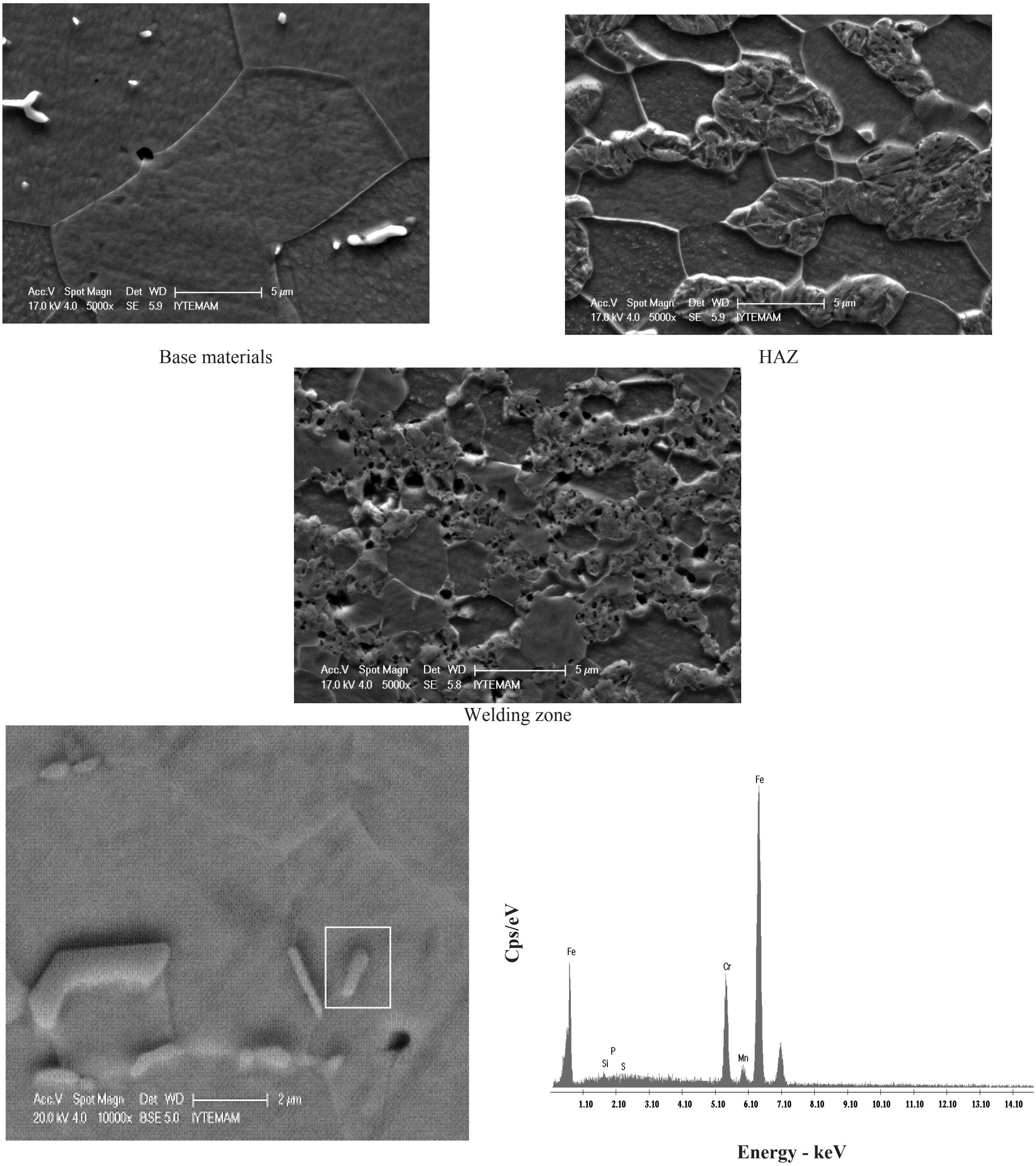


Fig. 7. The SEM results and EDX analysis of uncertain matrix structure in friction stir welded samples

Both purposes of microstructure investigation and EDX analysis of zones are to find σ-phase formation. As a result, any evidence about σ-phase formation was found. It couldn't be observed for FSW of ferritic stainless steels.Another investigation about σ-phase formation was made for micro hardness measurement of friction stir weldments. Micro hardnesses were found about 160-180 $HV_{0,01}$ for base metal, 180-220 $HV_{0,01}$ for HAZ, and 220-400 $HV_{0,01}$ for welding zone, Figure 8. It is well known that σ-phase has a great hardness, approximately 700-800HV. While investigating the microhardness of weldments it has not been measured hardness value over 400 HV anywhere. It is obvious that the micro hardness results are not enough to explain σ-phase formation or not. But it could still give some information about possibility of σ-phase formation or not.

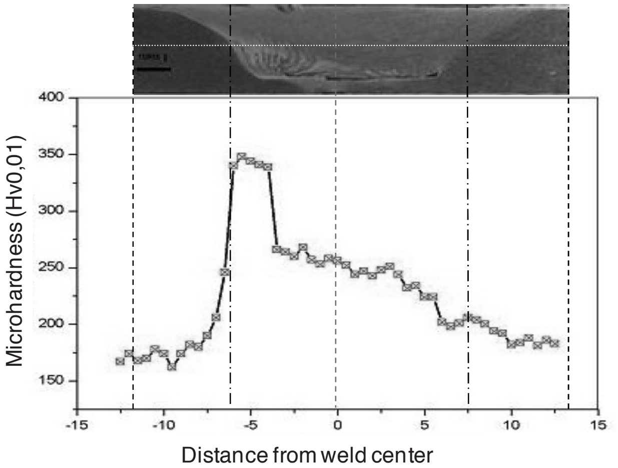


Fig. 8. Micro hardness distributions of friction stir welded sample

4. Conclusions

This study shows a comparison on formation of σ-phase in fusion welding processes and friction stir welding process of AISI 430 ferritic stainless steels. The following important conclusions can be drawn from the results of the present study:

- Because of higher heat inputs, formation of σ-phase can always be seen in classical fuse welding methods.
- As a newly solid state welding methot, FSW could prevent σ-phase formation as a result of lower heat input.
- Excessive grain growth problem in fuse welding can also be avoided by FSW for stainless steels.

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