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# A Comparative Study on Direct and Pulsed Current Gas Tungsten Arc Welding of 25Cr-35Ni Heat Resistant Steel

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**Abstract**

In this research, 25Cr-35Ni heat resistant steel was welded by ER-NiCr3 Inconel weld metal using pulsed current gas tungsten arc welding and continuous current gas tungsten arc welding and the effect of these welding processes on the unmixed zone of the steel was studied and compared. It was observed that when continuous current gas tungsten arc welding was used, due to incomplete mechanical mixing, an unmixed zone was observed in the interface between the 25Cr-35Ni heat resistant steel and ER-NiCr3 Inconel weld metal. This region was eliminated using pulsed current gas tungsten arc welding with peak current of 180 A, base current of 60 A, frequency of 10-12 Hz, percentage on time 40 and also grains of weld metal became finer.

**Keyword: Pulsed Current Gas Tungsten Arc Welding, Unmixed Zone, 25Cr-35Ni Heat Resistant Steel, Weld Metal ER-NiCr3**

## INTRODUCTION

25Cr-35Ni heat resistant steel firstly was introduced in 1960 during extensive researches on development of heat resistant steels [1]. This alloy in as-cast condition has good ductility and weldability [2]. Today, 25Cr-35Ni heat resistant steels are extensively used in different industries because of their high strength and good resistance to high temperatures, thermal fatigue and high temperature creep [1-3-4-5]. Therefore, conducting researches and investigations on welding and weldability of these steels is essential. Performed researches associated with continuous current gas tungsten arc welding (CCGTAW) of this alloy revealed that weldability of this steel in as-cast condition is good and obtained welds are crack free which leaves a good continuity between weld metal and base metal [5-6-7]. In some researches, an unmixed zone has been reported at interface of 25Cr-35Ni heat resistant steel and ER-NiCr3 Inconel weld metal welded by CCGTAW [6-7]. This zone is a boundary layer near the fusion line in which the base metals melt and solidify during welding without mechanical mixing between the base metals and the filler metal. This region exists along the fusion line and between the partially melted zone and the weld metal[8-9].Several investigations have indicated that in the environments which both base and weld metals are resistant to corrosion, corrosion occurs preferentially at these regions [9-10]. Welding technology parameters (welding method, geometry of joint and etc), electromagnetic and ultrasonic vibration of melt pool during welding can affect the unmixed zone [6-7-11].

Pulsed current gas tungsten arc welding (PCGTAW), developed in the 1950s, is a variation of CCGTAW which involves cycling of the welding current from a high level to a low level at a selected regular frequency. The high level of the Pulsed current welding is selected to give adequate penetration and bead contour, while the low level of the base current is set at a level sufficient to maintain a stable arc. This permits arc energy to be used efficiently to fuse a spot of controlled dimensions in a short time. It decreases the wastage of heat through the conduction into the adjacent parent material [12-13]. At high frequencies, the vibration amplitude and temperature oscillation induced on the weld pool are reduced to a greater extent resulting in reduced effect on the weld pool. Extensive research has been performed on this process and reported advantages include, Static magnetic field has been proved to have a significant effect on the solidification behavior of cast metal, such as reducing the chemical in homogeneity and breaking large dendrite arms. Magnetic field generated by pulsed welding current has also been shown to have an effect on grain refinement of the weld metal; moreover, greater tolerance to heat sink variations, lower heat input requirements and substructure, reduced width of HAZ [14-15-16].

In this paper, regarding the importance of welding technology parameters and mechanical vibration, the effects of PCGTAW and CCGTAW parameters on microstructure of 25Cr-35Ni heat resistant steel have been studied and compared.

