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Microstructure and Mechanical Properties of DC-LSND Double Cooling on A-36 Steel Welded Joints

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Abstract: The use of certain welding techniques to reduce distortion in the welding of thin plates to the hull of a ship has become one of the most recent objects of research. One of the alternative welding techniques developed is called the DC-LSND (Dynamically Controlled Low Stress No-Distortion) technique. The investigation concerned here was aimed at studying the effect of DC-LSND double cooling on the distortion, microstructure and mechanical properties in A36 steel welded joints. The DC-LSND double cooling treatments were performed by cooling the HAZ (Heat Affected Zone) behind the welding torch by using cryogenic liquid nitrogen. A sequence of tests was carried out involving distortion measurement, microstructure examination, hardness measurement and tensile testing in combination with SEM fractography. The results showed that DC-LSND double cooling treatments affected transverse distortion significantly. The strength of the welded joint was improved by the DC-LSND double cooling treatments, based on the results of the tensile testing and the hardness. The microstructure was also refined by increasing the acicular ferrite phase.

Key words: DC-LSND double cooling, welded joints, distortion, liquid nitrogen, microstructure, refined

INTRODUCTION

The carbon steel designated as A 36 has been widely applied in the ship building industry to form a hull. A 36 is chosen because of some of the advantages of its use such as a good strength at a good price and its relative ease in being welded. Ship engineers prefer to use thin plates in the hull construction because it could reduce weight and improve ship performance at higher speed with lower fuel consumption. However, thin plates tend to be easily subject to welding distortion of which the final effect is cost increase due to welding repairs (Conrardy *et al*., 2006).

Weld distortion is a problem in welding that is difficult to eliminate but it could be minimized. Severe distortion could cause undesirable impact on fabrication cost, since, additional work or repair needs to be performed. Distortion also reduces dimensional accuracy, causes loss of structural integrity and encourages premature damage, leading eventually to high repair cost, especially, labor cost. The estimated labor cost in repairing and adjusting a distorted element is 30% of the total cost of labor (Andersen, 2000).

A number of researchers have made studies with the aim of minimizing weld distortion. Controlled-distortion methods are developed to fix weld distortion by means of the finite element approach (Ma *et al*., 2014; Peric *et al*., 2014) and the experimental approach. The experimental methods such as that involving Static Thermal Tensioning (STT) (Ilman *et al*., 2016) carried out by applying static heating on the plate could minimize weld distortion. Meanwhile, Transient Thermal Tensioning (TTT), using dynamic heating could minimize weld distortion (Subeki *et al*., 2017) and decrease the rate of fatigue crack propagation (Ilman and Iswanto, 2013). The disadvantage of both methods are difficult to apply on wide plate. Another method that used double welding known as Double-Side Arc Welding (DSAW) can improve distortion level but requires complex tools (Yang *et al*., 2014).

Low Stress No Distortion (LSND) method first introduced by Guan in 1980 with water cooling on a part lower than the joint being welded while the workpiece is being heated in order to reduce residual stress (Feng, 2005). It has been developed with the use of cryogenic cooling materials which could quickly lower the temperature in the weld area. Such cooling produces abnormal welding temperature distribution and decreases residual stress and distortion.

A Dynamically Controlled Low Stress No Distortion (DC-LSND) method is developed from the LSND method with the use of the cooling system behind the weld torch

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in the weld metal area without the heating process. Several researchers report that the DC-LSND method with active cooling CO_2 snow could reduce weld distortion by about 81%. The DC-LSND method with liquid nitrogen as active coolant in the Tungsten Inert Gas (TIG) welding could significantly reduce the residual stress and distortion (Sudheesh and Prasad, 2014; Kala *et al*., 2014). However, it has adverse side effects such as weld metal embrittlement which reduces the mechanical properties of the weld joint.

Lately, the DC-LSND method in the welding process has begun to draw interest in view of its ability to reduce distortion, production cost and production time. In relation with this writing, the DC-LSND method has been modified by double cooling in the HAZ area to optimize distortion reduction and improve mechanical properties.

