International Journal of Materials Lifetime, 2015, Vol. 1, No. 1, 20-28
Available online at http://pubs.sciepub.com/ijml/1/1/4

DOI:10.12691/ijml-1-1-4

Production of Copper-Aluminum Bimetal by Using Centrifugal Casting and Evaluation of Metal Interface

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Received January 16, 2015; Revised February 04, 2015; Accepted February 08, 2015

Abstract The purpose of current paper is production of Copper-Aluminum bimetal by using centrifugal casting and evaluation of Copper-Aluminum interface and also optimization for creating metallurgical interface with appropriate and minimum discontinues between metals interface. In this research the solidification time of primary layer is calculated on base of chornief relation and second melt after different timescales that changed the interface temperature, was casted. The background structure, elements diffusion and hardness depending on the temperature of casted copper in a mold and Aluminum casting with different primary Copper bases in 100°C, 200°C, 300°C, 500°C is evaluated. The results are shown that by decreasing temperature, brittle intermetallic structures losse and hardness decrease. Two things are important for creation of complete metallurgical bonding between two metals, first the Copper temperature before Aluminum decanting and second is the lack of impurities and metal oxides in bonding.

Keywords: *centrifugal casting, bimetal, interface, chornief relation*

Cite This Article: J. Nazari, M. Yousefi, M.S. Amiri Kerahroodi, N.S. Bahrololoumi Mofrad, and S.H. Alavi Abhari, "Production of Copper-Aluminum Bimetal by Using Centrifugal Casting and Evaluation of Metal Interface." *International Journal of Materials Lifetime*, vol. 1, no. 1 (2015): 20-28. doi: 10.12691/ijml-1-1-4.

1. Introduction

Some application requires components that are combination of several properties and a pure metal cannot meet this required properties, on it ́s own. Bimetals are one of the simplest sorts of metal composites and as it is clear from their name, are combined from two metals or metal alloys. These two metals or metal alloys form two layers which a metallurgical bonding (metal bonding) between them is established constitute a single piece composite. purpose of bimetals production is to create the integrated components comprises of two metal so that each metal offer its own unique properties. Existence of Metallic bond at the interface of two metal pieces causes accretion of component. These two metals together will complement each other in terms of mechanical properties, chemical, physical or economic [1]. In making metallurgical bimetals، the main thing is creation of metal bonding between two metallic components. Metallic or metallurgical bonding forms between two metal when it is eligible to approximate the existence atoms at near the interface of two metals that would create repulsive and attractive force between them [2]. The purpose of this paper is to product bimetals from this method and components which are casted with this method are generally cylindrical, ring, roller and tabular forms, but it is possible to cast the bimetal components with other shapes. chemical industries, petrochemicals, power plants, nuclear power plants and metals mining industries (Copper, Iron, Steel) are the most important usage of bimetal pipes which are produced with centrifugal casting. In these industries bimetal pipes are widely used for heat covertures, reformers, reactors, condensers, pumps, radiation tubes, furnaces and materials and Concentrates conveying [1,12].