## MATERIALS AND METHODS

25Cr-35Ni heat resistant steel and ER-NiCr3 Inconelweld metal have been used as base metal and weld metal, respectively. 25Cr-35Ni heat resistant steels were prepared in the form of tubes with diameter of 250 mm and thickness of 13.5 mm. The chemical compositions of the base and the filler materials are given in Table 1. According to ASME IX standard, all butt joints were machined into 75° V-grooves and 2.4 mm root gap distance have been used for welding. Welding routes were then performed without any preheating by pulsed current gas tungsten arc welding with direct current electrode negative (PCGTAW-DCEN) and continuous current gas tungsten arc welding with direct current electrode negative (CCGTAW-DCEN). Welding parameters are listed in Table 2. Shielding was Achieved with 99% pure argon using 0.71 CHM[1] and 1.13 CHM flows for back and shielding.

Some samples with dimensions of 10×20×100 cm were cut from both base and weld metals. Metallography was used to study base metal and weld metal microstructure and cracks in the vicinity of the weld for different welding conditions. For this aim, the samples were ground with 80 - 1500 grit SiC papers and then were polished using 0.3 µm Alumina powder. The samples were etched by Marble solution (10 g $CuSO_4$+50 cc HCl+50 cc $H_2O$) for 25 seconds. Microstructures of different areas of weld and base metal were observed by an optical microscope. To determine chemical composition, phases and different structural regions of 25Cr-35Ni steel, scanning electron microscope (SEM) equipped with EDS was employed.

## RESULTS AND DISCUSSION

### Base Metal Microstructures

The base metal samples were polished and examined using optical microscope equipped with camera. Fig. 1 shows microstructure of as-cast 25Cr-35Ni steel at two magnifications. As demonstrated in Fig. 1a, microstructure of 25Cr-35Ni steel in the as-cast condition consists of an austenitic matrix with a continuous network of dendrite eutectic carbide at grain boundaries. At higher magnification (Fig. 1b) austenitic matrix is observed to be free of precipitations. The SEM image of the same sample recorded with back scatter electron detector in Fig. 2a shows that initial carbide networks at grain boundaries consist of two types of, dark and light, carbides. The EDS analysis of these carbides in Fig. 2b indicates that dark carbides are Cr and Fe rich and according to Fig. 2c, light carbides are Nb rich and NbC type carbides. Other researchers also reported similar initial carbides in their studies[17-6-7]

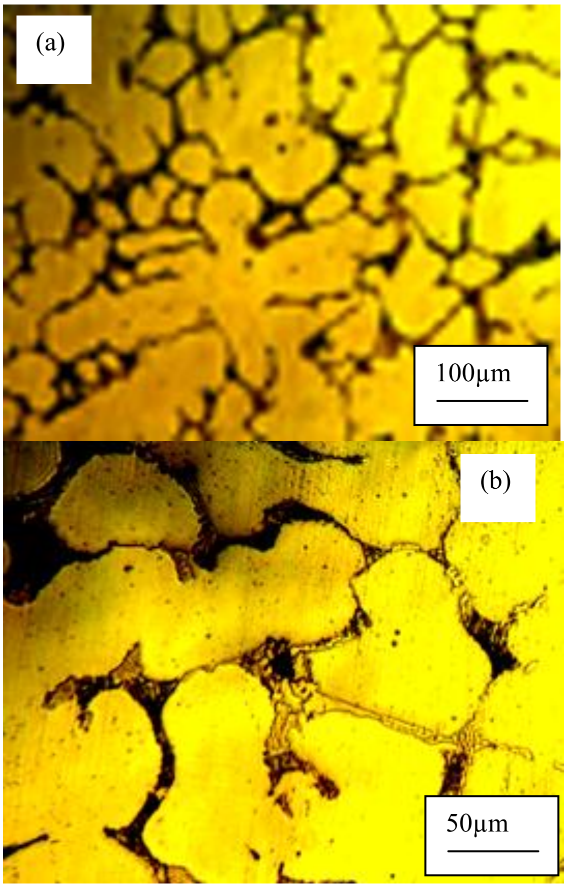


**Fig. 1**. Microstructure of 25Cr-35Ni heat resistant steel in different magnitude: (a)×200; (b)×500.

**Table 1.** Chemical composition of the base and the filler metals(wt%)

| | Fe | Ni | Cr | C | Nb | Ti | Al | Mo | Mn | Si |
|---|---|---|---|---|---|---|---|---|---|---|
| 25Cr–35Ni heat resistant steel | 35.4 | 35.8 | 24.4 | 0.4 | 1.3 | - | - | 0.04 | 1.3 | 1.3 |
| Inconel Weld Metal ER-NiCr3 | 3 | 67 | 18.2 | 0.1 | 2-3 | 0.75 | 0.3 | - | 2.5 | 0.5 |

