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Study Of Mechanical Properties And Microstructure Of Fe_3Al / Bni-2 / Steel Brazed Joints

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---ABSTRACT---
*Iron aluminides (Fe_3Al) intermetallic and steel were joined successfully by vacuum brazing using of BNi-2 braze alloy. Brazing experiments were carried-out at bonding temperature 1040 ^oC and at different bonding time 2-20 minutes. Fe_3Al/BNi-2/steel joints were thus formed. The microstructure features in the Fe_3Al/BNi-2/steel joints were analyzed by a variety of characterization techniques such as optical microscope and scanning electron microscope (SEM) with energy- dispersive spectroscopy (EDS), electronic probe microanalysis (EPMA) and an X-ray diffractometer. The micro-hardness from Fe_3Al to steel through BNi-2 braze alloy were measured with a Vickers microhardness. The shear strength of the Fe_3Al/BNi-2/steel joints were evaluated with a shear test machine and the maximum shear strength of Fe_3Al/BNi-2/steel joints was 496 MPa for joints bonded at bonding temperature of 1040 ^oC and bonding time of 5 minutes. The transition zones in the middle between the Fe_3Al and the steel were obviously observed and the width of the transition zone was 21 µm. Diffraction Standards indicates that there were chromium boron (CrB); chromium boron(CrB_4); aluminum nickel ($AlNi_3$); aluminum iron (FeAl); Iron aluminides (Fe_3Al); and nickel silicon (NiSi) phases are present at the fracture surfaces of the Fe_3Al/BNi-2/steel joint and aluminum iron silicon ($Al_{0.3}Fe_3Si_7$); nickel (Ni); Iron aluminides (Fe_3Al) phases are present at the Fe_3Al/BNi-2/steel joint surface perpendicular to the joint transition zone. The microhardness values at the transition zone increased from about 211 HV close to steel side to about 451 HV close to BNi-2 side. Along the BNi-2 braze alloy, the microhardness was about 608 HV and when reached the BNi-2/ Fe_3Al transition zone, the microhardness decreased to 347 HV close to Fe_3Al. Along the BNi-2 brazed alloy was higher than that at the Fe_3Al this indicates that there was possible formation of hard and brittle phases at the joint transition zone and at the BNi-2***,** *since the fracture occurred along the BNi-2/ Fe_3Al transition zone.*

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I. INTRODUCTION

Nickel base braze alloys both have good corrosion resistance and creep strength, so it was selected as filler metal. BNi-2 has high creep strength and low liquidus temperature among all Ni base braze alloys, the solidus and liquidus temperatures of this alloy are 970 and 1000 ^oC, respectively. Therefore, BNi-2 was chosen as a brazing filler metal in joining Fe_3Al by infrared brazing and its chemical composition in weight percent was 7.0 Cr, 3.1 B, 4.5 Si, 3.0 Fe, 0.06C, and Ni balance [1,2]. Joining of Fe_3Al is performed by using infrared vacuum brazing using BNi-2 as the brazing filler alloy. The species and morphology of phases in the brazed joint are extensively examined. Many transient phases, including: $(Ni,Fe)_3Al$, $(Ni,Fe)_3(Si,Al)$, $(Fe,Ni,Cr)_3B$ and BCr, were observed after infrared brazing. With increasing the homogenization time of the brazement at 1000 ^oC, the stoichiometry of both $(Ni,Fe)_3Al$ and $(Ni,Fe)_3(Si,Al)$ phase has changed into $(Ni,Fe)_2Al$ and $(Ni,Fe)_2(Si,Al)$. Most of BCr and $(Fe,Cr,Ni)_3B$ phases can be dissolved into the Fe_3Al matrix during homogenization of the brazement, so the amounts of the chromium boride and $(Fe,Ni,Cr)_3B$ phases are decreased with the time increment of homogenization [3,4].

Iron aluminides (Fe_3Al) intermetallic and steel were joined successfully by vacuum brazing using of B-Ni83 braze alloy. Brazing experiments were carried-out at bonding temperature 1040 ^oC and at different bonding time 2-20 minutes. Fe_3Al/B-Ni83/steel joints were thus formed. The maximum shear strength of Fe_3Al/B-Ni83/steel joints was 470 MPa for joints bonded at bonding temperature of 1040 ^oC and bonding time of 5 minutes[5,6]. Diffraction Standards indicates that there were chromium nickel ($Cr_{1.12}Ni_{2.88}$); Awaruite ($FeNi_3$); iron nickel-alpha-($Fe_{10.8}Ni$); nickel boron (Ni_3B); chromium boron (CrB) and iron nickel ($Fe_{0.64}Ni_{0.36}$) phases are present at the fracture surfaces of the Fe_3Al/B-Ni83/steel joint and Iron chromium (FeCr); nickel (Ni); aluminum iron (FeAl) and iron aluminide (Fe_3Al) phases are present at the Fe_3Al/B-Ni83/steel joint surface perpendicular to the joint transition zone [7].