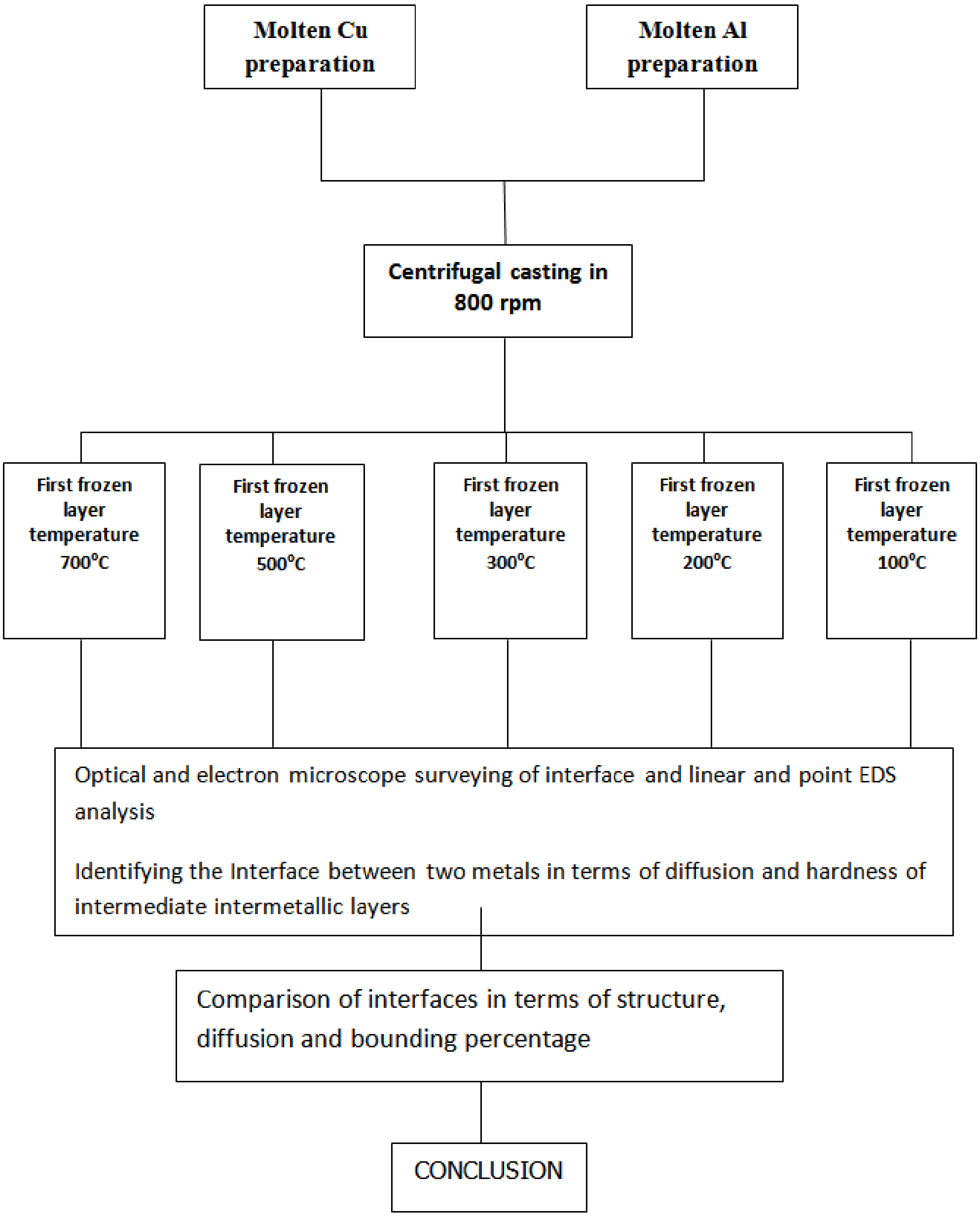
2. Experiment

Production of Aluminum-Copper bimetal from optimization of centrifugal condition for creation of metallurgical interface with appropriate structure and minimum discontinues at bimetal interface which is provided with material preparation flowcharts and experiments and also the results is taken.

3. Results and discussion

1. Centrifugal casting and melting equipments

Horizontal centrifugal casting set which is used in this research and is made specially has shown in Figure 1.



2. Melting equipments

Production of bimetals at least needs two furnaces which work simultaneously. For casting of produced ring by considering the mold volume, according to Figure 3-Figure 4 map amount of molten Copper and Aluminum were determined.

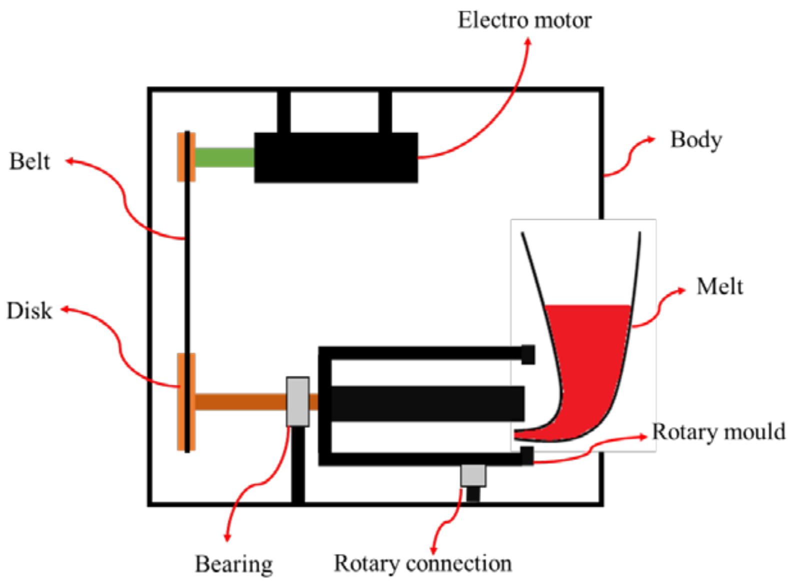


Figure 1. Schematic of Centrifugal casting machine

Figure 2. bimetal ring without dimension

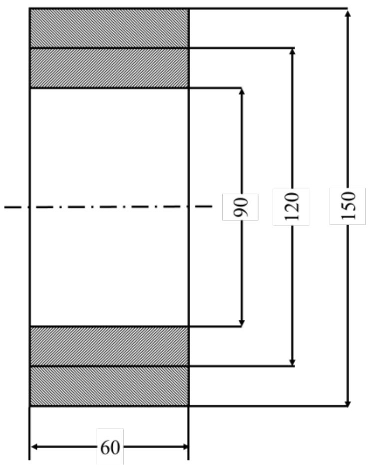


Figure 3. Map of bimetal ring

Therefore at first the Copper tube that should be casted firstly was containing certain volume. Also for considering the working tolerance, 5% extra volume has been added and total molten Copper volume has been considered 400 Cm^3. Therefore a ladle was prepared that accommodate specified volume and also for Aluminum casting, by considering below volume and 5% extra volume the ladle was prepared to accommodated Aluminum molten volume.