**Table 2.** Welding Parameters at 14 volt.

| No. | Pick current(A) | Base current(A) | Frequency(HZ) | On time percentage | Welding speed at root(mm/sec) | Welding speed from second to fourth pass (mm/sec) |
|---|---|---|---|---|---|---|
| 1 | 120 | - | - | - | 1.5 | 1.1 |
| 2 | 180 | 60 | 6 | 50 | 1.5 | 1.1 |
| 3 | 180 | 60 | 6 | 40 | 1.5 | 1.1 |
| 4 | 180 | 60 | 6 | 60 | 1.5 | 1.1 |
| 5 | 180 | 60 | 8 | 40 | 1.5 | 1.1 |
| 6 | 180 | 60 | 10 | 40 | 1.5 | 1.1 |
| 7 | 180 | 60 | 12 | 40 | 1.5 | 1.1 |

[1] Cubic meter per hour

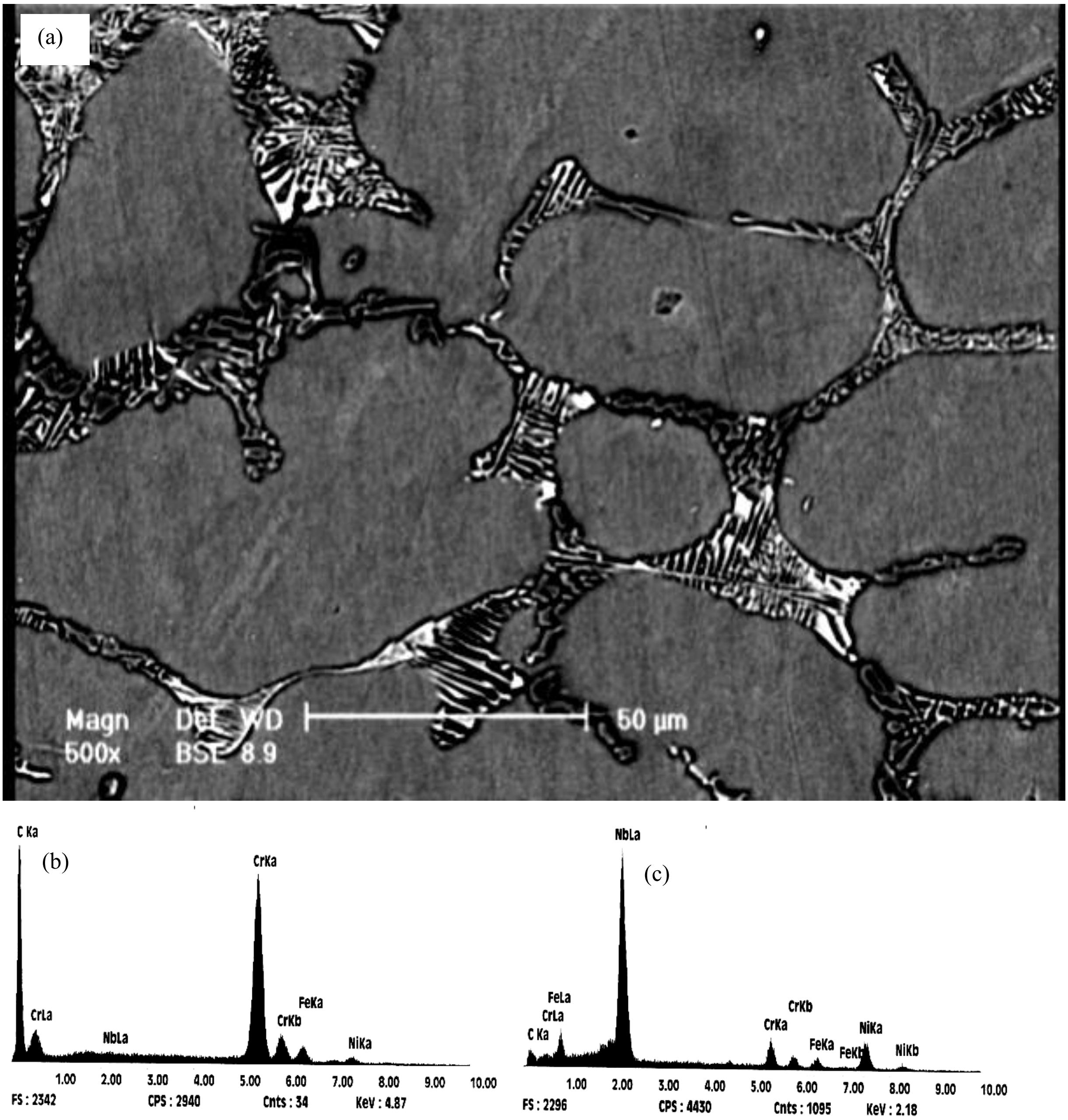


**Fig. 2** – Metallography of 25Cr-35Ni heat resistant steel: (a) SEM image using backscattered electrons. EDS spectra of the eutectic carbides; (b) Dark carbide and (c) bright carbide.

**Interfacial Microstructures**

Microstructures of interfaces of ER-NiCr3 Inconel weld metal with the as-cast 25Cr-35Ni steel using PCGTAW and CCGTAW with the same heat input were also analyzed. According to equation 1 and table 2, mean pulsed current intensity for sample 2 is calculated as follows:

Where $I_m$ is mean current, $I_p$ and $t_p$ are peak current and time respectively, $I_b$ and $t_b$ are base current and time respectively. Considering the equation 2, 3 and the current being same in sample 1 and 2, heat input is equal to 980 j/mm for PCGTAW and CCGTAW. The efficiency for calculating the heat input is 70% in both modes.

Where $Q_p$ and $Q_c$ are PCGTAW and CCGTAW heat input respectively, $I_m$ is mean pulse current, I is continues current, E is potential difference and V is the welding speed.

Since heat input is the same for both welding methods, the main microstructural differences can be attributed to change in welding process. In PCGTAW, frequency used was 6 Hz and percentage on time was considered to be 50. This condition allows weld metal to melt and solidify under oscillatory conditions. Therefore, heat is transferred with a lower rate towards base metal and the unmixed zone is smaller comparing to that in CCGTAW.