MATERIALS AND METHODS

Materials and welding parameters: Metal Inert Gas (MIG) welding was used to joint A 36 carbon steel plates with a dimension of 400×100×4 mm. The weld groove was machined with groove angle of 30°, root face of 2 mm and root gap of 1.5 mm. The chemical compositions of the plates and weld metal are given in Table 1.

The plates were welded using constant parameters of MIG welding that follows: voltage 23 V, current 145 A and welding speed 4.4 mm/sec. The filler metal used ER70S-6 electrode which 0.8 mm diameter. Wire speed of electrode was 140 mm/sec. Shielded gas used in this research was carbon dioxcide which gas flow of 10 L/min. The welding process was coupled with the DC-LSND treatment simultaneously in one process.

The DC-LSND treatment was carried out by locating the coolant nozzle behind the weld arc in the HAZ area as shows in Fig. 1. A partition was placed between the weld arc and the coolant nozzle to protect the weld metal from the negative effect of liquid nitrogen. In the research concerned here, the DC-LSND treatment used double cooling and termed DC-LSND-DC. The cooling system used the liquid nitrogen with a flow rate of 200 mL/min. The cooling nozzle was located at the various distances of 15, 30, 50 and 70 mm behind the weld arc.

Measurements of distortion: After welding process, plates were marked with grids with a dimension of 20×20 mm on the surface. Distortions were measured at all marked grids using dial indicator gauge having accuracy of 0.01 mm. The everage of distortions along transverse and longitudinal direction was calculated to determine transverse and longitudinal distortions. Distortion values were taken from the difference of distortions before and after welding.

Table 1: The chemical composition of A36 steel and filler metal (wt%)

Parameters	C	Si	Mn	P	Cu	Fe
A36	0.15	0.243	0.733	0.023	0.013	Bal.
Filler metal	0.10	0.730	1.640	0.010	0.230	Bal.

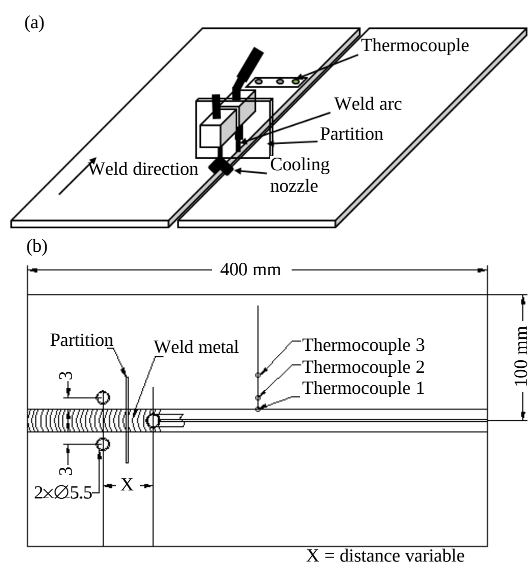

Fig. 1: a) The skematic of DC-LSND Double Cooling and b) Dimension of treatment

Microstructure examination: Microstructure examination of the weld joint was done with an optical microscope with 100×magnification by the objective lens. Specimens were prepared by three-step procedure as follows: sanding, polishing and etching. Examinations were focused in the Weld Metal area (WM) and Heat Affected Zone (HAZ). Result analysis of microstructure examination was carried out by ASTM method (Smallman and Bishop, 1999). The types of particles that were passed one by one under a framework of cross-linear were measured and calculated. This quantitative method obtained the volume fraction of the microstructure in a particular area.

Hardness and tensile tests: Hardness measurements were performed along Weld Metal (WM), Coarse Grain Heat Affected Zone (CG-HAZ), Fine Grain Heat Affected Zone (FG-HAZ), partially transformed region and unaffected Base Metal (BM). They were tested by Vickers micro hardness with a load of 500 grf with the distance from one point to another was 500 μm.

Tensile tests were performed on the longitudinal and transverse directions of the weld lines using a machine with a load of 2 and 4 tons, respectively. Specimens of longitudinal and transverse tensile tests, respectively followed the standard JIS Z2201 and ASTM E-8 shows in Fig. 2. The yield strength was calculated by intersection 0.2% parallel-line to the stress-strain chart.