Iron aluminides Fe_3Al intermetallic and steel were joined successfully by vacuum diffusion bonding and by using FeNi42 as interlayer. Diffusion bonding experiments were carried-out at different bonding temperature 1000-1200 ^{0}C and at different bonding time 10-60 min and under bonding pressure of 10 MPa. Fe_3Al/FeNi42/steel joints were thus formed. The highest shear strength value of Fe_3Al/FeNi42/steel joints were obtained in two bonding conditions were 344 MPa, the first condition joints bonded at bonding temperature of 1100 ^{0}C; bonding time of 60 minutes and bonding pressure of 10 MPa and the second condition joints bonded at bonding temperature of 1200 ^{0}C; bonding time of 30 min and bonding pressure of 10 MPa. X-ray diffraction results showed the existence of Taenite-(Fe,Ni), aluminum iron nickel ($AlFe_{0.23}Ni_{0.77}$) phases are present at the fracture surfaces of the Fe_3Al/FeNi42/steel joint and Fe, Taenite-(Fe,Ni) and Fe_3Al phases are present at the Fe_3Al l/FeNi42/steel joint surface perpendicular to the welded joint transition zone without brittle phases [8,9].

Iron aluminides Fe_3Al intermetallics and steel were joined successfully by vacuum diffusion bonding. Diffusion bonding experiments were carried-out at different bonding temperature 1000-1200 ^{0}C and at different bonding time 10-60 min and at bonding pressure of 10 MPa. Fe_3Al/steel joints were thus formed [10, 11]. The maximum shear strength of Fe_3Al/steel joints was 362 MPa for joints bonded by at bonding temperature of 1100 ^{0}C and bonding time of 60 min and bonding pressure of 10 MPa. X-ray diffraction results showed the existence of Aluminum iron carbide Fe_3AlC, Fe_3Al, FeAl and α-Fe in the Fe_3Al/steel diffusion-welded joint without brittle phases and with micro-hardness microhardness value at the transition zone increased from about 189 HV close to steel side to about 301 HV close to Fe_3Al side [12].

II. EXPERIMENTAL WORK

Fe_3Al was prepared by melting and casting in the vacuum furnace. The chemical composition of the Fe_3Al intermetallic was identified (wt.%) to be 86.028% Fe, 13.87% Al, 0.1% Zr and 0.002% B. The chemical compositions in carbon steel were: 0.16% C, 0.01% Si, 0.49% Mn and 99.23% Fe. Nickel base filler alloy discs was used as brazing filler alloy (BNi-2), and its chemical composition was 6.45% Cr, 13.74% B, 7.68% Si, 2.57% Fe, 2.4% C, and 67.16% Ni. The solidus and liquidus temperatures of this alloy are 970 and 1000 ^{0}C, respectively. The thickness of brazing filler alloy (BNi-2) tape was 100 μm throughout the experiment. Cutting of the Fe_3Al intermetallic and the steel rods in the form of discs of 16mm diameter and 4mm thick for Fe_3Al intermetallic samples and of 12mm diameter and 4mm thick for steel samples. The samples were ground on different emery paper of grades, 100, 320, 600 and finally 1000 on grinding machine. The samples were rough polished by using alumina on polishing machine. Before assembling the samples to be joined, all samples were subjected to two-step cleaning process, which include acetone and ultrasonic path in acetone. Figure 1 shows the microstructure of Fe_3Al, which was polished and etched by: 40ml HCl + 30ml HNO_3 + 20 ml glacial acetic acid + 10 ml glycerol. Figure 2 shows the microstructure of steel, which was polished and etched by 5% nital.

After cleaning, the BNi-2 braze alloy discs was sandwiched between the Fe_3Al intermetallic and the steel. The assembly samples were positioned in the inductor coil of bonding apparatus. The samples heated to a temperature of 400 ^oC for 20 minutes to clean outsides surfaces from contaminations, after that the samples heated to the required joining temperature (1040 ^oC) and held at that temperature until the end of joining time (2 to 20 minutes), at the end of joining time, the samples were cooled to room temperature. The heating and cooling rates were 10 ^oC/min. The vacuum during the joining experiments was held between 1-5x10^{-3} Pa. Thus, the Fe_3Al/BNi-2/steel brazed joint was formed. After joining processes have been completed, the specimens were cut perpendicular to the joint transition zone. The specimens were grinded on a series of emery papers containing successively finer abrasives (silicon carbide). The paper grades is usually 100, 220, 320, 600, and 1200. Polishing of specimens were done with polishing machine which was covered with a special leather that charged with carefully sized abrasive particles (alumina) in order to remove the fine scratches.

