Growth Types and Bonding Mechanisms for Copper / Steel Interface by Fusion Welding

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Abstract

The aim of this work is to study the possibility of joining copper (ASTM , C1020100) to low carbon steel (ASTM A36) using the shielded metal arc welding (SMAW) and the gas tungsten arc welding (GTAW) processes by eight types of electrodes ; ERNiCrFe-5 , ERNiCu-7 , ECu , ECuSn-A, E309L, E 312, E7018 , and ENi-1. Joint is designed as single – V – butt weld for 5 mm thickness plate . From the microstructure observation there were two kinds of boundaries ; the first is homogenous weld , which happens when fillers with chemical composition is similar to those of one of the parent metals . While the second type is heterogenous nucleation , which happens when the chemical compositions of the fillers and the parent metals are not similar . Three types of solidification were regonized ; the first is epitaxial from the copper side , the second is nonepitaxial from the steel side , and the third type is competitive which shown in the two sides . Solidification cracks on the steel side are shown , and these cracks are filled by brazing process . All tested specimens in tension and bending show the copper properties .

المستخلص

الهدف من اجراء هذه الدراسة لمعرفة امكانية لحام النحاس نوع (ASTM , C1020100) الى الفولاذ المتخفض الكاربون نوع (ASTM , A36) بطريقتي اللحام القوس المعدني المغطى (SMAW) ولحام القوس الكهربائي باستخدام قطب التنكستن (GTAW) . مادة الحشو المستخدمة هي :

ECuSn-A , ECU , ERNiCu-7 , ENRiCrFe-5 , ENi-1 , E7018 , E312 , E309 L

وصلة اللحام مهمة تناكبية احادية الحفر . سمك صفائح اللحام 5 ملم . من ملاحظات البنية البلورية اتضح لنا نوعين من الحدود البلورية ، الاولى حدود منتظمة والتي تحصل باستخدام اسلاك لحام مشابهة لأحد طرفي وصلت اللحام ، الثاني هي حدود هجينة والتي تحصل نتيجة لعدم تماثل سلك اللحام مع الاساس المعدني لثلاثة أنواع من الاغماد وحصلنا عليها الاولى نوع Epitaxial والذي كان على العموم في جانب النحاس ، الثاني يسمى Nonepitaxial والذي يكون من جانب الفولاذ ، اما الثالث فأنه نوع Competitiveوالذي يكون من كلا الجانبين . حدوث بعض التشققات على الساخن والتي لوحظ املائها بطريقة البرصمة وبذلك يرتفع مرة اخرى بمتانة وصلة اللحام . لوحظ تماثل المواصفات الميكانيكية للشد والحني لجميع الوصلات والتي تمثل المواصفات الميكانيكية للنحاس .

1. Introduction

In fusion welding the exiting base-metal grains at the fusion line act as the substrate for nucleation . Since the liquid metal of the weld pool is in intimate contact with these substrate grains and wets them completely (0 to 0) Figure (1) . Crystal nucleate from the liquid metal upon the substrate grains go without difficulties . Such a growth initiation process shown in Figure (2)is called epitaxial growth [1] . When welding with a filler metal (or joining two different materials) , the weld metal composition is different from the base metal composition , and the weld metal crystal structure can differ from the base metal crystal structure . When this occurs , epitaxial growth is no longer there and new grains will have to nucleate at the fusion boundary [1] .

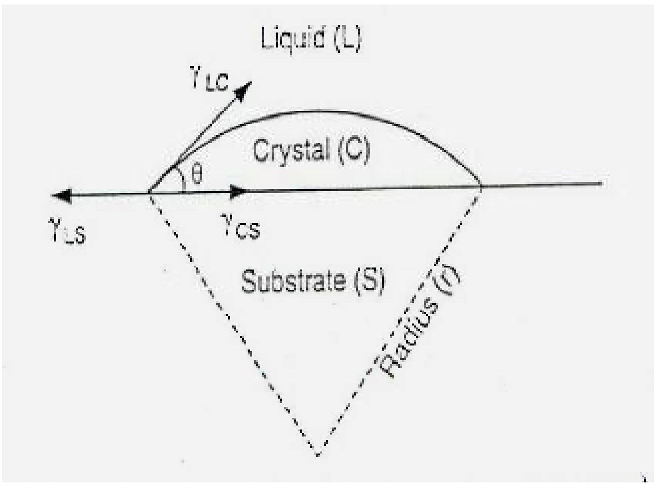


Figure (1). Spherical of crystal nucleated on planer substrate from liquid. [1]

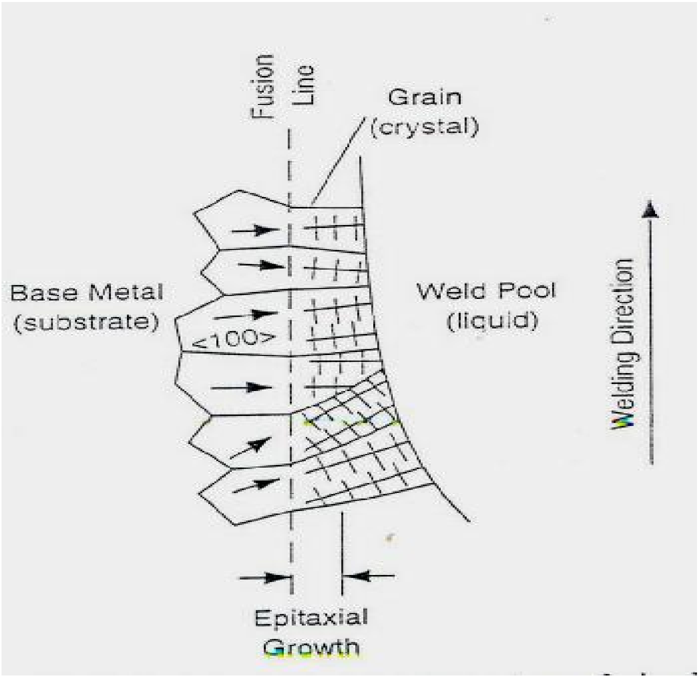


Figure (2). Epitaxial growth of weld metal near fusion line.[1]

Nelson et al [2] pointed out that weld type 409 St St of BCC structure with monel filler metal of FCC structure produce a FCC weld metal deposit . Figure(3) shows the fusion boundary or interface microstructure . They concluded that the neucleation of solid weld metal occurs on heterogeneous site on the partially melted base metal at the fusion boundary (Nonepitaxial growth) . The grains structure near the fusion line of a weld is dominated either by epitaxial growth , when the base metal and the weld metal have the same crystal structure, or by nucleation of new grains when they have different crystal structure a way from fusion line . However , the grain structure is dominated by a different mechanism known as competitive growth , as sown in Figure (4) [3] . The aim of this study is to realize the bonding structure and mechanisms for dissimilar weld of copper to steel by different fillers .

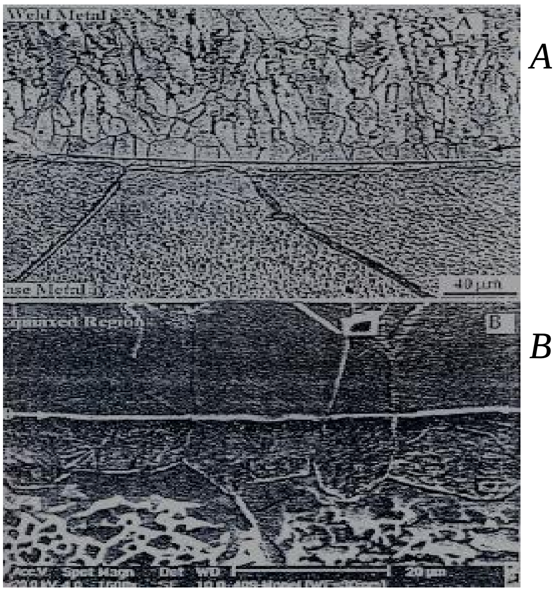


Figure (3). Fusion boundary microstructure in 409 ferritic st.st (bcc) welded with Monel filler wire (fcc):(A) optical micrograph : (B) scanning electron micrograph . White arrows:fusionboundary;dark arrows: new grains nucleated along fusion boundary .[2]

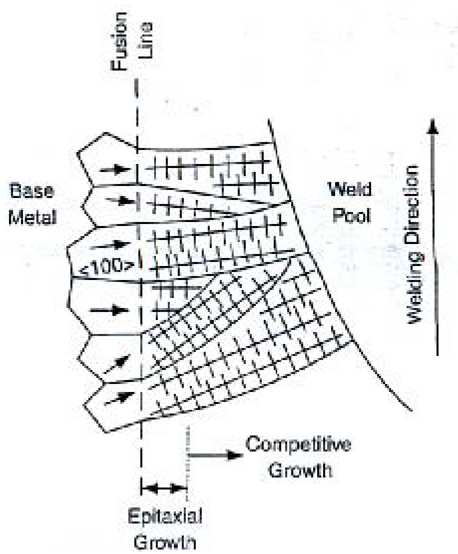


Figure (4). Competitive growth in bulk fusion zone .[3]

2. Experimental work

In order to accomplish the objective of this work , the following equipments were use : manual electric arc welding machine type ESAB LHF400 , gas tungsten arc welding machine type Miller 403 , grinding and polishing machine type Hergon MP 200 to prepare microscopic test specimens , gas torch for preheating , tensile test machine type Instrom 1195 of 2500 Kg capacity , and optical microscope connected to a computer with a digital camera . Steel plates type AISI 1015 ASTM A 36 , and copper plates type OFHC , ASTM DS – 65 , C10100 – C15735 , them of 5 mm thickness . Table 1 shows the nominal chemical composition of steel and cooper compared to standard specifications AISI-ASTM for both metals [4] .