$$V = \frac{\pi}{4}\left(D^2 - d^2\right)\times L = \frac{3.14}{4}\left(12^2 - 9^2\right)\times 6 = 296.73\,cm^3$$

$$V = 296.73\times 1.05 = 311.56\,cm^3$$

3. Experimental method for measuring the K factor of Chornief relation

The K factor of mold for centrifugal casting that is used for producing bimetals in this research should be specified because the solidification time of produced ring could be determined through Chornief relation. The casting machine is containing Steel mold with short length and rotates freely in two headstock and ball bearing through a rotation adjustable system by electromotor. The mold of set is tabular form with internal diameter of 15 cm and external diameter of 18 cm and wall thickness of 1.5 cm. the type of set loading system is short studs type that melt is poured on small region at the beginning of mold and is directed to the mold. The rotation rate is adjusted on 800 rpm by using the (chamber land) diagram and two separate furnaces for melting the Aluminum and Zamak with specified information in Table 1 was prepared.

Table 1. the material used in production of bimetals

Pouring temperature	Operations performed on the molten metal	Chemical compound	Alloy
700°C	Covering the melt with coverall and dehydrogenation by degasser capsule	Al Si 13	Aluminum
700°C	Covering the melt by coal powder	Zn Al Cu Mg	Zamak 2

For the experimental measurement of K factor in case of Aluminum in the centrifugal casting mold with characteristics listed above, certain amount as 354/400 cm Aluminum melt was poured in the rotating mold and then in a short space of time but identified (11 second), after that certain amount of Zamak melt 356/311 cm was poured in mold. In a short and certain space of time, a part of Aluminum was solidified and other part of melt was still molten due to the difference between specific gravity of Zamak with Aluminum, Zamak put away the molten Aluminum and is solidified and then Aluminum is solidified simultaneously with Zamak. In Desired figures, Figure 4 this mater during Machining of produced ring and etching of sample by solution (2.5 cc Nitric acid, 1.5 cc Chloric acid, 1cc Hydrofluoric acid, and 95 cc distilled water) and a few drops of Cobalt was used for coloring Aluminum.

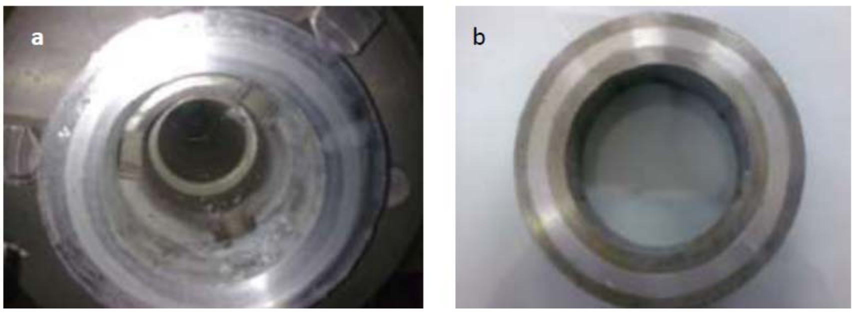


Figure 4. a) ring after machining b)ring after etching

In a Figure 4-a three layer ring of Aluminum \ Zamak \ Aluminum was during machining that layers are determined without etch.

Figure 4-b showed Aluminum layers are gotten dark after etching.

For calculating the K factor of mold, outer layer that is made by Aluminum, dividing the volume of layer to its surface (heat transfer surface) solidification module of outer layer is obtained solidification time of outer layer is interval between molten Aluminum and Zamak that was

11 second in the experiment. By using Chornief relation and determining the time (t) and A/V K factor can be calculated. So, by considering that the average thickness of outer layer in two layer ring is 5.5 mm and 11 second as a solidification time (time between pouring the melt), K factor for centrifugal casting machine produced in workshop is calculated.