Finally, Steel etched by: 5% nital and intermetallic etched by: 40ml HCl + 30ml HNO_3 + 20ml glacial acetic acid + 10ml glycerol. The microstructure in the Fe_3Al/BNi-2/steel brazed joint was observed by means of an optical microscope and EDX Oxford type ISIS scanning electron microscope (SEM) with energy-dispersive spectroscopy (EDS). The micro-hardness from Fe_3Al to steel through BNi-2 braze alloy was measured by a Vickers microhardness, with a test loading of 100g and a loading time of 10 sec. The shear strength was evaluated with a shear testing machine (Instron). The phases formed in the Fe_3Al/BNi-2/steel joint were analyzed with an X-ray diffractometer.

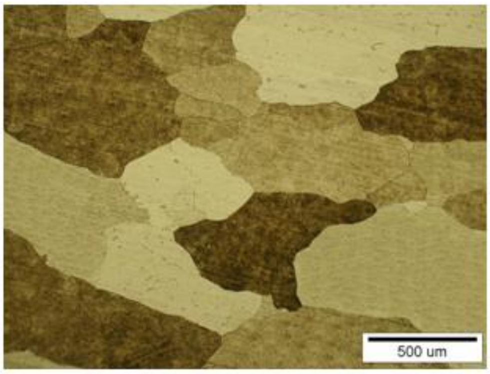

Figure 1 Optical micrograph of Fe_3Al (100x).

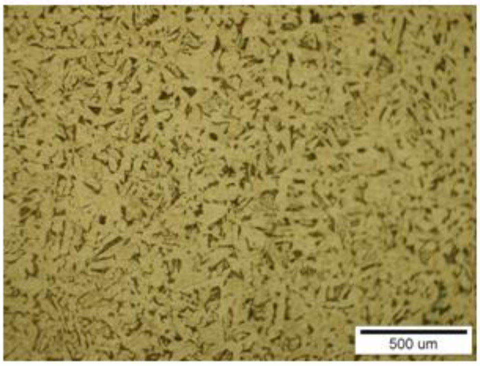

Figure 2 Optical micrograph of steel (100x).

III. RESULTS AND DISCUSSION

Brazing was used to join Fe_3Al to steel by using BNi-2 as Braze Alloy. The highest shear strength value of Fe_3Al/BNi-2/steel joints was 496 MPa for joints bonded at bonding temperature of 1040 ^oC; bonding times of 5 minutes. Bonding parameters and shear strength results of Fe_3Al/BNi-2/steel joints are listed in table 1.

Table (1) Bonding parameters and shear strength results of Fe_3Al/BNi-2/steel joints.

Sample No.	T_b (^oC)	t_b (min)	Results	Strength (MPa)
1	1040	2	B	462
2	1040	5	B	496
3	1040	10	B	448
4	1040	20	B	370

Explanations: T_b= bonding temperature; t_b= bonding time; and B= bonded.

Figure 3 shows the effects of holding time on the joint strength of the Fe_3Al/BNi-2/steel joints bonded at 1040 ^oC. It can be seen that the joint strength increased with increment of holding time and the maximum joint strength value was achieved when joints bonded at 5 minutes was 496MPa. Further increased in the bonding time, the joint strength decreased to 448 MPa for joint bonded at 10 minutes and to 370 MPa for joint bonded at 20 min.

Figure 4 presents the microhardness values of Fe_3Al/BNi-2/steel joint bonded at bonding temperature of 1040 ^oC and bonding time of 5 minutes. From the figure it can be seen that at the BNi-2/steel transition zone the microhardness increased from about 211 HV at the transition zone close to steel side to about 451 HV close to BNi-2 side and at the BNi-2/Fe_3Al transition zone the microhardness decreased from about 347 HV at the transition zone close to BNi-2 side to about 270 HV close to Fe_3Al side. Along BNi-2 toward Fe_3Al, the microhardness was not changed until the BNi-2/Fe_3Al transition zone and when reached the BNi-2/Fe_3Al transition zone, the microhardness decreased to 347 HV. Measured results show that steel microhardness was about 147 HV; BNi-2 microhardness was about 608 HV and Fe_3Al intermetallic compound microhardness was about 271 HV.