Table (2) shows the mechanical properties for steel and copper compared to standard specifications AISI-ASTM for both metals [4]. Different types of electrodes as filler metals alloys were used according to ASME specification (section 11, part C). Table 3 shows

Table (1). Chemical composition of steel and copper. [4]

ELEMENT	LOW CARBON STEEL AISI 1015 ASTM A36		COPPER (OFHC) ASTM DS-65(C10100-C15735
	Nominal %	Actual %	Nominal %
C	0.13-0.18	0.15	-
Mn	0.3-0.6	0.402	-
P	-	0.04	-
S	-	0.05	-
Si	0.129	0.06	-
Cr	-	-	-
Ni	-	-	-
O2	-	-	0.002-0.003
Cu	-	0.034	99.9
Fe	Rem	Rem	-

Table (2). Mechanical properties for steel and copper.[4]

MECHANICAL PROPERTIES	COPPER (OFHC) ASTM DS-65(C10100-C15735		LOW CARBON STEEL AISI 1015 ASTM A36	
	Actual	Nominal	Actual	Nominal
Tensile Strength (N/mm²) MPa	216	200-250	410	380- 450
Modulus of elasticity GPa	112	110	210	205 min
Elongation%	46	60	28	25 min
Hardness (Kg/mm^2) Vickers	85	80	185	180

Table (3) . Chemical composition of electrodes and filler (FMA).[5, 6]

Electrode(filler) type	Fe	C	Mn	Si	Cu	Ni	Cr	P	Mo	Ti	Sn
E Cu	0.2	_	0.1	0.1	Rem.	_	_	_	_	_	
E CuSn-A	0.25	_	1.5	_	Rem.	_	_	0.05 to 0.35	_	_	4.0 to 6.0
E Ni-1	o.75	0.1	0.75	1.25	0.25	92.0 min.	_	0.3	_	1.0-4.0	4.0 to 6.0
ER NiCrFe-5 Inconel Alloy	6.0	0.08	1.0	0.35	0.5	70.0 min.	14.0	0.03	_	_	_
ER NiCu-7 Monel Alloy	2.5	0.15	4.0	1.25	Rem.	62.0 to 69.0	_	0.02	_	_	_

E 309L	**Rem.**	**0.04**	**0.25 to 0.5**	**0.9**	**0.75**	**12-14**	**22 to 25**	**0.04**	**0.75**	**_**	**_**
E312	**Rem.**	**0.15**	**0.25 to 0.5**	**0.9**	**0.75**	**8 to 10.5**	**28 to 32**	**0.04**	**0.75**	**_**	**_**
E 7018	**Rem.**	**0.04**	**1.6**	**0.75**	**_**	**0.3**	**0.2**	**_**	**0.3**	**_**	**_**

the nominal chemical composition of these electrodes [5,6]. Table 4 shows the mechanical properties for these electrodes [5,6] . The steel and copper plates were cutted to 300 x 150 x 5 mm for mechanical testing , and to 50 x 50 x 5 mm for microstructure testing . The steel surfaces were sand blasted , while copper surfaces were cleaned by alcohol . The welded plates were arranged as in figure 5 [7] , which welded by different types electrodes ECu , ECu-Sn-A , E7018 , E309L , E312 , and ENi-1 . by shielded metal arc welding (SMAW) process .

Table (4). Mechanical properties for electrodes and filler (FMA). [5, 6].

Electrodetype	**Yield strength Mpa**	**Tensile strength Mpa**	**Elongation%**
E312	500	750	25
ER NiCrFe-5 Inconel Alloy	410	640	40
E 309L	470	580	32
E 7018	445	540	29
ER NiCu-7 Monel Alloy	330	530	45
E Ni-1	320	450	25
E CuSn-A	235	330-390	25
E Cu	170	225	20

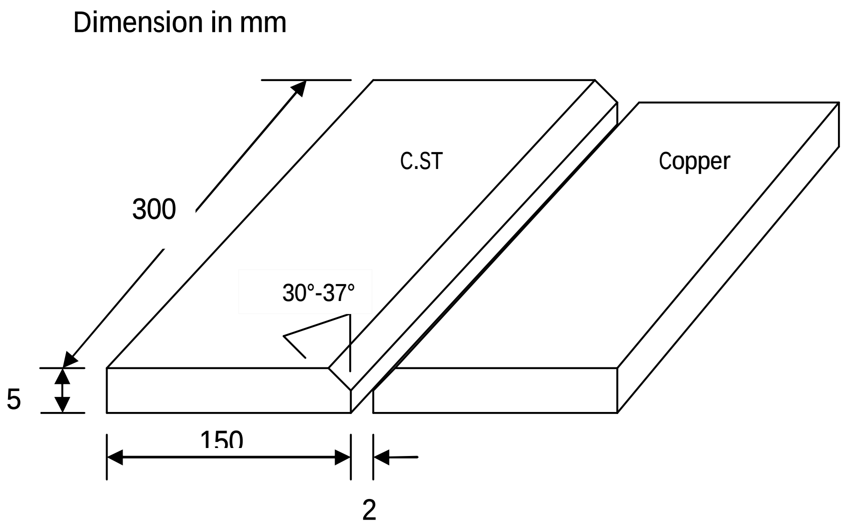


Figure (5). Dimensions of specimen according to ASME Section IX.[7]

Also the same dissimilar joint as in Figure (1) be welded by gas tengsten arc welding (GTAW) process using electrode types ERNiCrFe-5 , and ERNiCu-7, as shown in Table (5). The welded specimens were cutted according to AWS specification as shown in Figure (6). The tensile samples were prepared according to ASTM E 8M-88 specification as in Figure (7). While , the Figure (8) shows the standard dimensions for bending test according to ASTM E 190 specification .

Table (5). Variable parameters for electrodes and filler.

processes	Electrode& filler		Current		voltage	speed mm/min.	Gas flow L/min.	preheat C°	Interpass temp.C°
	type	Dia. mm	polar	Amp.					
GTAW	ERNiCrFe-5	2.4	DCSP	170-200	11	15	3.5	400-500	250-300
	ERNiCu-7	2.4	DCSP	170-200	11	15	3.5	400-500	250-300
SMAW	ENi-1	3.2	DCRP		24	16	-	400-500	250-300
	ECu	3.2	DCRP		22	15	-	400-500	250-300
	ECuSn-A	3.2	DCRP		23	15	-	400-500	250-300
	E309L	3.2	DCRP AC		24	18	-	400-500	250-300
	E312	3.2	DCRP		25	17	-	400-500	250-300
	E7018	3.2	DCRP AC	110-150	23	17	-	400-500	250-300

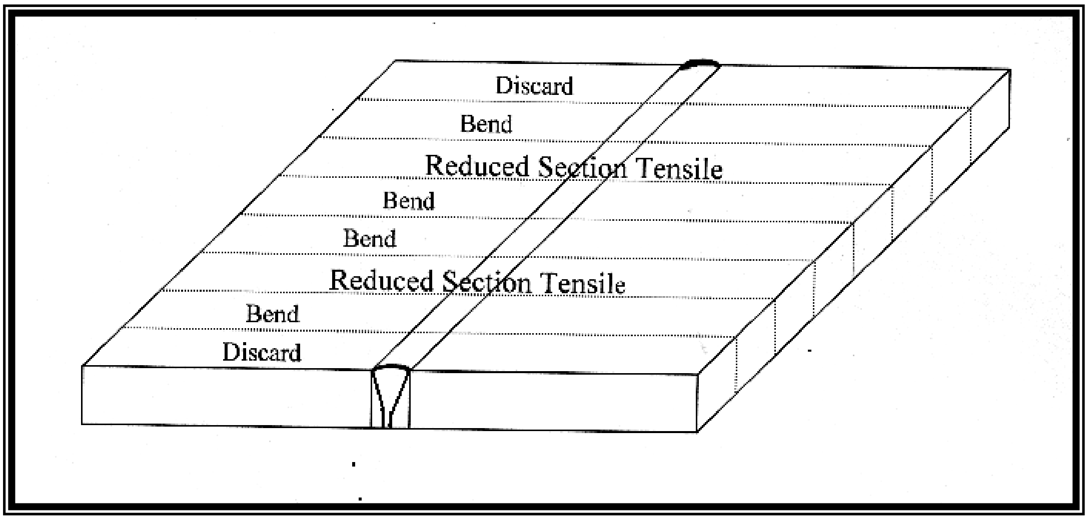


Figure (6).Specimen of the sample to be tested, according to AWS specification [7].