(External area) outer layer diameter

$$D = 144\,mm = 14.4\,cm$$

(Internal area) internal layer diameter

$$d = 133\,mm = 13.3\,cm$$

(Primary) solidified layer thickness

$$e = 5.5\,mm\, e = \frac{D-d}{2} = \frac{144-133}{2} = 5.5\,mm$$

(Primary) layer length $L = 60\,mm = 6\,cm$

External area layer

$$A = \pi DL = 3.14 \times 14.4 \times 6 = 271.296\,cm^2$$

External layer volume

$$V = \frac{\pi}{4}\left(D^2 - d^2\right) \times L = \frac{3.14}{4}\left(14.4^2 - 13.3^2\right) \times 6 = 143.513$$

$$t = K\left(\frac{V}{A}\right)^2 \rightarrow K = \frac{t}{\left(\frac{V}{A}\right)^2} = \frac{11}{\left(\frac{143.5137}{271.296}\right)^2} = 39.3\frac{\sec}{cm^2}$$

$$K = \frac{39.3}{60} = 0.65\frac{\min}{cm^2}$$

$$\text{Solidification constant} = \left(\frac{1}{K}\right)^{\frac{1}{2}} = \left(\frac{1}{0.65}\right)^{\frac{1}{2}} = 1.24\frac{cm}{\min}^{\frac{1}{2}}$$

4. Melting and preparation of proper melts and casting of bimetal rings.

First, Copper and Aluminum in two separate furnaces are melted and degassed. similar to the below table with certain interval 5 bimetal rings was produced. During preparation of melt before each casting the mold is preheated and rises to 220°C and then coated with 3 mm thickness by casting sand with density of 1/4 gr/cm^3 which was contained phenolic glue. Coating of mold is made the extract of casted component easier and is reduced the thermal conductivity of the mold(melt could move more in mold before solidification) and moreover is increased the life of metallic mold.

Table 2. Bimetal rings casted in listed temperatures

Aluminum casting temperature	Copper temperature in machine	Time between to melts	Copper casting temperature	Sample number
700°C ± 10	700°C ± 5	21	1250°C ± 20	T700
700°C ± 10	500°C ± 5	32	1250°C ± 20	T500
700°C ± 10	300°C ± 5	54	1250°C ± 20	T300
700°C ± 10	200°C ± 5	83	1250°C ± 20	T200
700°C ± 10	100°C ± 5	92	1250°C ± 20	T100

According to Figure 5. the produced component is shown before machining.

Figure 5. produced component before machining

The surface of samples is machined. Figure 6. is Shown the samples after machining operation. In machining operation it has been tried to remove the lowest possible surface of sample during the machining.

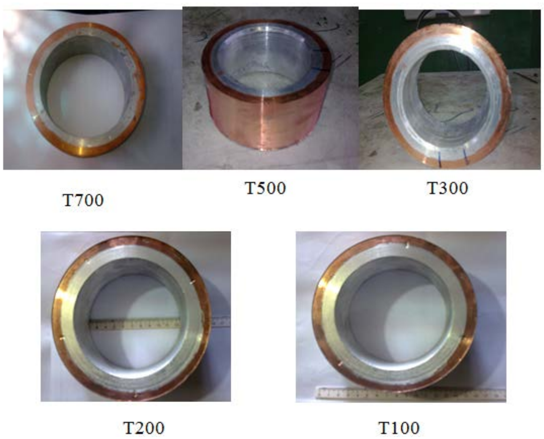


Figure 6. bimetal rings after machining

5. Samples preparation method

Casted bimetal rings were 6cm length, 14/4 cm outer diameter and 9 cm internal diameter and after machining diameters changed to the 14 cm and 9.5 cm. according to the Figure 7. Samples cuts for next experiments and after machining to reach the 6× 2×2 cm dimension from each ring 3 samples for analysis, optical microscope, electron microscope experiment and hardness test were separated.

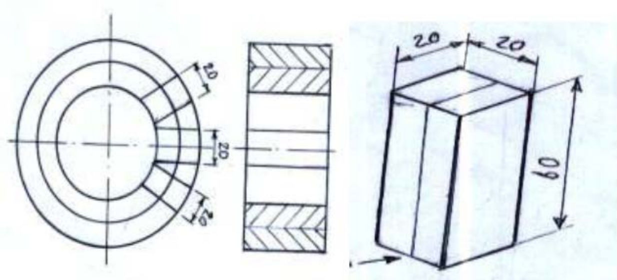


Figure 7. How to separate samples from ring bimetals

Figure 8. samples separated from ring bimetals

6. Microstructure and interface evaluation by optical microscope

The purpose of this evaluation is to determine the amount of bonding percentage that is created in interface and evaluation of intermetallic phases.