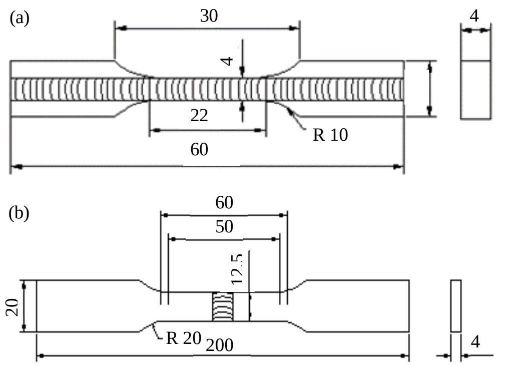

Fig. 2: a) Longitudinal tensile test specimen and b) transversal tensile test specimen

RESULTS AND DISCUSSION

Weld distortion: The results of distortion measurements along the transverse directions in the DC-LSND treatment at the distances of 15, 30, 50 and 70 mm between the weld torch and the cooling system are as shown in Fig. 3. The effectivity of the DC-LSND treatment during the welding process could be proven by the reduction of the transverse distortion. In the experiment, the closest distance between the cooling system and the welding torch was 15 mm. It could be seen that the distortion decreases as the cooling system moves closer until a distance of 30 mm but the distortion increases at the distance of 15 mm. The distance of 15 mm could not reduce distortion to the optimum because of cooling system disruption in the Gas Metal Arc Welding (GMAW) process. This finding is consistent with (Sudheesh and Prasad, 2014; Kala *et al*., 2014), stating that the change in the distance between the cooling system and the weld torch could reduce distortion. In the study concerned here, the DC-LSND double cooling treatment could reduce transverse distortion most effectively at the distance of 30 mm as shows in Fig. 4.

The distortion caused by thermal stress (σ_s) is greater than that caused by the critical buckling stress of material. The DC-LSND double cooling treatment could reduce thermal stress by minimizing the total heat input, so that, it causes a lowering in distortion. Thermal stress (σ_s) was influenced by several factors as formulated in Eq. 1 (Feng, 2005):

$$\sigma_3 = \mu \frac{\alpha_T (Q_t/v)}{c\rho h}.E \quad (1)$$

Where:

μ = Longitudinal stiffness factor
α_T = Thermal diffusivity
Q_t = Total heat input
v = Traveling speed

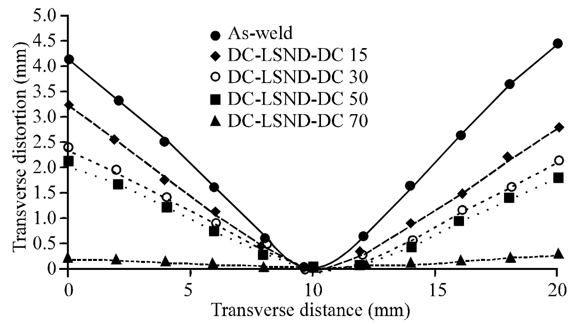

Fig. 3: Distortion in DC-LSND treatments on tranverse direction

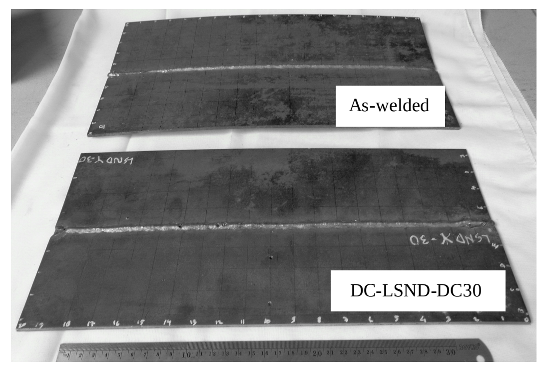

Fig. 4: Comparison distortion of A36 plates welded

$c\rho$ = Heat specific per volume
h = Plates thickness
E = Modulus elasticity of the material

The critical buckling stress that resists distortion was heavily influenced by material properties and geometry of the welded plate.