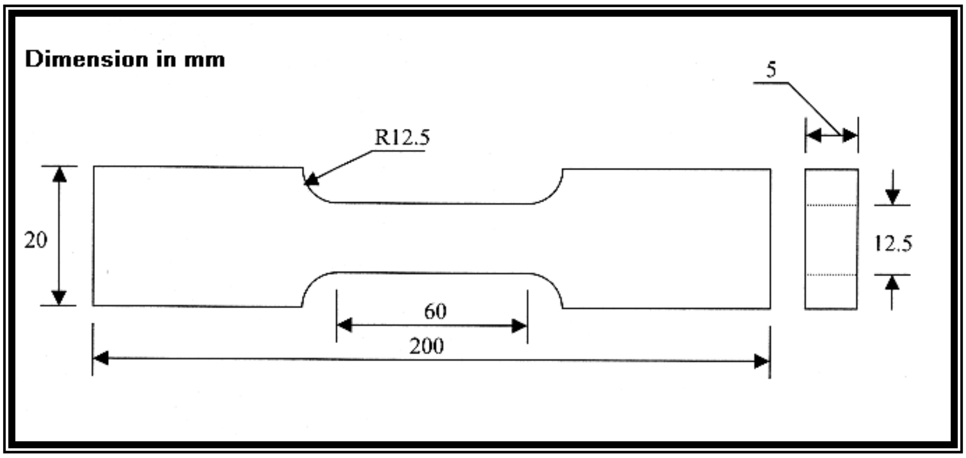


Figure (7) .Tensile test specimen, according to ASTM (E 8M-88) specification [7].

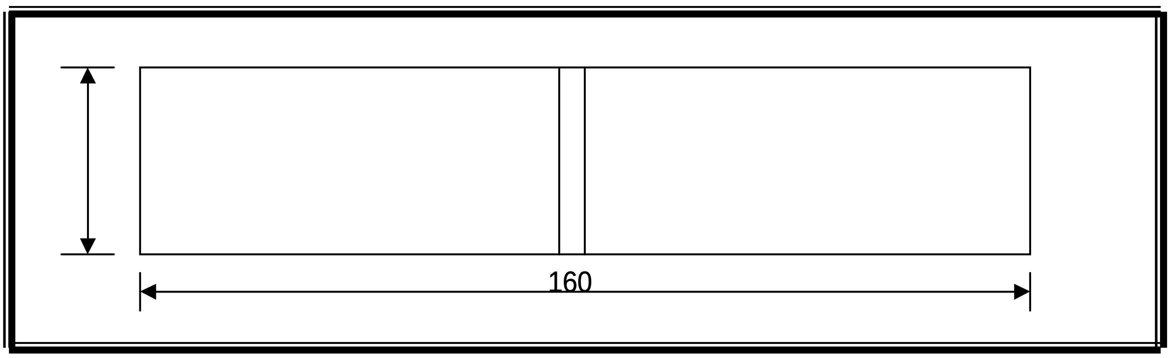


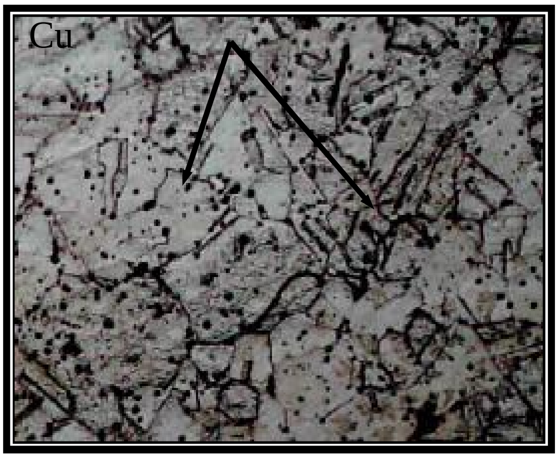
Figure (8). Bending test specimen, according to ASTM (E 190) specification [7].

3. Results and discussion

3.1 E7018 Weld Deposits

A dark dots appear in the copper weld pool , which are represent an oxide particles due to the new process of dissimilar joining (Figure 9 – a) . Epitaxial nucleation is formed during the solidification process at the fusion boundary, Figure (6–b) . While a homogenous weld interface is produced because of the similarity in the chemical composition at the steel side , (Figure 9 – C) .

Porosity



Figure(9-a)

Epitaxial

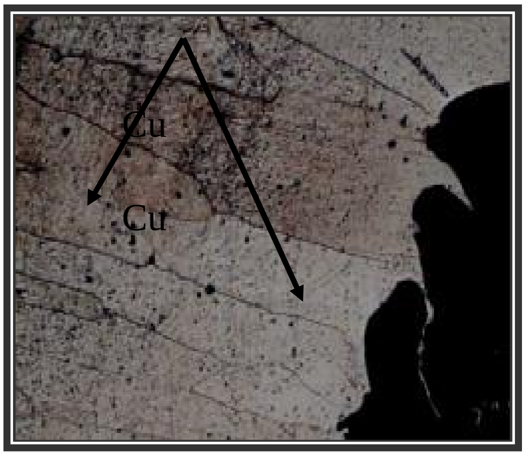
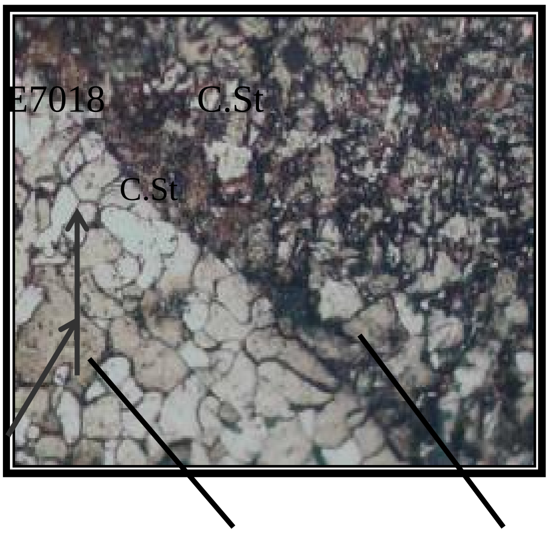


Figure (9-b)



Interface

Ferrite

Figure(9-c)

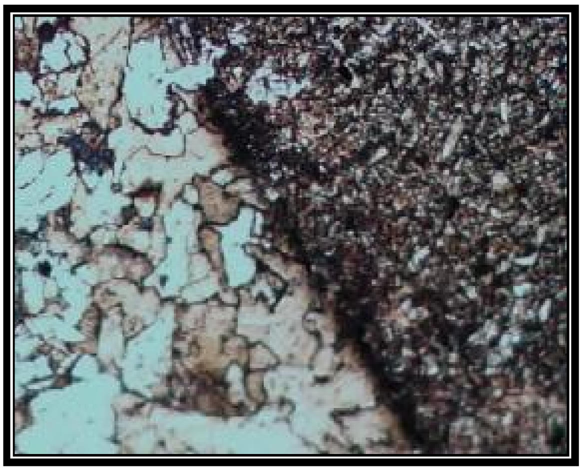


Figure (9-d)

Figure (9) .Cu/C.St system with E7018,SMAW, (a) Cu base metal, X 108, (b)Cu interface with E7018, X 108.(c,d) C.St interface with E7018, X 270.

3.2 ERNiCu-7 weld deposits

The nonepitaxial solidification had appear at the interface zone of copper/filler as shown in figure 10 c , d . The characteristics of this type of solidification is a copper grain structure parallel to the fusion line, which show a transion stage between the new structure of copper and the deposite . Figure 10 – e shows a micro crack due to solidification cracking which occurs when partitioning of elements during solidification causes low melting point films to form along solidification grain boundaries . As the weld metal cools and shrinks , a level of strain will develop and causes separation of the grain boundary along the liquid films . This type of cracking usually appears along the weld centerline , especially in a thick or heavily restrained weldment , and its occur immediately after welding [8] . This cracks will brazed immeadiatly because of presence an elements have low melting point will act as brazing filler to weld this cracks .

3.3 ECuSn-A weld deposits

Epiazial nucleation was appear from the copper side as shown in figure 11 – a , while showing nonepitaxial nucleation from the steel side . (Figure 11 b – c) .

3.4 E309L welded deposits

Nonepitaxial nucleation and hot cracking with brazing process was pointed out at the steel/ filler side . (figure 12 a ,b, c) . While shows competitive growth in bulk fusion zone of copper / filler side (figure 12-d, e and f) .