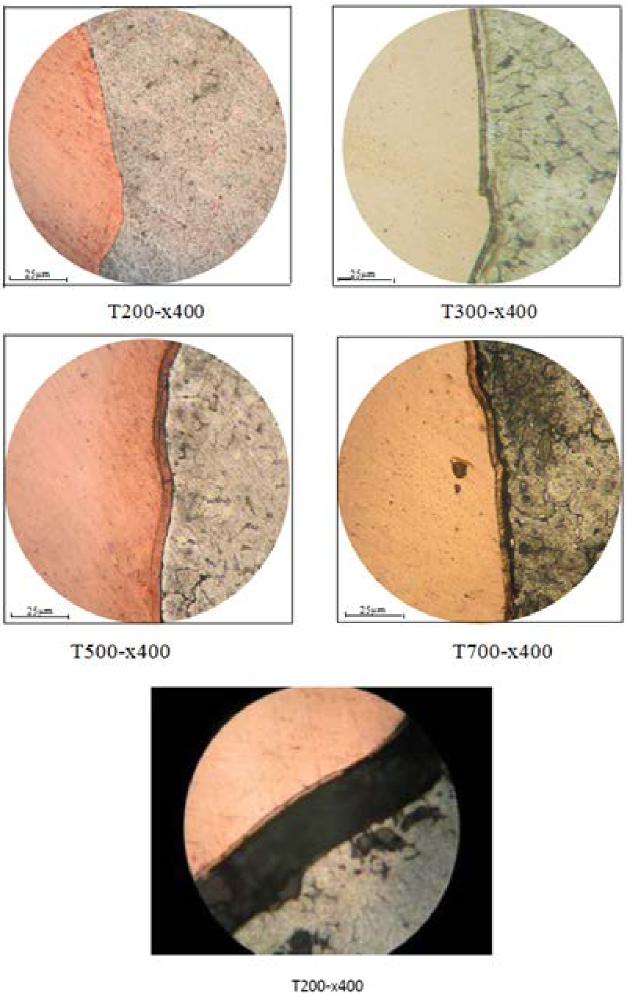
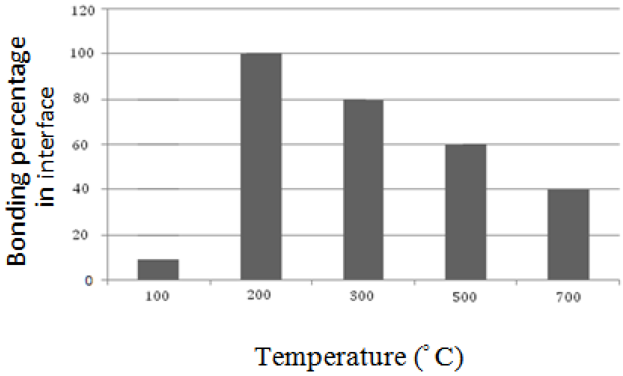


Figure 9. optical microscope images from metallurgical bond of 5 samples with magnification of x 400 from samples of T100 up to T700 that is etched with KOH 10%

According to the microscopic images it can be observed that the bonding percentage in Aluminum-Copper bimetal has been increased by decreasing the temperature and in 200°C bonding percentages reached to the maximum and the bonding width has been reached to the minimum about dc micron.



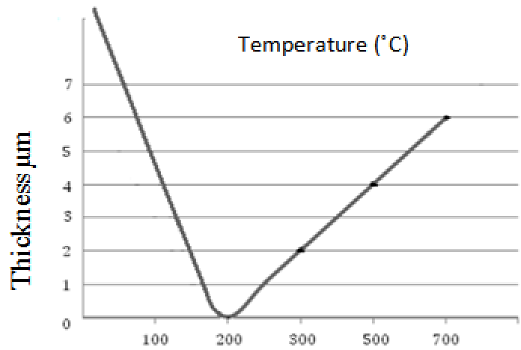


Figure 10. Bond width in bimetal boundary

According to Figure 10. in 200°C bonding width is in the metallic grain boundaries form it means that there is no width and it is approximately zero. And from 700°C to 200°C width has been decreased but in 100°C bonding width doesn't exist and impurities form this width.

7. Analysis of electron microscope images

The purpose of electron microscope Analysis is determining the intermetallic phases at interface and width of this phases and determining that the boundary is poly structure or single structure. Bimetal samples were analyzed by SEM type electron microscope.

According to SEM analysis:

1. The micro-structure of the samples was photographed at high magnification.
2. By linear analysis and point analysis, Distribution of a particular element can be obtained from specific locations.