Thermal cycles: Figure 5 shows the welding thermal cycle during a welding process on DC LSND treatments and as-welded condition at a distance of 5 mm from the welding center. Based on the thermal cycle graph, the heating grows very fast until the peak temperature and followed by cooling at a low rate. The cooling rate can be analysed to know the effect of DC-LSND treatment in weld metal area. The result of cooling rates from temperature of 800-500°C on DC-LSND-DC30 and DC-LSND-DC50 treatment around 28.8 and 28.4°C/sec, respectively. Compared to the cooling rate on as-welded of 15.8°C/sec, the DC-LSND-DC treatment can accelerate the cooling rate in the weld metal area. Based on the Continuous Cooling Transform (CCT) diagram (Radaj, 2012) the change of cooling rate will affect the phase of micro structure and mechanical properties of the weld.

Microstructures: Figure 6 shows the microstructures of Weld Metal (WM) in as-weld condition and treatment using DC-LSND double cooling at the cooling distances of 30, 50 and 70 mm from the weld torch. It could be seen that the microstructures could be examined in terms of the change in the type and size of grain due to DC-LSND treatments.

The microstructure of the weld metal in as-welded condition in Fig. 6a shows Witmanstatten Ferrite (WF), Acicular Ferrite (AF) and dominant grain Boundary Ferrite (GF). The use of DC-LSND treatments seems to present sameness in microstructure phases but changes occur in their size and volume. The DC-LSND-DC30 treatment has increased the percentage of AF more greatly than other treatments and refined the size as shown in Fig. 6b-d. The DC-LSND treatments also result in decrease of GF and change of volume of the WF plate. The quantitative data of various phases with and without DC-LSND treatments are shows in Fig. 8.

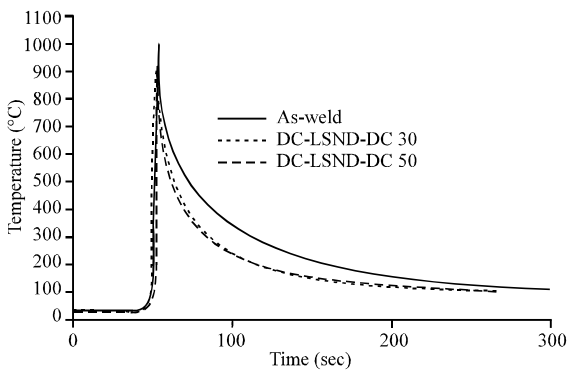

Fig. 5: Thermal cycles of DC-LSND treatments at a distance of 5 mm from welding center

Figure 7 exhibits microstructures of CG-HAZ (coarse grained-heat affected zone) in as-welded condition and the DC-LSND double cooling treatments. It could be seen that the grain size gets smaller due to DC-LSND treatments. This phenomenon indicates that DC-LSND treatments could reinforce the tensile strength of CG-HAZ. This statement is consistent with the Hall-Petch relationship (Dieter and Bacon, 1988) where certain high strength was associated with the fine-grained structure that is given by Eq. 2:

$$\sigma_y = \sigma_0 + k_y d^{-1/2} \quad (2)$$

The change in size could be analyzed with the ASTM method. The results of the analysis of grain size with and without LSND treatments are shown in Fig. 9.

Hardness distribution: Hardness distribution in the weld joints starting with WM, through CG-HAZ, FG-HAZ and partially transformed region and ending with BM (base