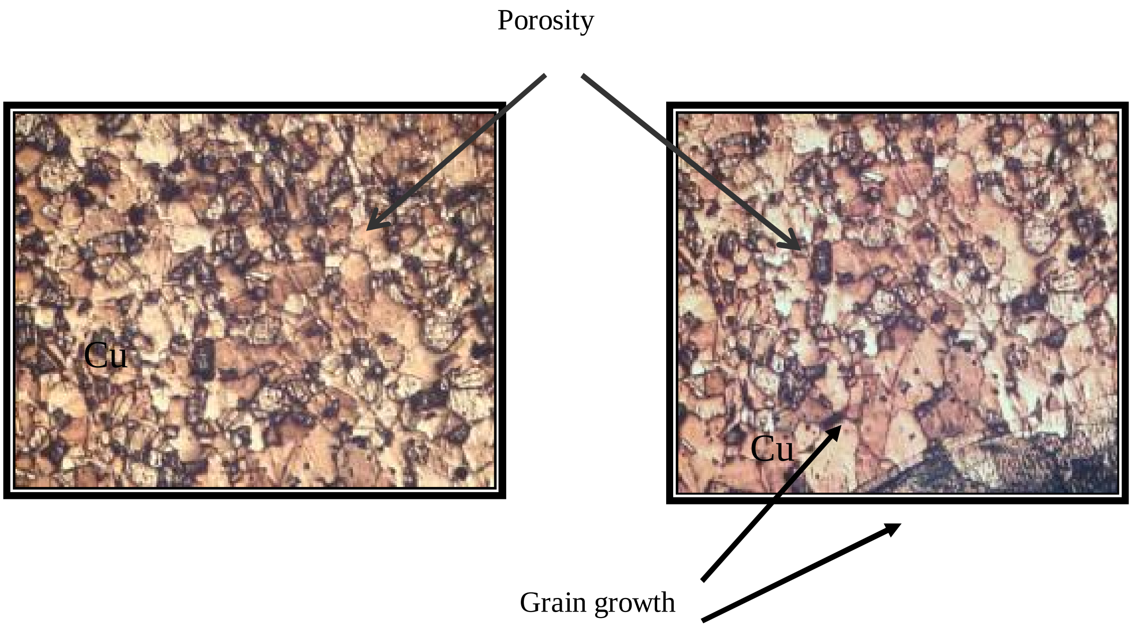


Figure (10- a) **Figure (10-b)**

Figure (10). Cu / C.St system with ER NiCu-7, GTAW. (c, d) Cu interface with ERNiCu-7, X 108. (e) C.St interface with ERNiCu-7, X 270. (f) C.St base metal, X 270.

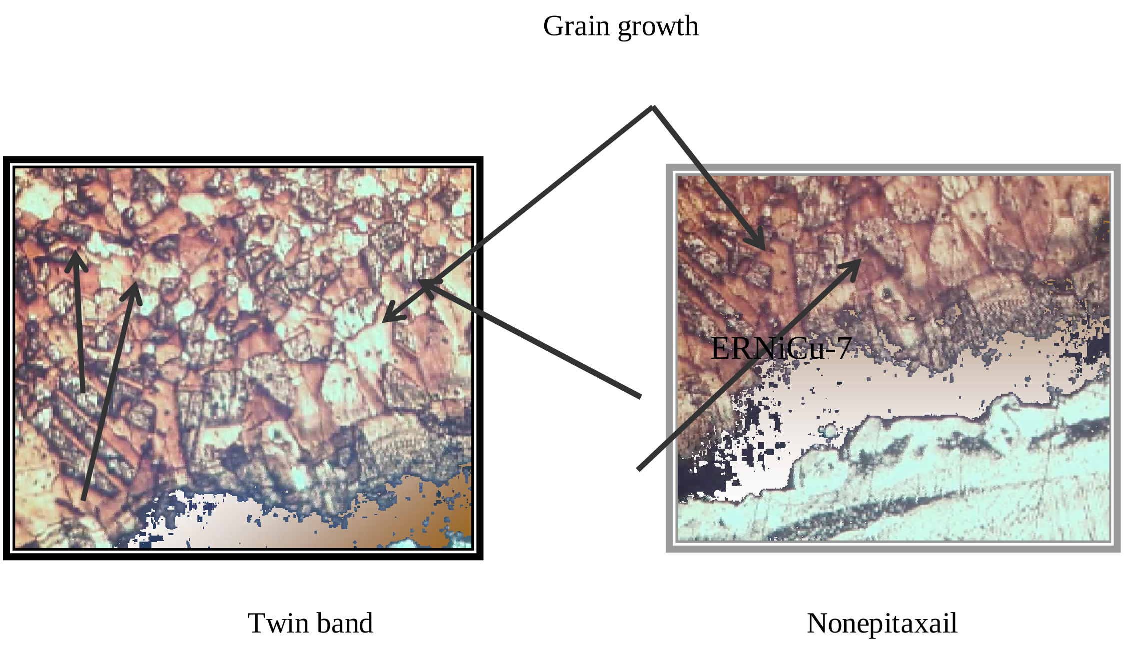


Figure (10-c) **Figure (10- d)**

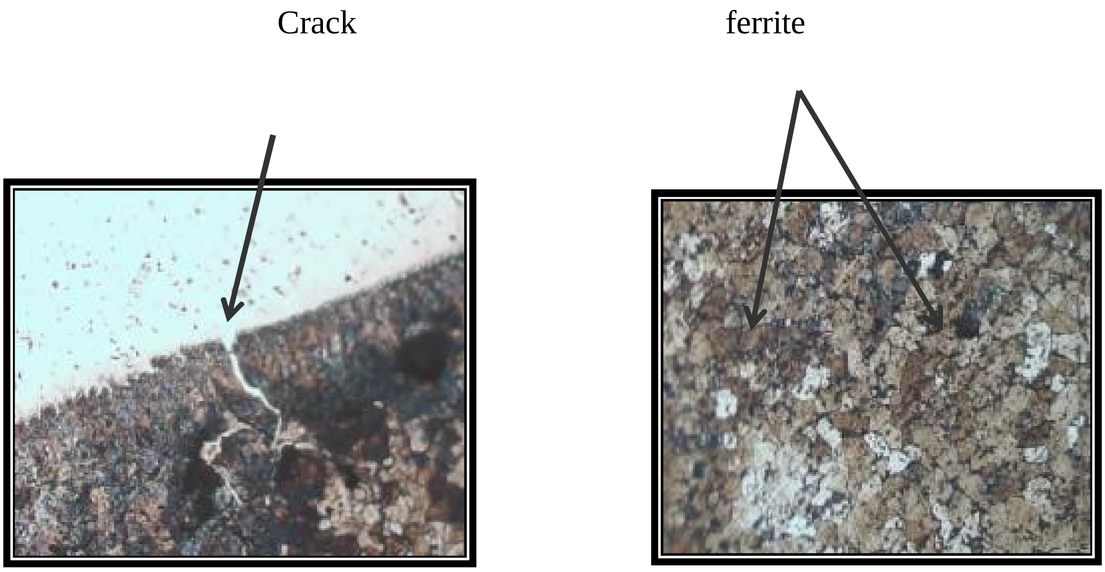


Figure (10- e) **Figure (10- f)**

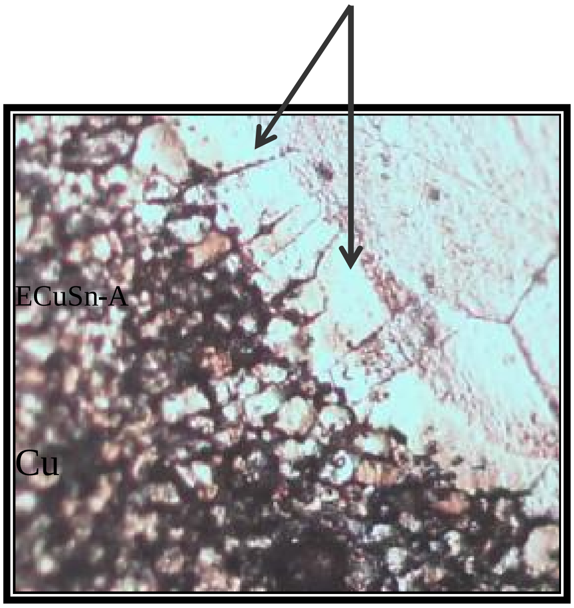


Figure (11- a)

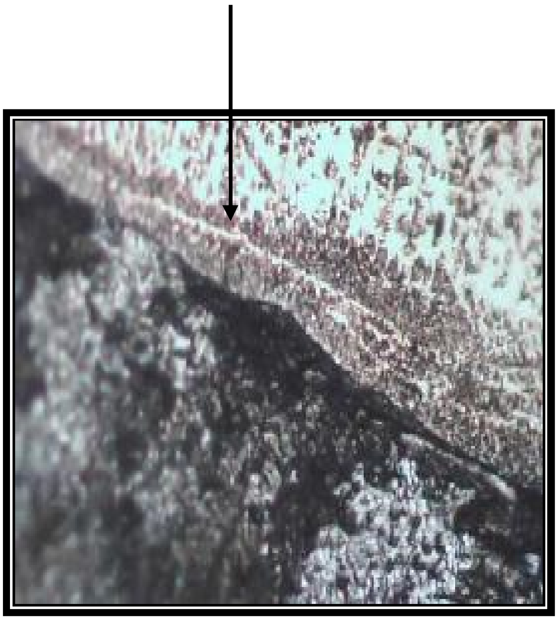


Figure (11- b)

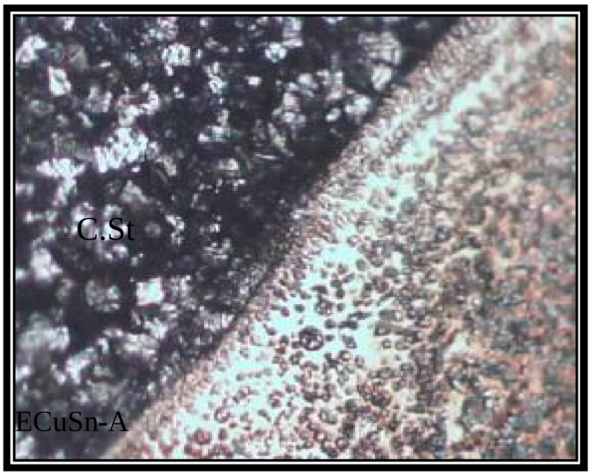


Figure (11- c)