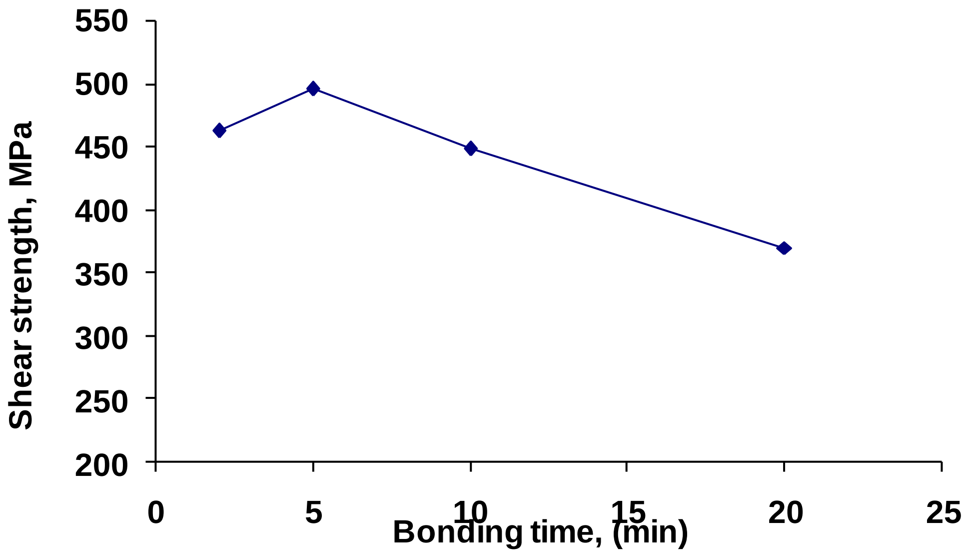

Figure 3 The effect of holding time on the joint strength of Fe_3Al/BNi-2/steel joints bonded at:T_b=1040 ^oC.

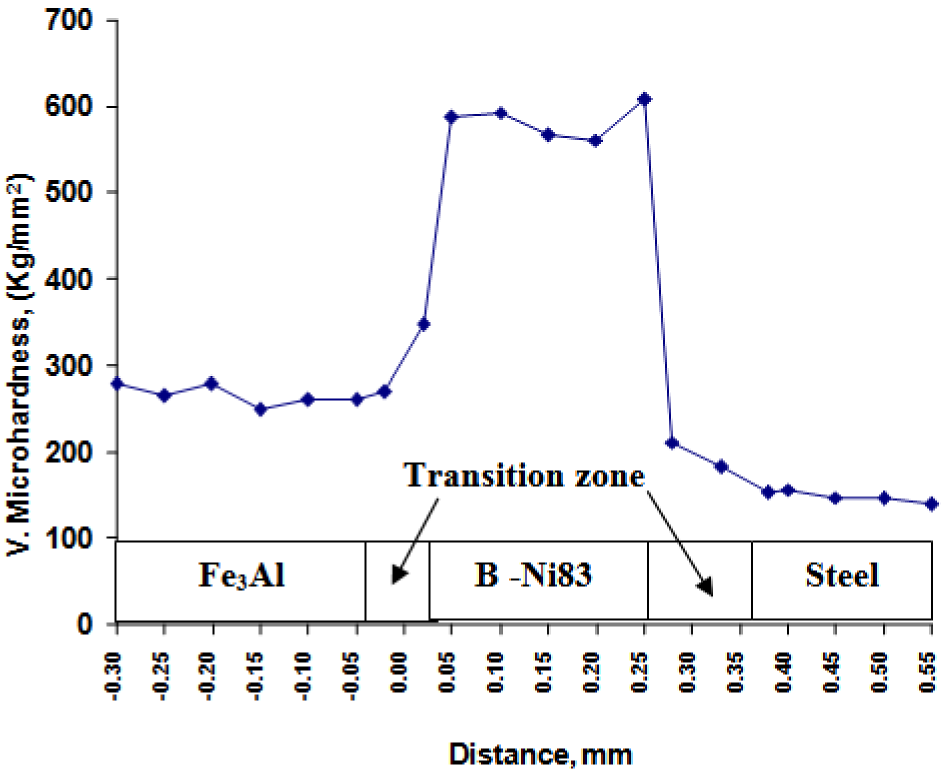

Figure 4 Vickers Microhardness of Fe_3Al/BNi-2/steel joint bonded at: T_b =1040 ^0C; t_b= 5