Fig. 3 shows interface of ER-NiCr3 Inconel weld metal and 25Cr-35Ni heat resistant steel. As it can be seen, weld metal has a finer microstructure than base metal although it has the same austenitic matrix with initial eutectic carbides. The difference between microstructure of weld and base metal is due to the difference in their cooling rates and consequently the difference in how they solidify. Fig. 3a shows that 25Cr-35Ni steel which was welded by CCGTAW has a continuous interface with weld metal and no cracks present at the interface or regions near the weld. But there is an unmixed zone at vicinity of the weld and along the fusion boundary, which is formed due to incomplete mechanical mixing of weld metal and base metal. Such an unmixed zone is observed when the melting range of filler materials is similar to or higher than the melting ranges of base metal[2].According to Fig. 3a , microstructure of weld metal consists of columnar grains (cellular-dendritic) and almost no secondary dendritic branches are seen. Fig. 3b shows microstructure of the interface for PCGTAW. Based on the selected parameters for pulsed welding, the unmixed zone is not completely eliminated in the microstructure shown in Fig. 3b. Therefore, these welding parameters are not proper for eliminating of this unmixed zone. On the other hand , under the condition that heat input is the same for both welding processes, no significant change is observed in the microstructure and weld metal microstructure is a completely austenitic structure because no transformation has occurred during its solidification but dendrites morphology changes. In Fig. 3a columnar grains of weld metal at vicinity of fusion line are cellular-dendritic and almost no secondary dendritic branches are seen. As it is seen in Fig. 3b, in PCGTAW many of dendritic grains are brokendown. Competitive growth of columnar grains in weld metal can be clearly observed in Fig. 3b. According to Fig. 3, dendrites formed in PCGTAW are finer than those formed in CCGTAW because the rate of heat input is lower in pulsed welding. Due to nature of pulsed current welding, pulsed current locally causes weld metal grains to become finer. Similar results for PCGTAW of aluminum alloys have reported by other researchers. while no considerable changes were observed in grain sizes of aluminum alloys weld metal by post - weld heat treatment [18].