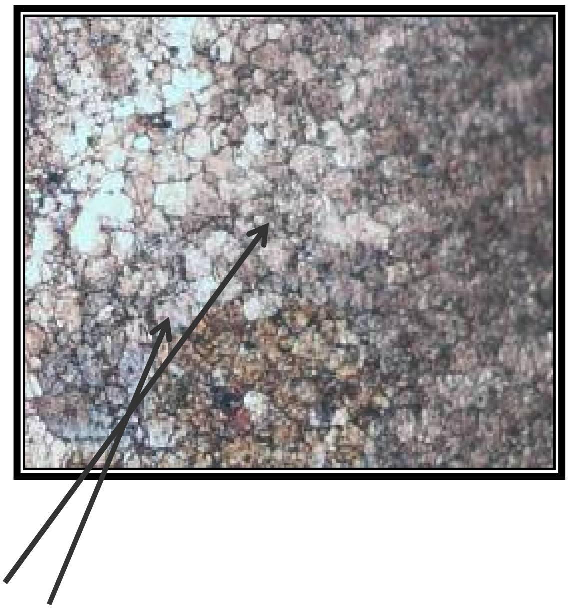


Figure (11- d)

Figure(11). Cu/C.St system with ECuSn-A,SMAW,(a)Cu interface with ECuSn,X 108.(b,c) C.St interface with ECuSn-A, X 108. (d)C.St base metal, X 270.

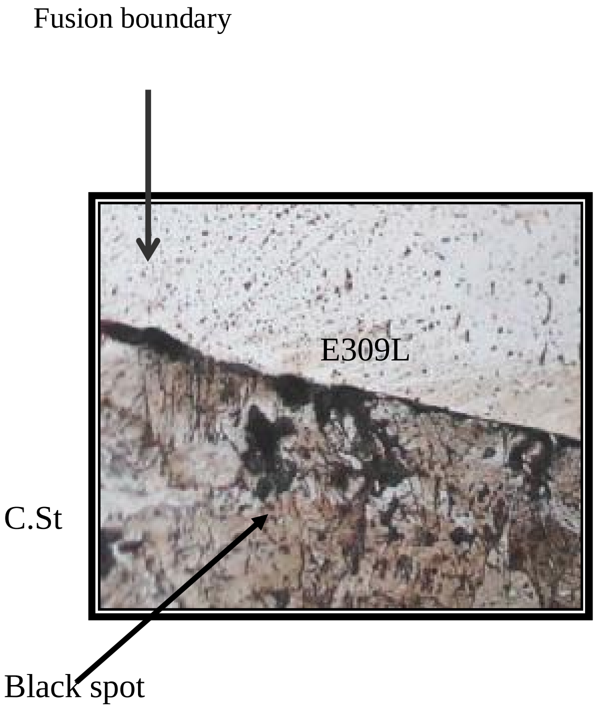


Figure (12- a)

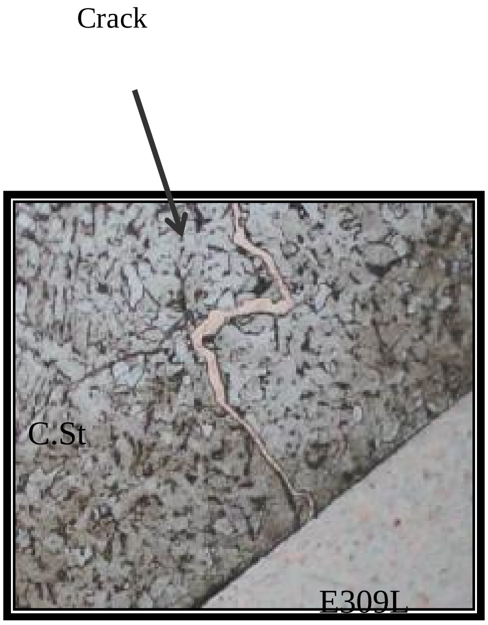


Figure (12- b)

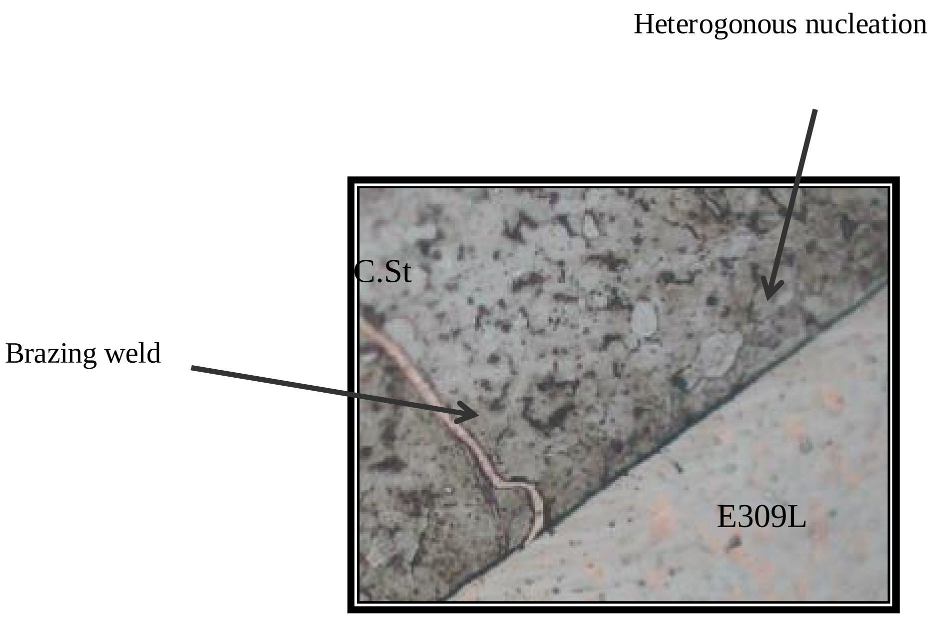


Figure (12- c)

Figure (12). Cu/ C.St system with E309L, SMAW. (a, b) C.St interface with E309L, X 108 .(c) C.St interface with E309L, X 270.

3.5 ECuweld deposits

The same welding mechanisms be shown with this filler , that an nonepitaxial nucleation with brazing action at the steel / filler side , while an competitive epitaxial growth from the copper / filler side . This clearly shown in the figure 13 , a , b and c for steel side , and 13-d , e , f and g for copper side .

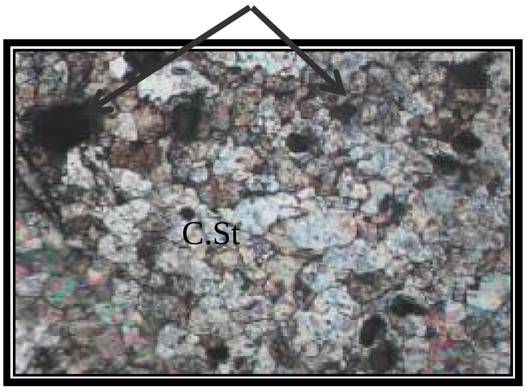


Figure (13- a)

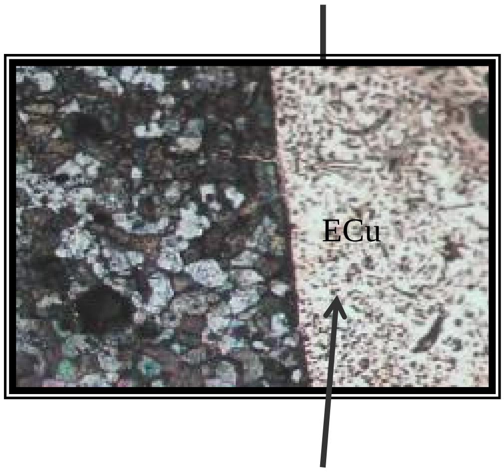


Figure (13-b)

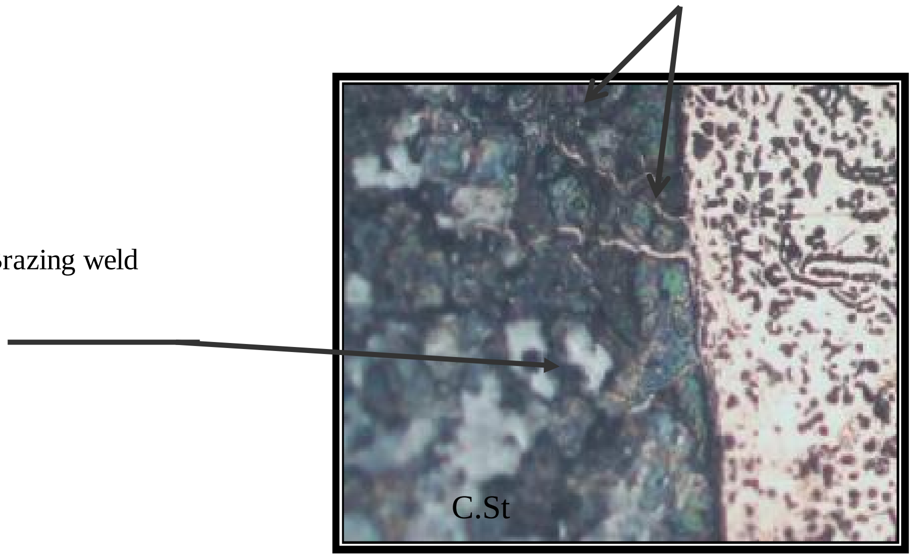


Figure (13- c)

Figure (13). Cu/ C.St with ECu, SMAW. (a) ECu ,weld metal, X 108, (e)Cu interface with ECu,X 108 . (f)Cu interface with ECu, X 270. (g) Cu base metal, X 108.