The effects of bonding time on the microstructures of Fe_3Al/BNi-2/steel joints bonded at bonding temperature 1040 ^oC are shown in figure 5. In figures 5 the upper parts is the steel and the lower part is the Fe_3Al intermetallic compound and in the middle is the BNi-2 brazed alloy

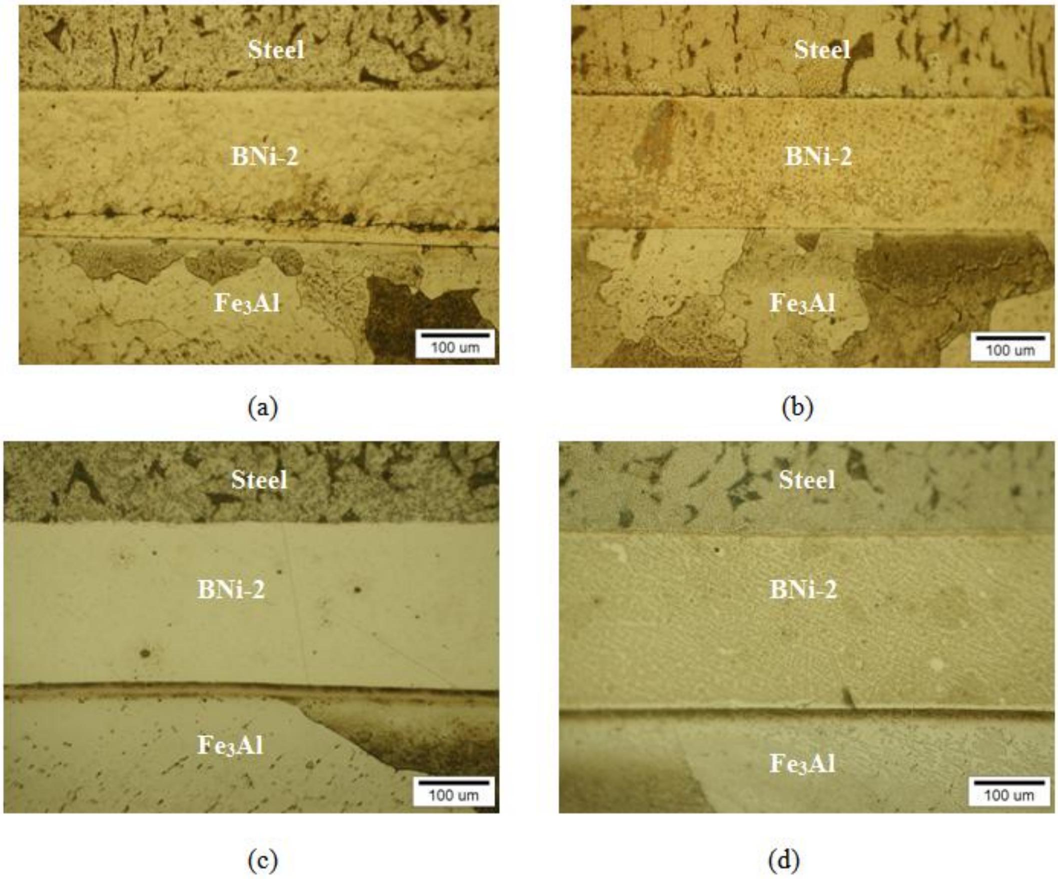

Figure 5 Optical micrograph of cross-section of Fe_3Al/BNi-2/steel joint bonded at: T=1040 ^{0}C and at: (a) t_b=2 min. (b) t_b=5 min. (c) t_b=10 min. t_b=20 min. x200.