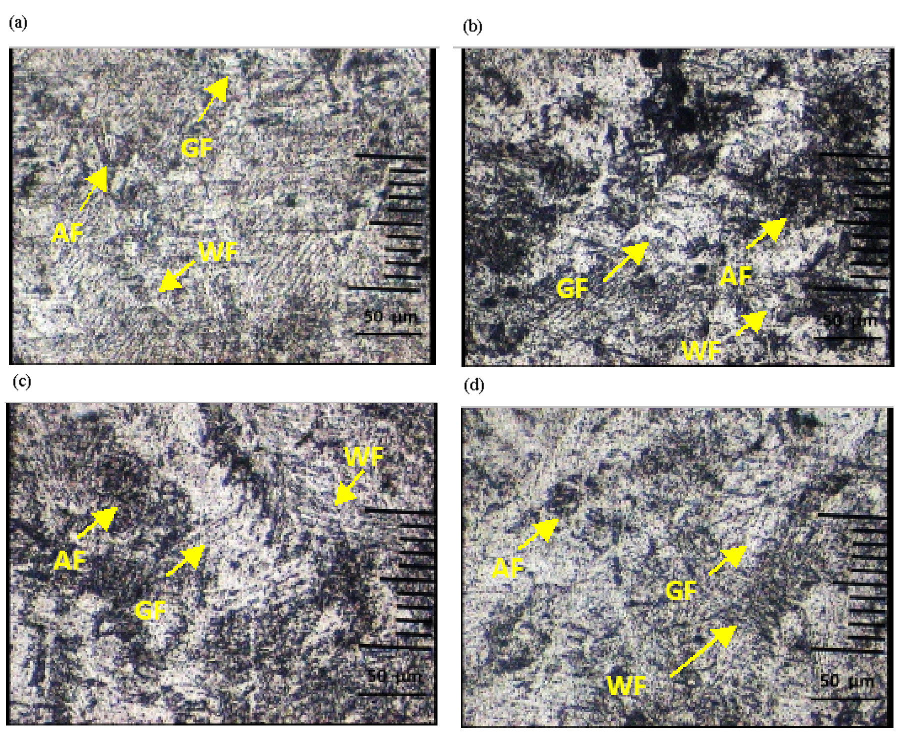

Fig. 6: WM microstructures at; a) As-welded; b) DC-LSND-DC 30; c) DC-LSND-DC 50 and d) DC-LSND-DC 70

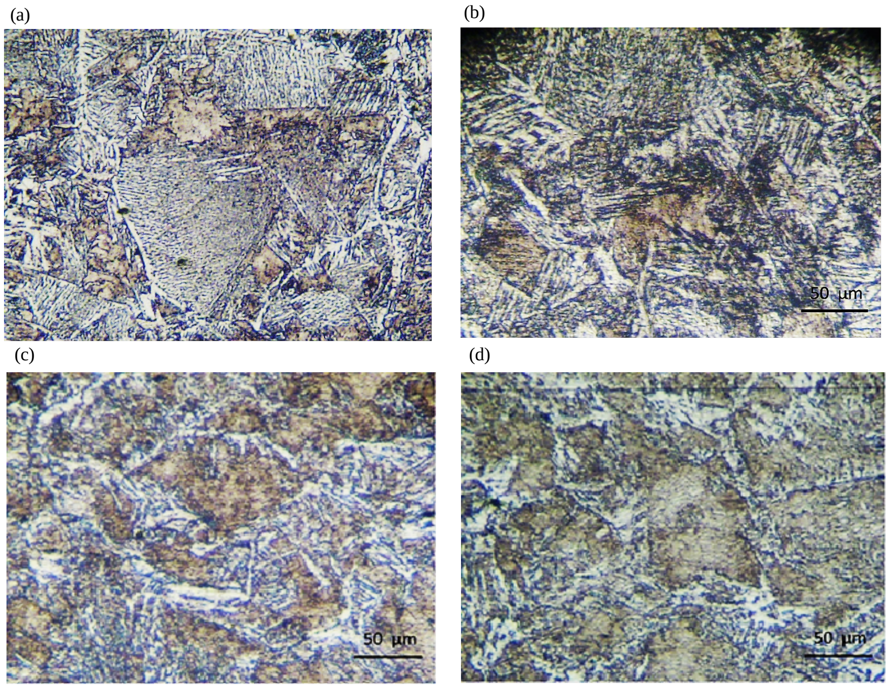

Fig. 7: CG-HAZ microstructures at; a) As-welded; b) DC-LSND-DC 30; c) DC-LSND-DC 50 and d) DC-LSND-DC 70