Regarding the great importance of pulse on time, some studies were conducted at various 40, 50 and 60% duty cycle. Under the condition that pulse on times are equal to 40, 50 and 60%, arc weld is stable during welding. Therefore, for producing a stable arc and smooth weld, the peak Current time must be selected from a specific time interval and if not the arc will be unstable. At peak Current time, more heat transfers to base metal. Consequently when current level reaches its lower limit, base current, the time needed for cooling the component , is larger and grains will grow. Therefore, in an allowable range the lower the percentage on time, the lower the superheat of weld bead. As it is seen in Fig. 4a, by increasing pulse on time to 60%, no changes occur in width of the unmixed zone. This can be attributed to an increase in weld metal superheat which is affected by temperature of molten metal. According to Fig. 4b with decreasing pulse on time to 40%, width of the unmixed zone does not change comparing to conditions that pulse on time is 50%. Therefore, increasing and decreasing peak current time in an allowable range of pulse percentage on time for welding under stable arc condition has no effect on elimination of the unmixed zone.

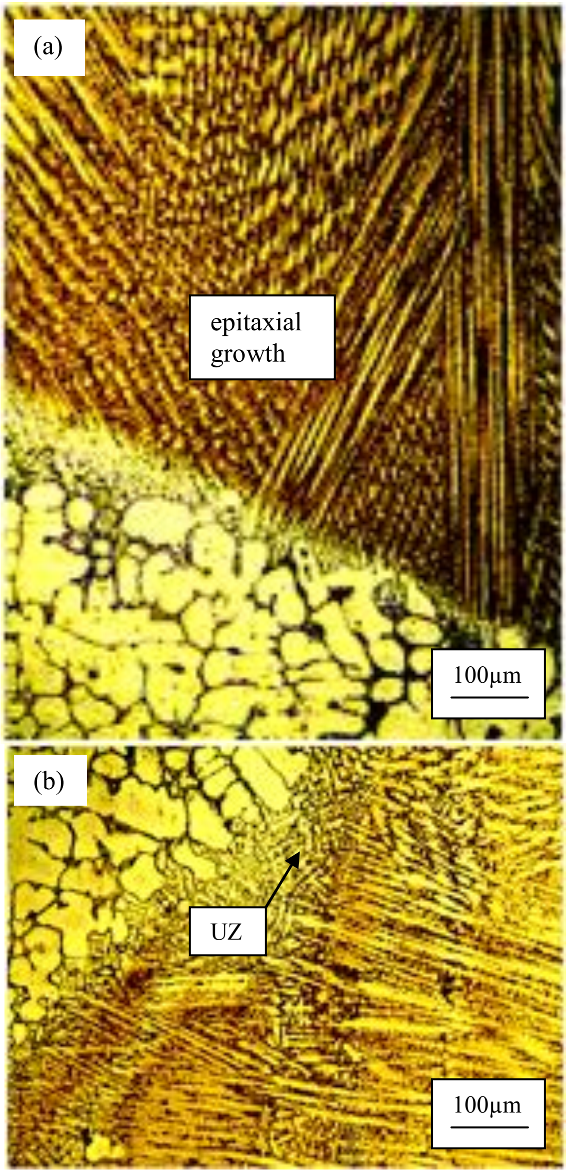


**Fig. 3.** Interface between ER-NiCr3 Inconel weld metal and 25Cr-35Ni heat resistant steel at heat input of 980 j/mm: (a) CCGTAW; (b) PCGTAW with frequency of 6 HZ.