The results of EPMA linear distribution of Al, Cr, Fe, Ni, and Si across the Fe_3Al/BNi-2/steel joints bonded at 1040 ^oC and bonding time 5 min are illustrated in figure 6. it can be seen that Fe concentration was regular during passing along the steel and when reach the steel/BNi-2 transition zone, the Fe concentration decreased until the concentration of BNi-2 brazed alloy has been reached. Along the BNi-2 brazed alloy, Fe-concentration appears to be uniformly distributed and when reaches Fe_3Al/BNi-2 transition zone, Fe-concentration increased in two steps until the concentration of the Fe_3Al has been reached and along the Fe_3Al intermetallic the Fe-concentration was regular. Ni-concentration was nil during passing along the steel and when reaches the steel/BNi-2 transition zone, the Ni-concentration increased until the Ni-concentration of the BNi-2 brazed alloy have been reached. Close to the steel/BNi-2 transition zone, Ni-concentration was regular. Along the BNi-2 brazed alloy, Ni-concentration appears to be nonuniformly distributed in the BNi-2 brazed alloy. Some peaks in Ni-concentration line may give some evidence of possible reactions of Ni with other elements in the BNi-2 brazed alloy. Before the end of the BNi-2 brazed alloy, Ni-concentration gradually decreased until the Fe_3Al/BNi-2 transition zone and when crossing the transition zone to the Fe_3Al intermetallic, Ni concentration decreased to nil. Al-concentration was nil during passing along the steel and the BNi-2 brazed alloy and when reached the Fe_3Al/BNi-2 transition zone, Al-concentration increased and show its maximum at the Fe_3Al/BNi-2 transition zone when passing from the Fe_3Al/BNi-2 transition zone to Fe_3Al intermetallic the Al-concentration was regular Si-concentration was nil during passing along the steel and BNi-2 brazed alloy, Si-concentration appears to be nonuniformly distributed and when passing from the Fe_3Al/BNi-2 transition zone to the Fe_3Al intermetallic, the Si-concentration decreased to nil. Cr-concentration was nil during passing along the steel and when the steel/BNi-2 transition zone has been reached, the Cr-concentration gradually increased until the Cr-concentration of the BNi-2 brazed alloy has been reached and the Cr-concentration was regular then Cr-concentration appears to be nonuniformly distributed in the BNi-2 brazed alloy. Some peaks in Cr concentration may give some evidence of possible reactions of Cr with other elements in the BNi-2 brazed alloy. At the end of the transition zone, the concentration becomes regular and when passing from the Fe_3Al/BNi-2 transition zone to the Fe_3Al intermetallic, the Cr-concentration decreased to nil [13].

The phase constitutions formed in the Fe_3Al/BNi-2/steel joints were further researched by means of X-ray diffractometry. The results of XRD investigation which were performed on sample cut perpendicular to the joint transition zone is shown in figure 7. Diffraction Standards indicates that there were aluminum iron silicon ($Al_{0.3}Fe_3Si_7$); nickel (Ni); and aluminum iron (Fe_3Al) phases are present at the surface perpendicular to the joint transition zone of Fe_3Al/BNi-2/steel joints bonded at 1040 ^oC and bonding time 5 minutes. The results of XRD investigation which were performed on sample fractured during shear testing on the intermetallic part and the steel part is shown in figure 8. Diffraction Standards indicates that there were chromium boron (CrB); chromium boron(CrB_4); aluminum nickel ($AlNi_3$); aluminum iron (FeAl); aluminum iron (Fe_3Al) nickel silicon (NiSi) phases are present at the fracture surfaces of the Fe_3Al/BNi-2/steel joint bonded at 1040 ^oC and bonding time 5 minutes.