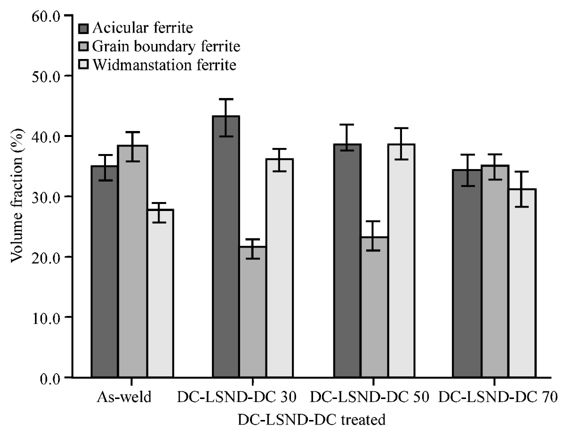

Fig. 8: Volume fraction on weld metal microstructure

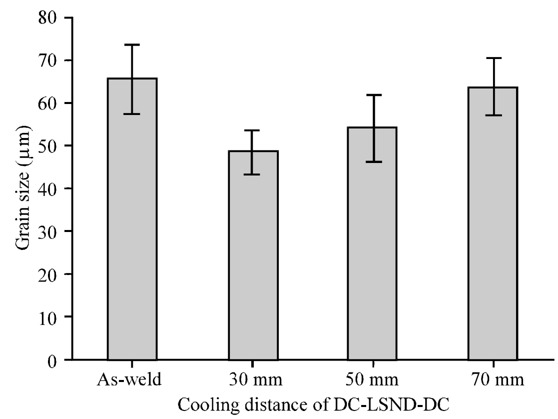

Fig. 9: Grain size on CG-HAZ

metal) are shows in Fig. 10. The hardness decreases gradually as the distance goes away from the weld metal and then the hardness becomes relatively constant at the BM. The DC-LSND treatments could increase the hardness of WM compared with that in the as-welded condition. The relatively high values of hardness in WM are linked to the high percentage of AF microstructure. This statement is consistent with (Rama *et al*., 2009) that microstructure is a main factor that effects the hardness. The DC-LSND treatment increases the cooling rate and results in fine AF as the dominant phase.

Tensile stresses: Figure 11 shows results of transverse and longitudinal tensile testing of the welded joints without and with the DC-LSND treatment. The transverse and longitudinal yield stresses are around 0.7 of their maximum stresses. Figure 10a shows that the tensile stresses of weld joints in the transverse direction tend to be similar for all treatments between 483-504 MPa as a result of the fracture in the base metal (Fig. 12a). It indicates that the tensile stresses of the weld metal are higher than those of the base metal, so that, the transverse tensile stress is a representation of the tensile strength of the base metal.