As peak current time is reduced, time during which current is equal to base current is increased by the same amount. This causes a reduction in temperature of molten metal as well as an increase in cooling rate of weld pool at base current. In Fig. 4a columnar austenites formed at weld boundary are wave-like and In Fig. 4c grain boundaries migration has increased. In all three samples, cellular dendrites as well as broken cellular dendrites are seen. In Fig. 4a and c where percentage on times are 60 and 50 respectively, increased growth of dendrites results in coarser grains comparing to pulse on time 40%. This is due to an increase in superheat of molten weld metal and consequently a reduction in cooling rate of weld metal. According to Fig. 4, in all samples, cellular dendrites are not completely broken down ; therefore, it can be concluded that the amount of oscillation was not adequate for breaking down the cellular-dendritic microstructure.

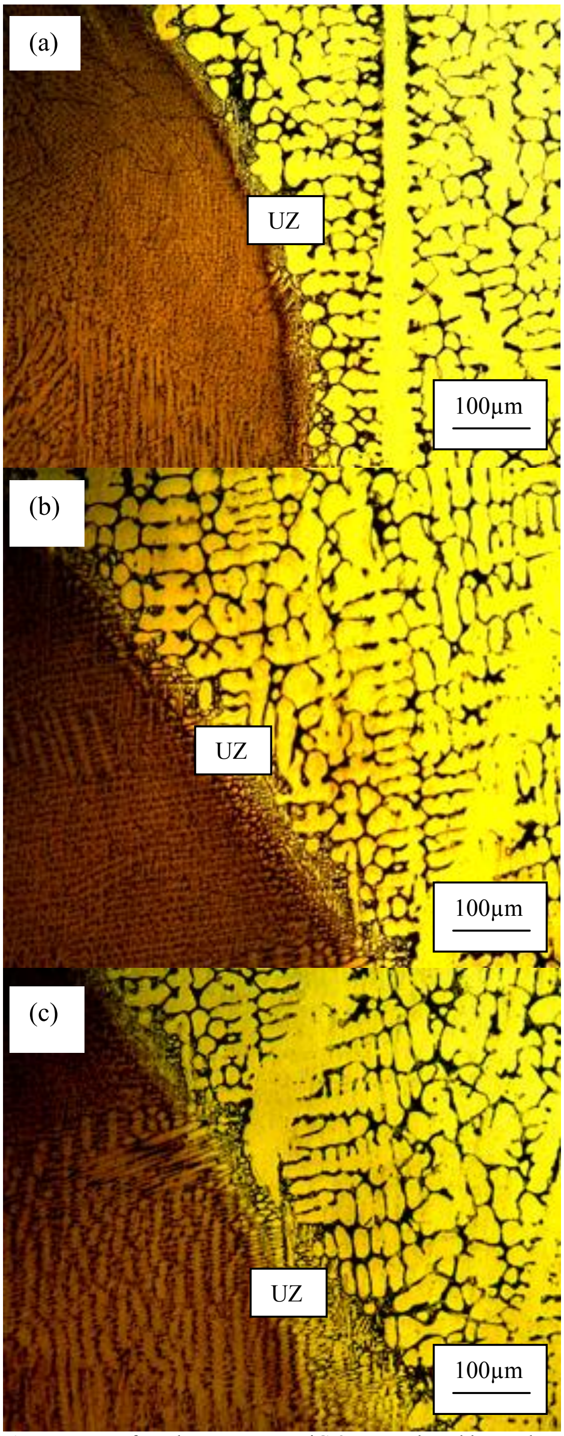


**Fig. 4** – Interface between ER-NiCr3 Inconel weld metal and 25Cr-35Ni heat resistant steel with peak current of 180 A, base current of 60 A and frequency of 6 HZ: (a) pulse on time 60%; (b) pulse on time 40%; (c) pulse on time 50% (c).