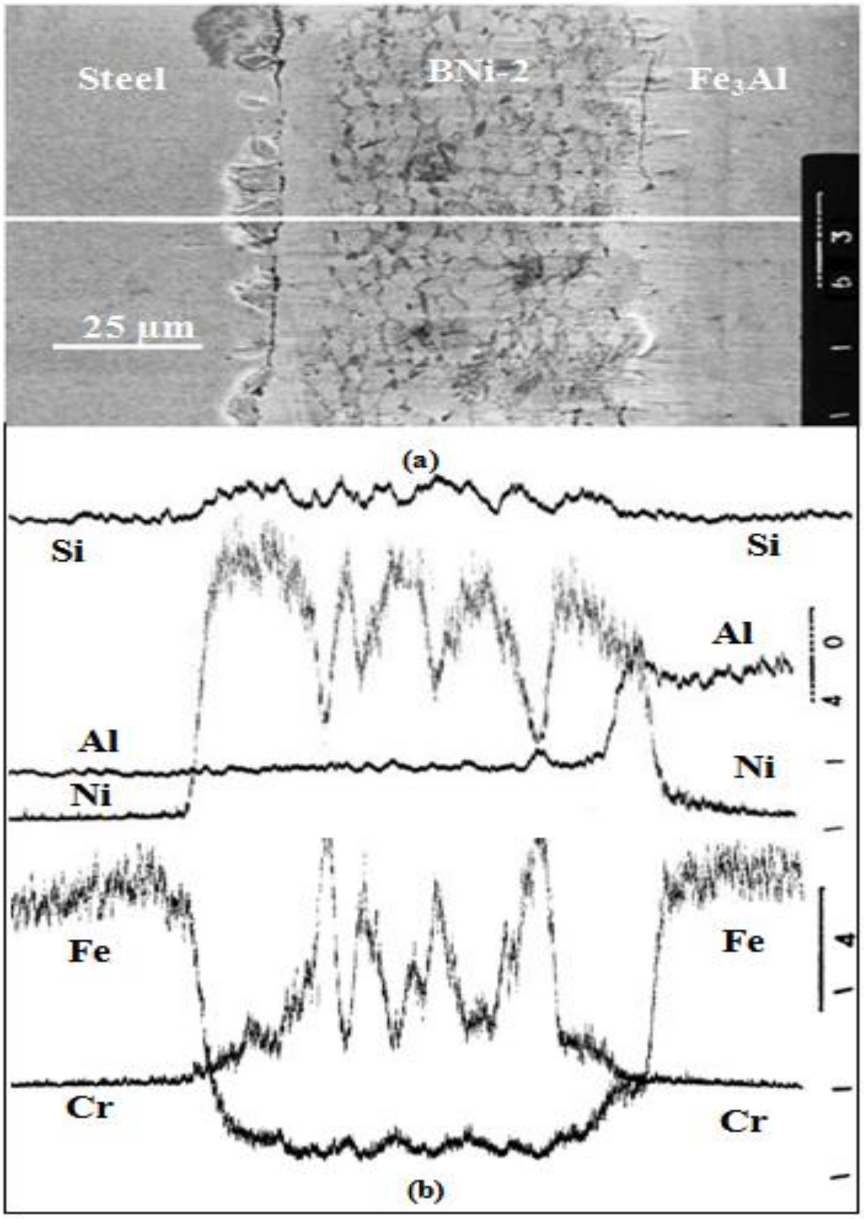

Figure 6 EPMA line analysis across the Fe_3Al/B-Ni83/steel joint bonded at: T_b =1040 ^0C and t_b= 5 min:
(a) View of the transition zone with line of microanalysis.
(b) Distribution of Al, Fe, Mn, Ni, Cr, Si and Zr elements across the B-Ni83/ Fe_3Al transition zone.

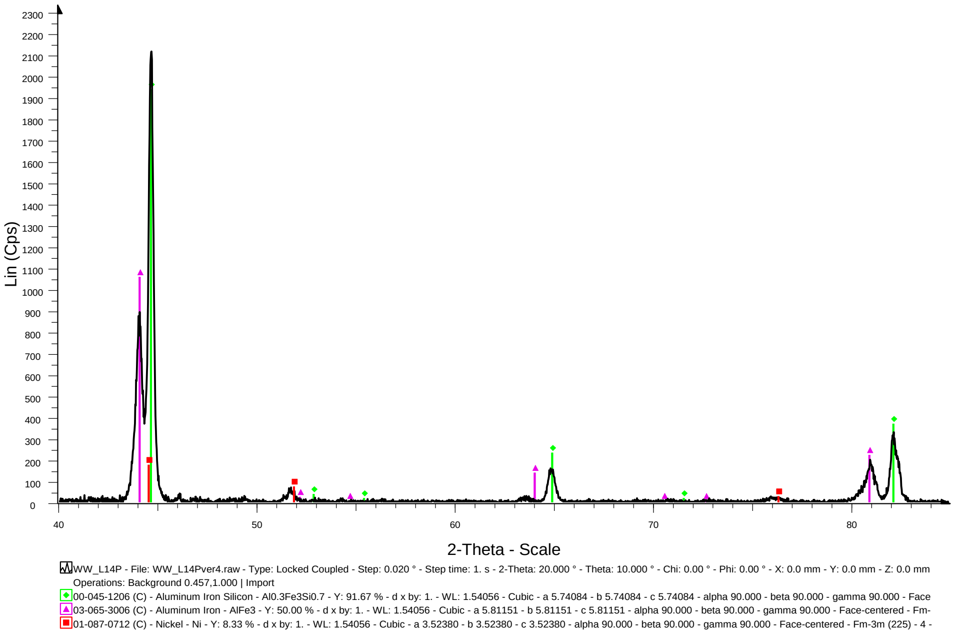

Figure 7 XRD patterns of the cross- section of the Fe_3Al/BNi-2/steel joint Bonded at: T_b = 1040 ^oC and t_b= 5 minutes.