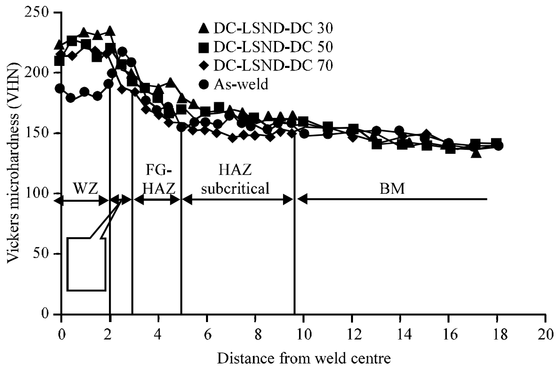

Fig. 10: Hardness distribution on weld joints of A36 steels

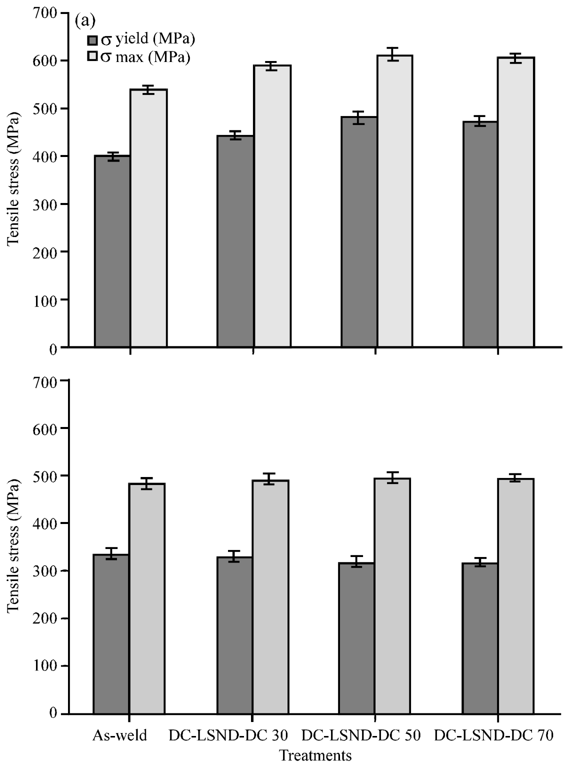

Fig. 11: Tensile strength of weld joints in; a) Transverse direction and b) Longitudinal direction

Fig. 12: Fracture of tensile tests; a) Transverse direction and b) Longitudinal direction

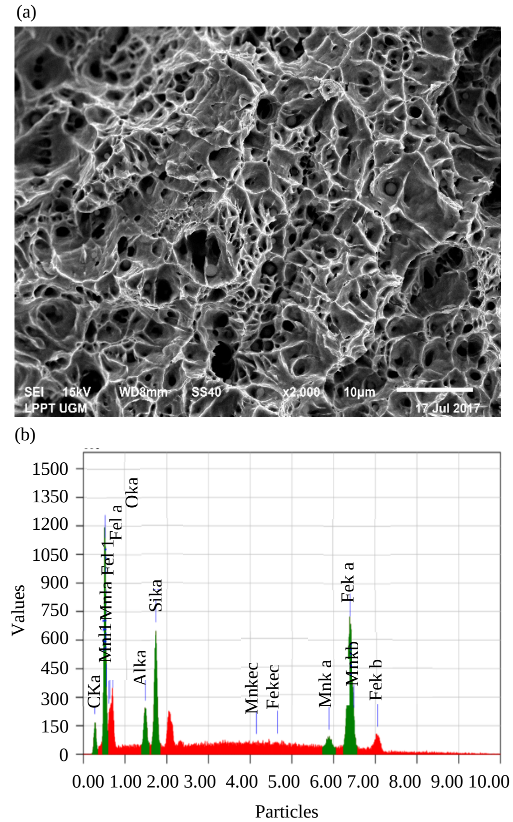

Fig. 13: a) SEM micrography of tensile fracture surface and b) EDX spectra of inclusion particle

Figure 11b presents the tensile stresses of weld joints in the longitudinal direction. It could be seen that the DC-LSND-DC treatments could increase tensile stresses, especially, those in the weld metal. It was also consistent with the hardness measurements where the tensile strength was linearly related to the value of hardness. The high tensile stresses under DC-LSND-DC are associated with increase in percentage of AF in the weld metal as supported by a number of works (Fan *et al*., 2014; Digheche *et al*., 2017). According to the fracture in the longitudinal tensile testing (Fig. 12b), the DC-LSND-DC treatments do not cause brittleness in the weld metal as characterized by a large elongation before fracture.

The Scanning Electron Microscope (SEM) fractography on the welded joints in the DC-LSND-DC30 treatment has been shows in Fig. 13a. It presents the dimples and the deep striations that appear on the fracture surface of the tensile test that indicate the ductile fracture. These results have proved that tensile tests of the DC-LSND-DC30 treatment don't cause brittle fracture.

A microanalysis of these inclusions using the EDX-ray analysis (Fig. 13b) shows that the particles are composed of mainly Al, Si, Mn and O that may be in the form of Al_2O_3, SiO_2 and MnO. These inclusions seem to aid microvoid coalescence leading to dimples on the fracture surface. This phenomenon is consistent with the statement by Zhang *et al*. (2015) that the cooling rate in the welding process would affect the density of inclusions.

CONCLUSION

The DC-LSND double cooling treatments changed the distortion, microstructure and mechanical properties of welded joint. These treatments reduce best the transverse distortion with liquid nitrogen cooling at a distance of 30 mm behind the welding torch. They also increased the hardness of WM and refined the microstructure by increasing the acicular ferrite phase. The tensile strength of the welded joint was improved and did not cause brittleness in the weld metal as proven by SEM micrography of the fracture in the tensile testing.

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