If pulse percentage on time is considered to be constant, the amount of average current remains constant. Consequently, the melting rate of electrode and heat input remain constant which allows studying the effect of frequency. For this aim, different samples were welded with pulse on time 40%, peak current of 180 A and base current of 60 A at various frequencies of 6,8,10 and 12 Hz.

As it is seen in Fig. 5a, the amount of pulsed intermixing in frequency of 6 Hz was not adequate for breaking down the cellular dendrites. Due to lack of mechanical mixing, an unmixed zone is produced at fusion boundary of 25Cr-35Ni heat resistant steel in CCGTAW.

Since the melting point of ER-NiCr3 Inconel Weld metal(1340°c-1355°c) is higher than 25Cr-35Ni steel(1340°c-1348°c), regions near fusion line are melted because of high temperature of ER-NiCr3 Inconel molten metal but they are not mixed with weld metal and due to their higher cooling rates their grains are finer. This causes formation of the unmixed zone. Solidification of this liquid zone in the interface between the 25Cr-35Ni heat resistant steel and 309 weld metal causes tensile stress that can form the cracks [2, 6, 19].

Therefore, in PCGTAW higher frequencies are needed for an appropriate mechanical mixing to eliminate the unmixed zone and break down the dendrites. As it was indicated , percentage on time has no acceptable effect on elimination of the unmixed zone. On the other side, a mechanical mixing by frequency of 6 Hz was not completely eliminated this region. As it is seen in Fig. 5a, the width of unmixed zone in frequency of 6 Hz is 74µm. Therefore to eliminate this region completely, more mechanical mixing is required. Fig. 5b shows samples which welded with frequency of 8 Hz. As it is seen, the unmixed zone still has not been eliminated completely. The width of unmixed zone in this condition is 46µm. Regarding equation 4, Frequency of 8 Hz means production of one pulse per 0.125 s and optimum pulse on time was determined to be 40%.

were F denotes frequency and $t_p$ and $t_b$ represent peak and base current time, respectively. With increasing frequency, peak current time is reduced in each cycle while both percentage on time and heat input remain constant. Therefore, with increasing frequency from 6 Hz to 8 Hz, the amount of produced heat per second is transferred more often to weld and base metals. As it is observed in Fig. 5b, cellular dendrites near fusion line are somewhat broken down in frequency of 8 Hz. Samples welded with frequencies of 10 and 12 Hz have a continuous interface between weld metal and base metal and no crack is observed at interface or near the weld. As it is seen in Fig. 5c and d because of complete mechanically intermixing weld metal and base metal at frequencies of 10 and 12 Hz, the unmixed zone is completely eliminated.

## CONCLUSIONS

In this research, 25Cr-35Ni heat resistant steel was welded by ER-NiCr3 Inconel weld metal using PCGTAW and CCGTAW and the obtained microstructures were analyzed and some results were obtained as follows :

a) By selecting appropriate welding parameters for PCGTAW, the unmixed zone was completely eliminated while this region remains unchanged in CCGTAW.

b) The effect of percentage on time is less important when compared to the frequency to eliminate unmixed zone.

c) Best welding condition for eliminating the unmixed zone and producing a finer microstructure was obtained with peak current of 120 A, base current of 60 A, percentage on time 40 and frequencies of 10 and 12 Hz.