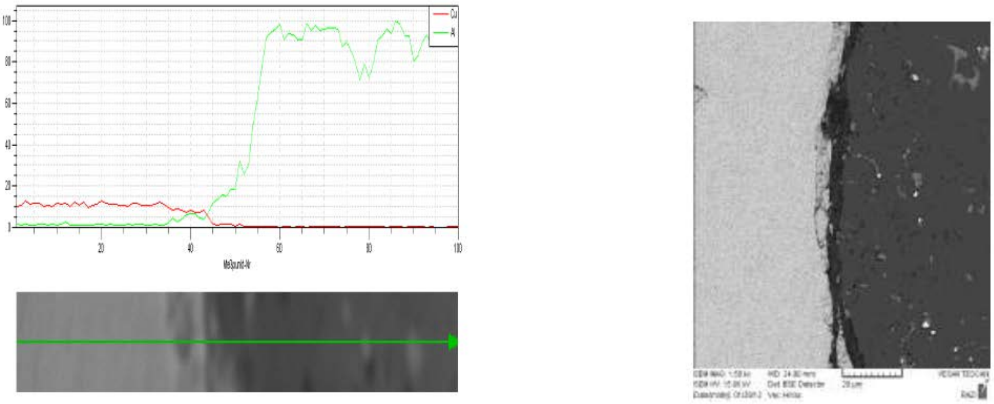


Figure 11. Images and linear analysis from sample number 1, T700

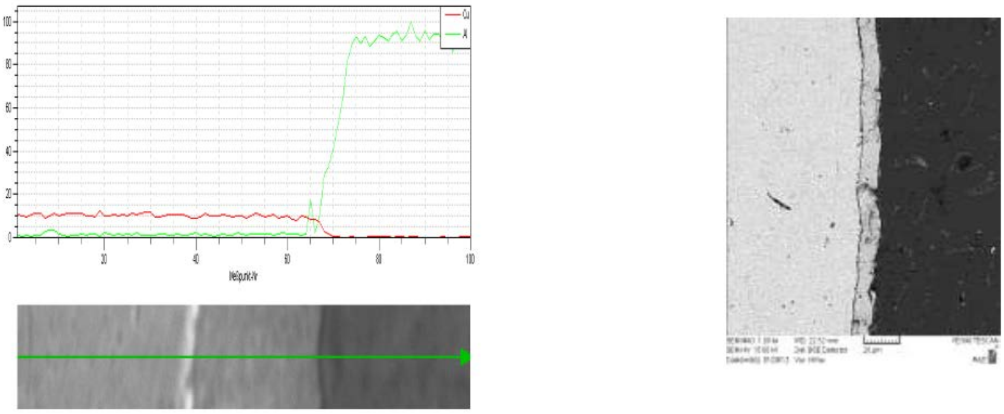


Figure 12. Images and linear analysis from sample number 2, T500

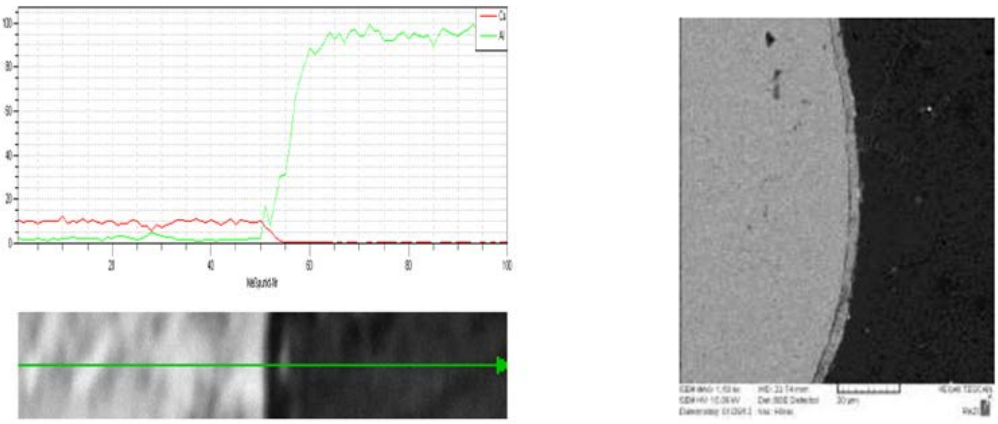


Figure 13. Images and linear analysis from sample number 3, T300

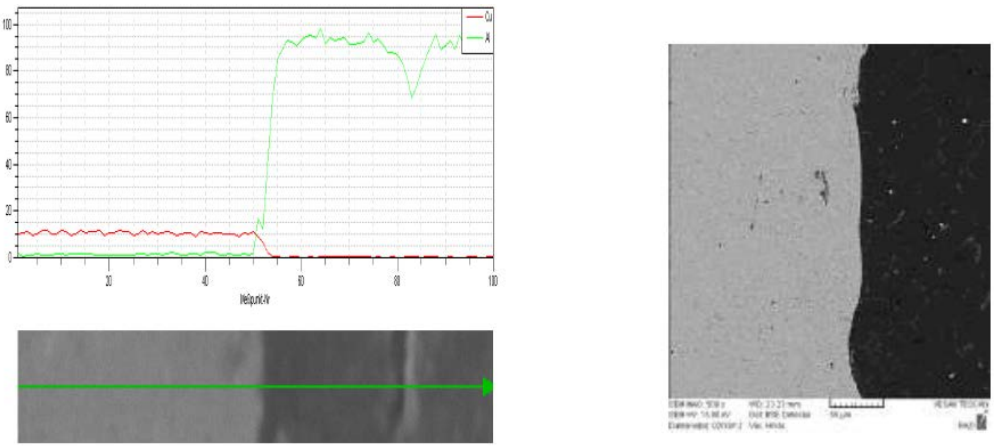


Figure 14. Images and linear analysis from sample number 4, T200

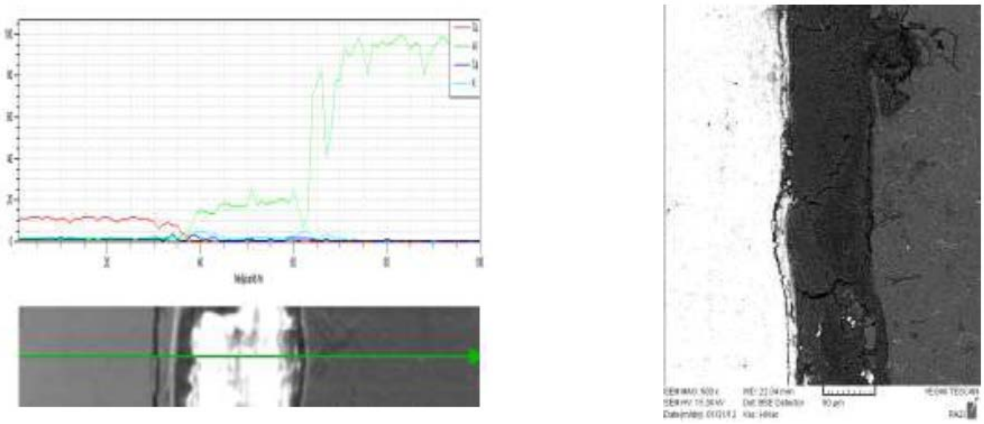
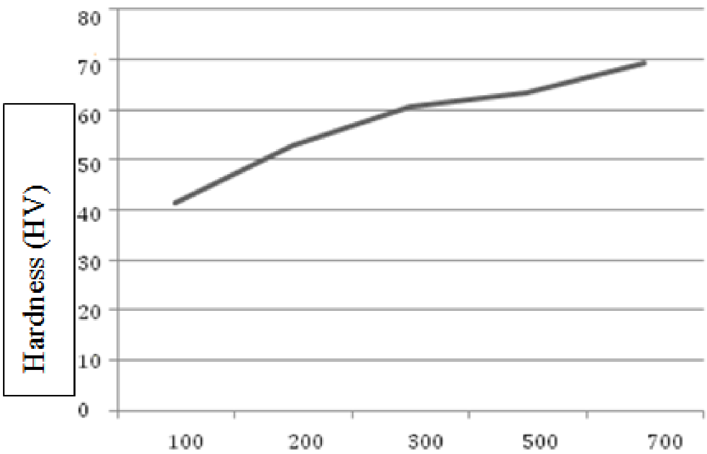


Figure 15. Images and linear analysis from sample number 5, T100

Table 3. EDS quantitative analysis of all samples in boundary(C points) for determining the ingredients of each intermetallic compound

Desired point	Cu atomic percentage	Al atomic percentage	Atomic percentage of impurites						Nearest intermetallic compound
			C	O	K	Ca	Si	Fe	
C-T700	78.30	88.68	-	-	-	-	-	34.0	CuAl (θ)
C-T500	85.91	15.8	-	-	-	-	-	-	Aluminum solid solution
C-T300	28.92	72.70	-	-	-	-	-	-	Aluminum solid solution in copper
C-T200	38.52	62.47	-	-	-	-	-	-	CuAl (η)
C-T100	45.00	27.21	85.00	69.00	54.50	9.20	-	-	There is no standard



sample	hardness
T700	68.46
T500	63.51
T300	60.65
T200	53.03
T100	41.40

Figure 16. Microhardness (HV) diagram at bimetal interface of Aluminum-Copper from 5 samples casted

In boundary survey between two metals in number 1 casted sample at 700°C determined that the bonding of this boundary type was a result of interphase, intermolecular and intermetallic compounds attraction and repulsion force. Strength of this type of bonding depends on forces between existence phases. These forces are usualy lower than nuclear forces. In the most cases intermetallic compounds are created new phases that are brittle and low strength. In this type of connection, intermetallic bonding and attraction and repulsion atomic forces are reached to it's minimum، mechanical, physical and chemical properties of intermetallic phase is completely different with two metal properties. According to the visual evidences and results of quantitative and qualitative analysis existence of brittle $CuAl_2$ intermetallic phase was characterized and hardness diagram of sample is proved that the hardness (68/46 HV) formed in the bond is more than Aluminum and Copper and the bonding percentage of border was approximately 40% that the width of boundary has been reached to the maximum value and is about 6 µm and therefore for producing the bimetals it should be tried to prevent the formation of intermetallic phases which is continuously put between two main metal.