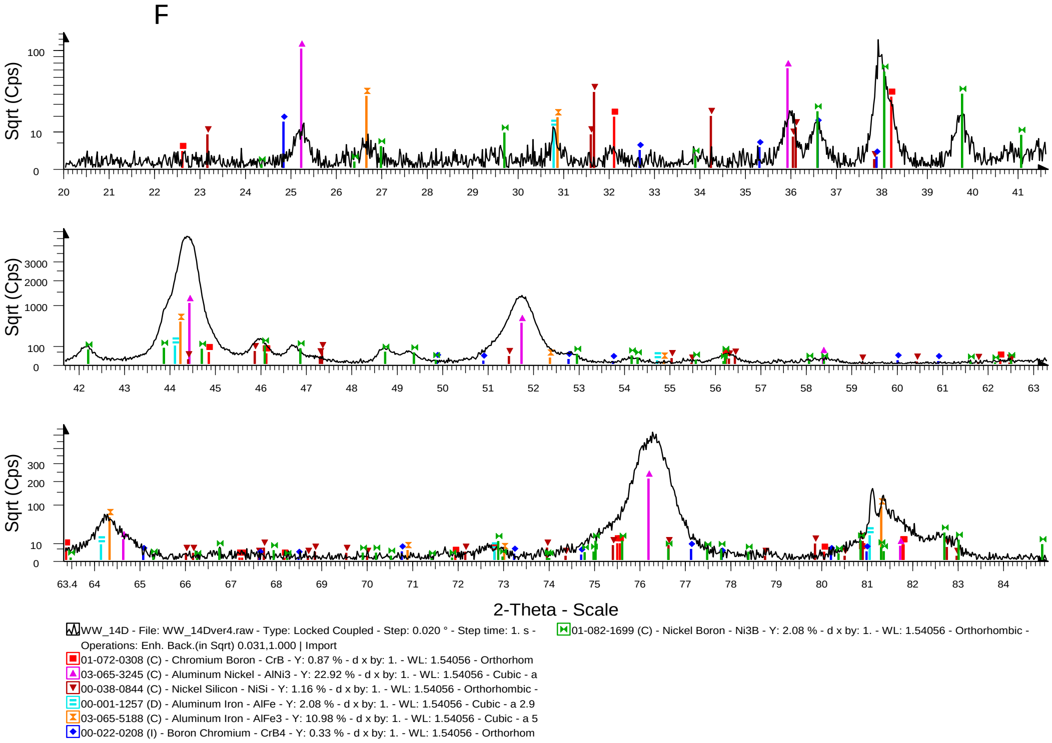

Figure 8 XRD patterns of the fracture surface of the Fe_3Al/BNi-2/steel joint Bonded at: T_b = 1040^{0}C and t_b= 5 minutes.

Finally, the results of shear strength and microstructure of Fe_3Al/BNi-2/steel joints indicated that the highest shear strength was 496 MPa for joint bonded at 1040 ^oC and bonding time of 5 minutes. The results of the microhardness indicated that the microhardness along the BNi-2 brazed alloy was higher than that at the Fe_3Al intermetallic, this indicates that there was possible formation of brittle phases at the Fe_3Al/BNi-2 transition zone and at the BNi-2**,** since the fracture occurred along the Fe_3Al/BNi-2 transition zone. The linear distribution indicated that, the concentrations of Al; Fe, Cr, Si and Ni were changed along the BNi-2 brazed alloy and at steel/BNi-2 and Fe_3Al/ BNi-2 transition zones it is also evident that Al; Fe; Cr; Si and Ni diffused to the transition zone and reactions between these elements occurred and these reactions was investigated by using X-ray diffraction and the results showed the existence of the new phases such as were aluminum iron silicon ($Al_{0.3}Fe_3Si_7$); nickel (Ni); aluminum iron (Fe_3Al); chromium boron (CrB); chromium boron(CrB_4); aluminum nickel ($AlNi_3$); aluminum iron (FeAl); aluminum iron (Fe_3Al); and nickel silicon (NiSi) at steel/BNi-2 and Fe_3Al/BNi-2 transition zones and along the BNi-2 braze alloy[14].

IV. CONCLUSIONS

1. The maximum shear strength of Fe_3Al/BNi-2/steel joints was 496 MPa for joints bonded at bonding temperature 1040^0C and bonding time 5 minutes.
2. X-ray diffraction results showed the existence of the new phases such as chromium nickel ($Cr_{1.12}Ni_{2.88}$); Awaruite ($FeNi_3$); iron nickel-alpha-($Fe_{10.8}Ni$); nickel boron (Ni_3B); chromium boron (CrB); iron nickel ($Fe_{0.64}Ni_{0.36}$) and chromium (FeCr)**.**
3. The microhardness along the BNi-2 brazed alloy was higher than that at the Fe_3Al intermetallic this indicates that there was possible formation of hard and brittle phases at the joint transition zone and at the BNi-2**,** since the fracture occurred along the Fe_3AlBNi-2 transition zone.
4. The optimum conditions for joining Fe_3Al intermetallic to steel joints was at: T_b=1040 ^oC and t_b= 5 minutes.

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