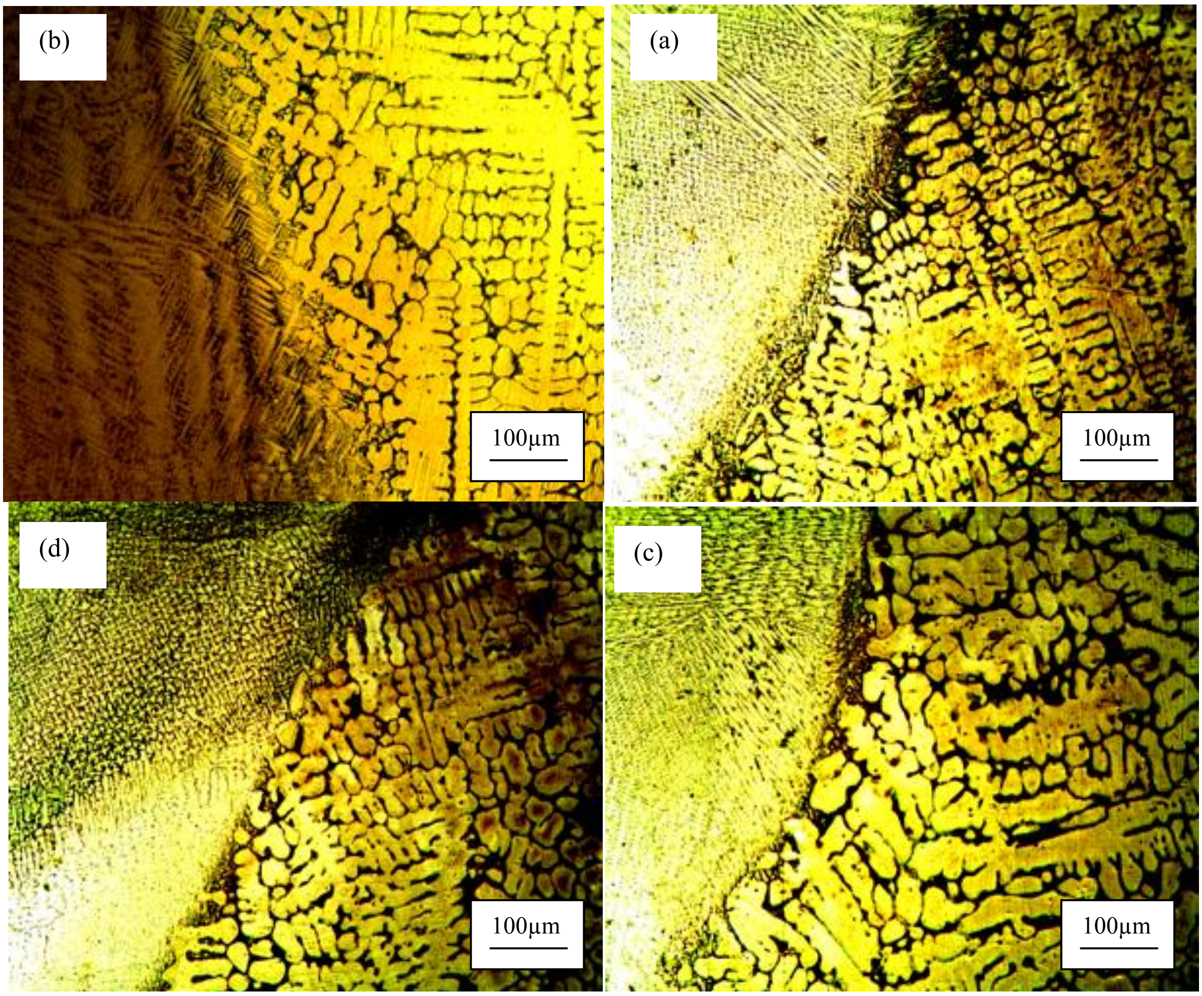


**Fig. 5.** Interface between ER-NiCr3 Inconel weld metal and 25Cr-35Ni heat resistant steel with pulse on time 40%, peak current of 180 A and base current of 60 A: (a) frequency of 6 HZ; (b) 8 HZ; (c) 10 HZ; (d) 12 HZ.

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