In samples number 2 and 3 at 500°C and 300°C the boundary is polystructure and in transverse width between the base metal and atoms metallurgical bonding exists and diffusion accrued among atoms and new phases sporadically on the border between two base metals has arisen which can completely be observed as a bond in images of optical microscope because of heat or changing the elements density in width of boundary. In these types of boundaries, two major metal have no chemical affinity towards and intermetallic compounds is not created in samples number 2 and 3 and is transversed width due to length of interference structure formed with volume changes and the inner stress basin from tensile and shear type in the neighborhood boundaries is created which decreases the strength of boundary and semi interference structure which can be seen as band in an optical microscope is brittle and act as weak boundary and bond. The bond percentage in 500°C is about 60% and its transverse width is about 4 μm while by decreasing the sample temperature in 300°C the bonding percentage is shown about 80% and transversed width reaches to 2 μm.

In linear analysis and electron microscope images it is clear that the atoms are diffused and a structure is formed and in hardness of micro hardness it is clear that the hardness in boundary at 500°C is 63.51 and at 300°C is about 60.65 which is different with the main part of the metal and by escaping from boundary the hardness of main metal became visible. The Possible tensions in the border can be reduced with the help of thermal annealing and is created a balanced microstructure in boundary whatever the transverse width is decreased the better mechanical, physical and chemical properties would be resulted in binding region.

In sample of number 4 after set preparing and pouring the molten Copper, and reaching the Copper to the 200°C, then pouring the Aluminum in 700°C and cooling them, sample is excited and according to the optical and electron microscope images, the single structure and monolithic boundary is formed this boundary is created through diffusion between atoms of two metal and metal bonding exists between atoms. At this state there is no new phase and intermetallic compounds in boundary and intermediate layer between two metals.

In this bimetal mechanical, physical and chemical properties in the boundary are completely continued and they are the best possible bondings among bimetals. The boundary structure width is about a few tenths of a micron and the purpose to reach the monolithic boundary has been accomplished in this bimetal and diffusion between two metals just accrued in interface, it means that diffusion is accrued in surface and not in two metals volume. According to optical microscope images the bonding percentage is 100% and the boundary width between two metal is about a few tenths micron and its structure is like grain boundaries. The bonding between atoms is metal type and no new phase has been formed. Qualitative and quantitative analysis which are performed in the boundary are showed that the diffusion between Aluminum and Copper is only existed in the boundary and immediate in side of boundary the percentage of copper which was solved in Aluminum is reached to the zero and also the Aluminum percentage solved in Copper.

In accordance with hardness diagram of microhardness, the boundary hardness (53.03) and Copper hardness had no significant changes around the boundary and in Aluminum part the statue is the same as Copper.

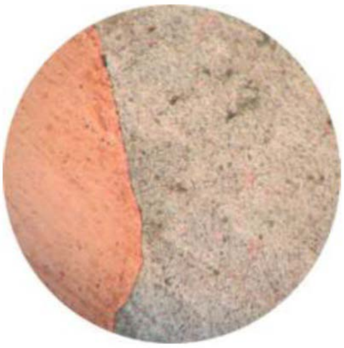


Figure 17. Optical microscope image from T200-X400 sample

In sample number 5 at 100°C according to the optical and electron microscope images, the metal oxides and protective oxides are glued to the Copper and molten Aluminum pressure couldn't exclude these metal oxides and be replaced with them therefore according to the results of micro hardness for sample T100 it can be seen that in boundary region due to impurities compounds and oxides, there is no special bonding but two metals are separated from each other and no bonding and diffusion is not created between them because of casting surface and border inequality, of course in a small part of sample bimetal compounds are existed but after that are replaced with metal oxides and bonding percentage is zero which is lower than pure Aluminum hardness therefore, in this temperature the border transverse width is more and it is most impurities.

4. Conclusion

The obtained results:

1- As the experiment has shown, two kinds of bimetals were produced with centrifugal casting method, which follows:

A. Aluminum –Copper Two layer bimetal and interface evaluation

B. Aluminum-Zamak- Aluminum three layer bimetal

2- Effective parameters on creation of metallurgical bonding between two metal in centrifugal casting were evaluated among different parameters specified temperature for the first metal and then pouring second metal creates a metallurgical bond with proper quality. If the temperature is too high the intermetallic compounds create at interface between two metal and if the temperature is too low metal oxides glues and cool the second melt and doesn't quiet the surface of two metal and no bond is formed.

3- In 200°C in two metal boundary, a monolithic bond is created and bond percentage was 100% and the width of it the same as its grain boundary and hardness is acceptable.

4- An experimental method for measuring the Chornief constant of noniron metal casting in centrifugal mold was obtained.

5- it was found in evaluation of Aluminum-Copper casted rings that the resulted metallurgical bond just occurred in a case that in length of tube about 60%-70% was interface and in interface shrinkage voids, metal oxides and pure metal bonding region exists therefore for creating appropriate metallurgical bond between Aluminum-Copper in centrifugal casting the surface of Copper should be clean, without oxides, and also formed in occurs oxygen free environment.

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