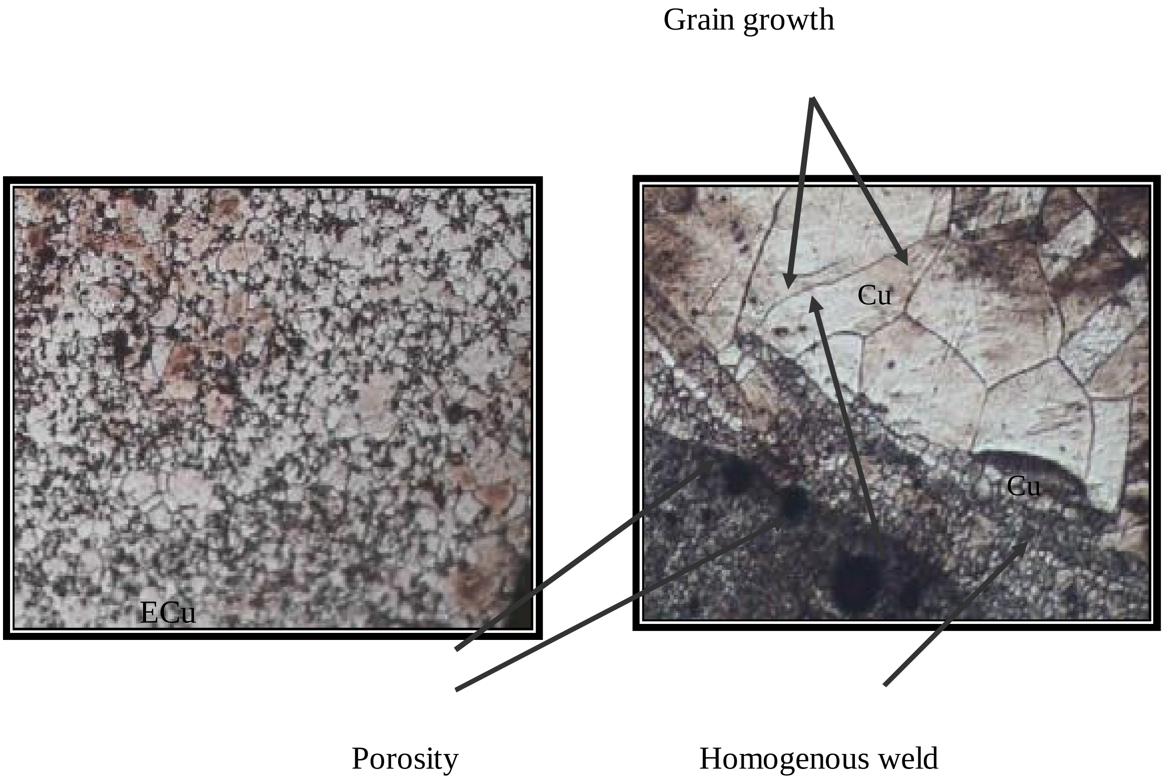


Figure (13- d) **Figure (13- e)**

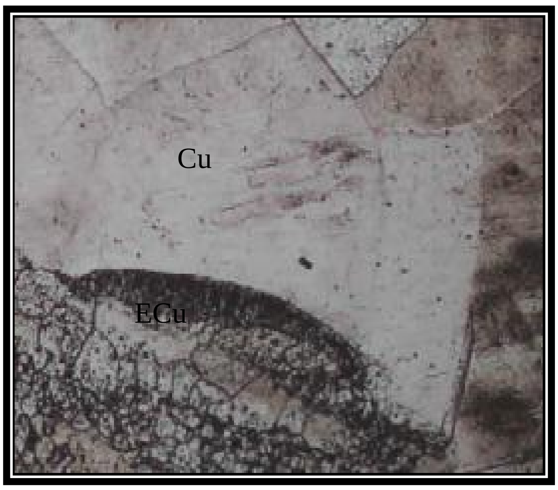


Figure (13- f)

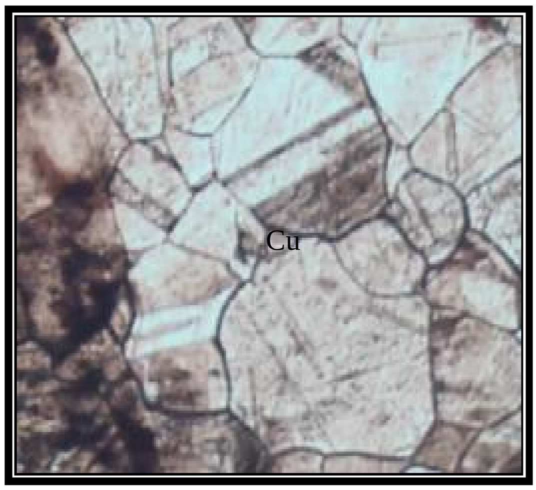


Figure (13- g)

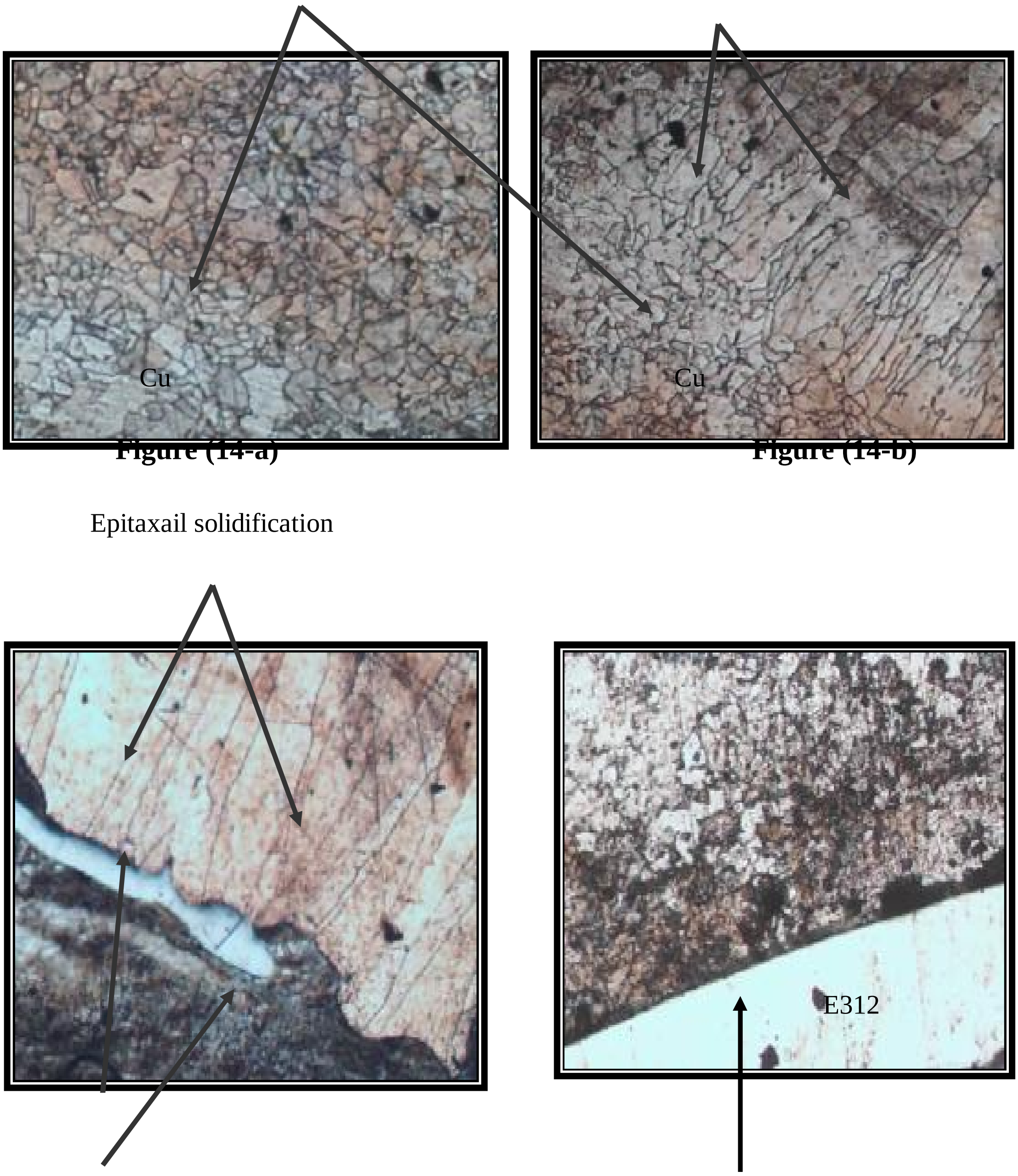
3.6 E312 Weld Deposits

Figure(14,b)shows an competitive growth in fusion line from the copper side, while filler / copper interface show hetrogenous nucleation with some of dissolution of E312 filler as appear in figure (4 , c).

3.7 ENi-1 Weld Deposits

This filler show excessive dissolution at the copper side with competitive epitaxial growth , while nonepitaxial nucleation from the steel side as shown in figure (15).

Equaixed columnar crystal



Dissolution for E312 Heterogeneous nucleation

Figure (14-c) **Figure (14-d)**

Figure (14). Cu/C.St with E312, SMAW. (a, b) Cu base metal, X 108. (c) Cu interface with E312, X 108. (d) C.St interface with E312, X 108.

3.8 ERNiCrFe-5 Weld Deposits

This filler shows an hetrogenous nucleation from both sides , copper / filler and steel / filler as appear clearly in figure 16 . Some dissolution of this filter in copper side will help to produce nonpitaxial solidification as in figure 16 – e .

3.9 Results of Tensile and Bend Test

The results obtained from the tensile and bending tests are equal the properties of copper , this result document that welding procedure is well because that all failure happen at copper side as shown in the figure (17 and 18), which represent the properties of copper . While bending shows no difference in bending properties for all joints (Figure 19 and 20) .

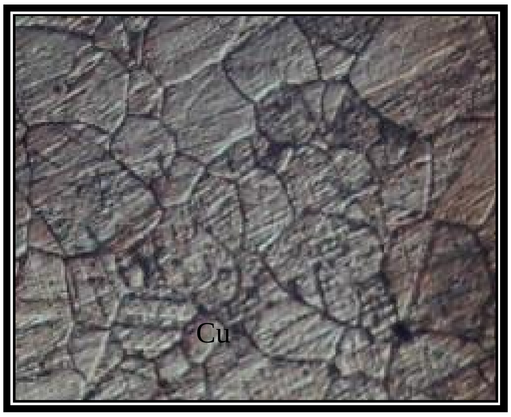


Figure (15-a)

Transformation zone

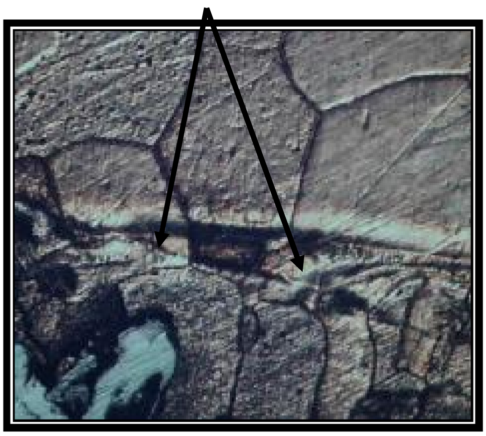


Figure (15-b)

Figure (15). Cu/C.St with E Ni-1, SMAW.(a)Cu base metal ,X 108.(b,c,d)Cu interface with ENi-1,X 108.

Competitive solidification

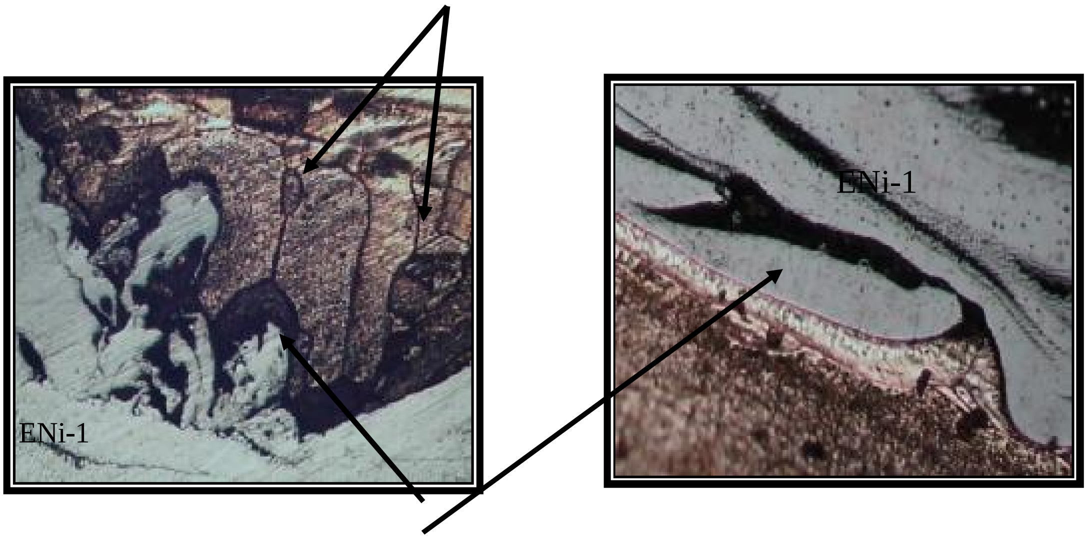
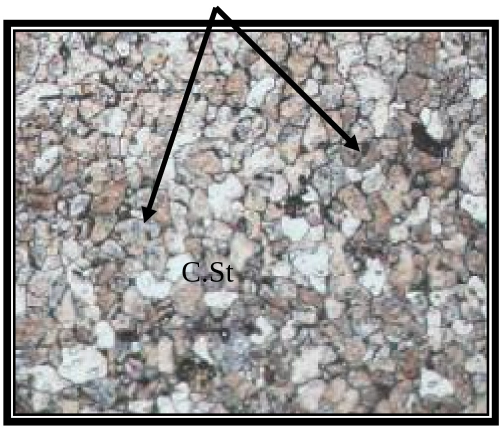


Figure (15-c) Dissolution for ENi-1 **Figure (15**-d)

Ferrite



particleoxide

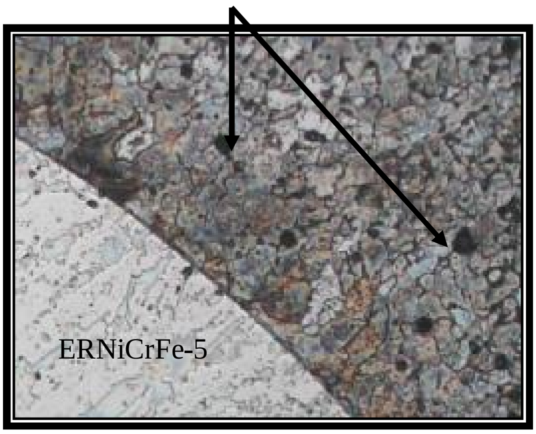


Figure (16-a) **Figure (16-b)**

Figure (16). Cu/C.St with ER NiCrFe-5, GTAW.(e) Cu interface with ERNiCrFe-5, X 108.(f) Cu base metal , X 108.

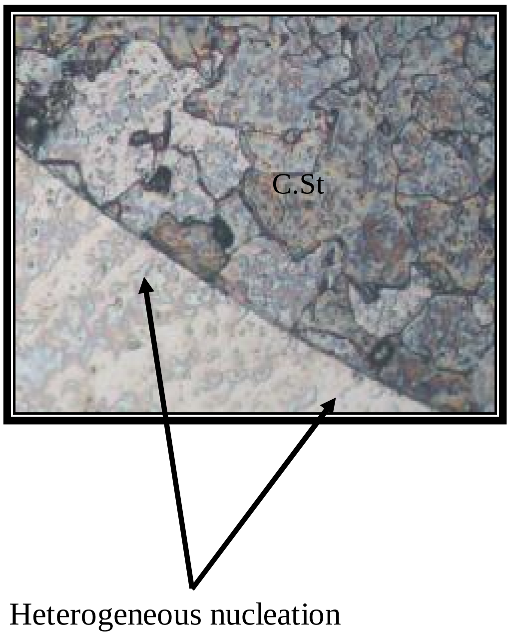


Figure (16-c)

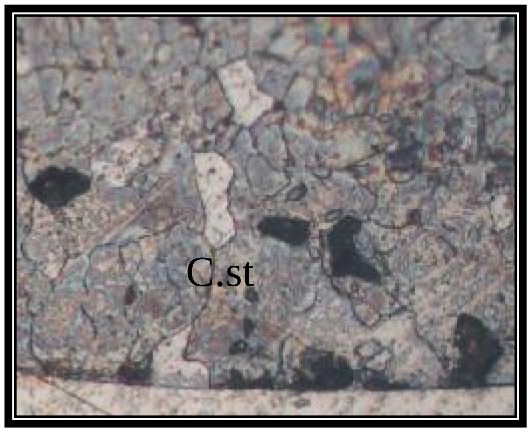


Figure (16-d)

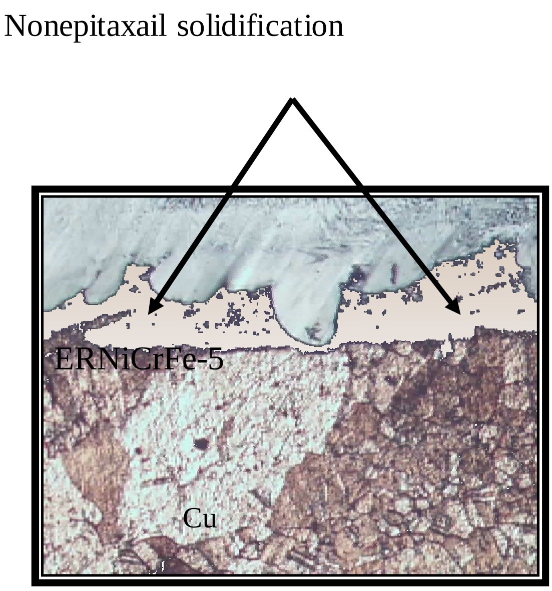


Figure (16-e)

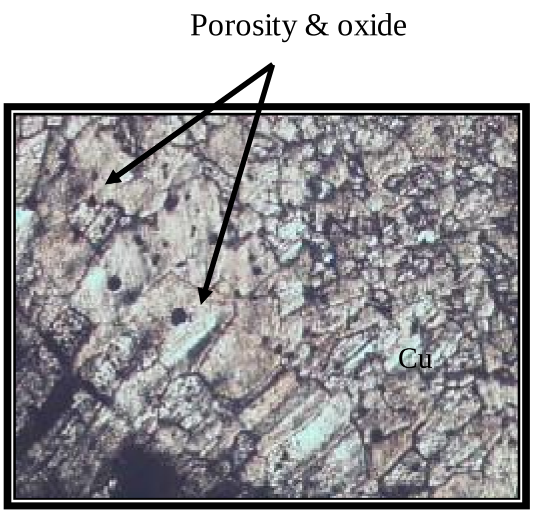


Figure (16-f)

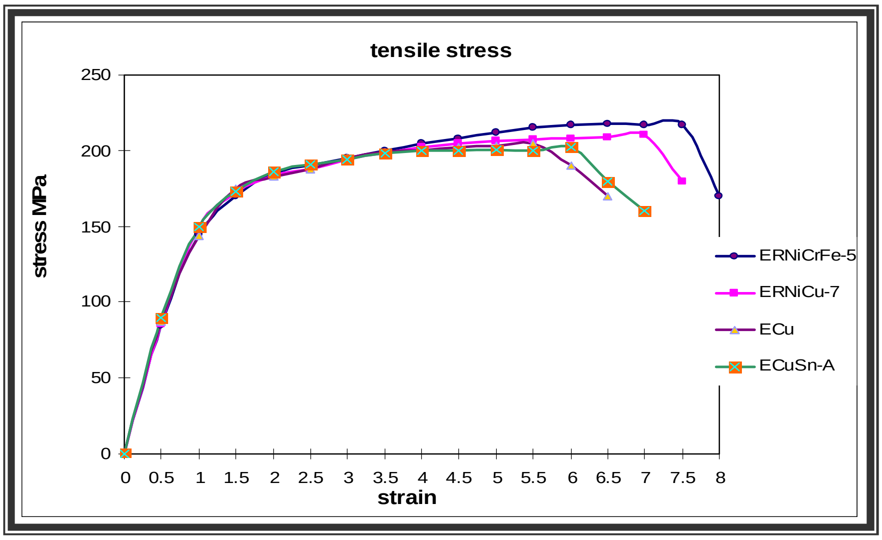


Figure (17). Tensile test data for copper / steel weldments by SMAW and GTAW processes using different filler metals (FMA).

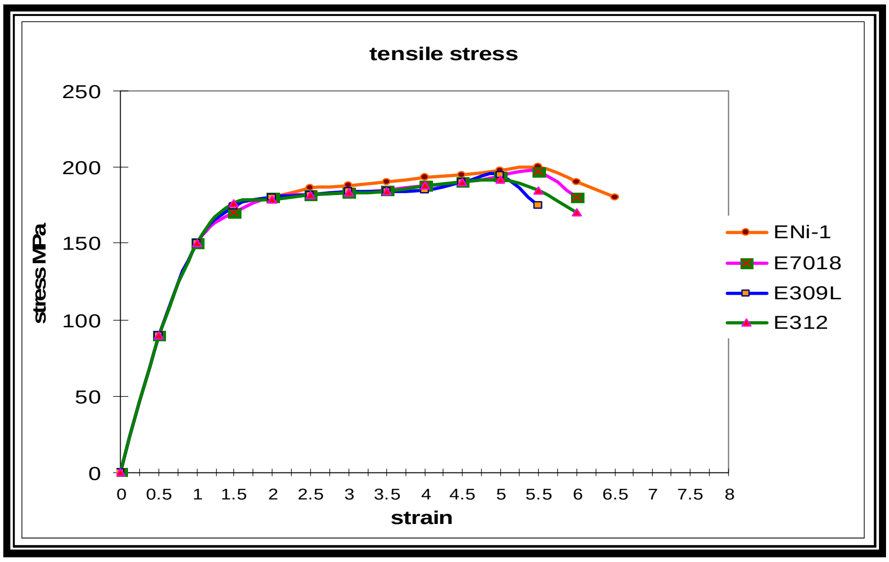


Figure (18). Tensile test data for copper / steel weldments by SMAW and GTAW processes using different filler metals (FMA).

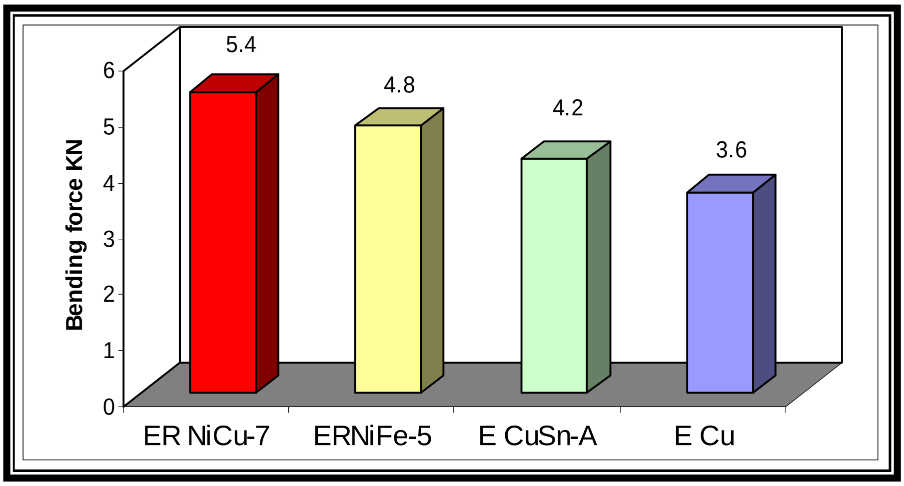


Figure (19). Bending test data for copper / steel weldments by SMAW and GTAW processes using different filler metals (FMA).

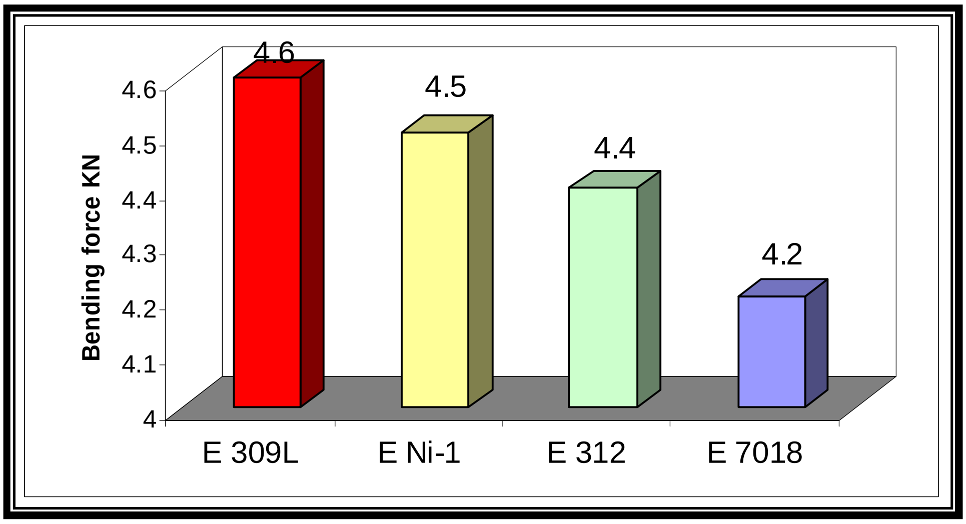


Figure (20). Bending test data for copper / steel weldments by SMAW and GTAW processes using different filler metals (FMA).

3.10 Bonding Mechanism

From joining of copper/steel system by using arc welding (SMAW and GTAW) , the bonding mechanism is as follows :

A. The arc is causing high dissolution or high mobility between dissimilar metals .

B. Because these metals are dissimilar , there is low affinity between them as compare with same filler / metal . This will results in segregation or separation between the mixed weld .

C. This will result and create a hot cracks (solidification cracks) almost at steel side .

D. Cracks will filled by copper liquid in a process like brazing .

E. Brazing happens after steel has solidified , then brazing start because part of filler and copper are not yet solidified .

F. The final stage is the closing of steel side cracks by capillary action of brazing causing the returned of strength of the joint .

4. Conclusions

Joining of copper and steel can be accomplished by using different electrodes by using SMAW and GTAW processes . Different solidification types can happen when using different filler and different welding processes .

Solidification cracks appear on the steel side of the weld when using any of the three following electrode ERNiCu-7 , E-309L , and ECu .

Brazing welds happen after steel solidification , the brazing mechanism takes place because the filler / copper have not yet solidified .

Brazing process is an intermediate process that helps strength to return to weld joints .

5. References

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