Interface Structure and Elements Diffusion of As-Cast and Annealed Ductile Iron/Stainless Steel Bimetal Castings

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Abstract—**Bimetal casting is considered to a promising technique for the production of high performance function materials. Heat treatment process for bimetal castings became an essential tool for improving interface structure and metallurgical diffusion bond. Molten iron alloy with carbon equivalent of 4.40 is poured into sand mold cavities containing solid 304 stainless steel strips insert. Specimens are heated to 720^{0}C in an electrical heating furnace and holded at 720 ^{0}C for 60min and 180min. For as-cast specimens, a good coherent interface structure of ductile cast iron/304 stainless bimetal with four layers interfacial microstructure are obtained. Low temperature annealing at 720^{o}C has a significat effect on the interface layers structure, where, three layers of interface structure are obtained after 180min annealing time because of the complete dissolving of thin layer of ferrite and multi carbides (Layer 2). Low temperature annealing shows a significant effect on the diffusion of C and otherwise shows slightly effect on the diffusion of Cr and Ni. Plearlite phase of Layer 3 is trsformed to spheroidal shape instead of lamallar shape in as-cast bimetals by low tempeature annealing at 720^{o}C. The percent of the performed spheroidal cementit increases by increasing anneaaling time. Hardness of interface layers is changed by low temperauture annealing due to the significant carbon deffussion.**

Keywords-annealing; interface; bimetal; stainless steel; ductile iron; composite

I. INTRODUCTION

The demand for excellent physical, chemical and mechanical properties and for long life time of spare parts is still an issue in many industrial applications. A single material cannot satisfy all the high performance needs of long lifetime spare parts. In some applications, both high strength and high impact toughness are need. In other applications, wear resistance and corrosion resistance are needed. Bimetallic materials have been considered as advanced functional materials for their unique physical and mechanical properties. Referring to the species of application, the physical and mechanical properties of constituent metals should be considered for selecting high quality metals. The wettability, diffusion, melting temperature, thermal conductivity and thermal expansion of constituent metals should be suitable in order to bond with each other [1-4]. Bimetallic materials can be fabricated by joining of both similar and dissimilar metals. The selection of working surface layer and base of bimetallic material usually are depending on the proposed application. For bimetal materials, the two metals play different roles. The exterior alloy may be resistant to corrosion or wear and the interior alloy is the one with better machining or toughness properties. Nowadays, the bimetals have wide applications in fields such as radiators, reservoirs, bearings, pistons etc. [5–10].

Ductile cast irons (known as spheroidal graphite irons), are mainly heat treated to create certain matrix microstructures for specific mechanical properties that are not readily obtained in the as-cast conditions. Matrix microstructures usually consist of ferrite or pearlite or combinations of both in its as-cast condition, that mainly depending on cast section size, cooling rate and/or alloy composition. If maximum ductility and good machinability are desired and high strength is not required, ductile iron castings are generally given a full ferritizing annealing process. The microstructure is thus converted to ferrite, and the excess carbon is deposited on the existing nodules [11]. Fabrication of bimetal material that has both of higher impact toughness on one hand and corrosion resist (304 stainless steel) on the other, can serve in many industrial applications. However, the transition zone between metals has a great effect on the fabricated bimetal performance. Previous researches [12–13] stated that the properties of bonding bimetal products are greatly affected by the properties of a very thin transition zone of the metallurgical bonding interface, which is mainly influenced by the element diffusion behavior through it [14–17]. The influence of low temperature annealing on interface structure of gray iron/stainless steel bimetallic castings was investigated in [18]. It was found that low temperature annealing at 760°C changed interface structures [18]. However, influence of low temperature annealing on interface structure of ductile iron/ stainless steel bimetal casting is still ambiguous. In current study, the effect of low temperature annealing at 720°C on interface structure and elements diffusion of ductile iron/stainless steel bimetal casting composites are investigated.

II. EXPERIMENTAL METHODS

A. Materials

The iron alloy is melted in a medium frequency induction furnace. The molten iron alloy is inculcated with Fe–Si alloy and spherodized with Fe-Si-Mg alloy. Open mold cavities of 25.4x25.4mm^2 cross section and 250mm long were made in sand molds. 304 stainless steels strips of cross section of 5x 25.4mm width and 250mm long were grinded with 400 mesh emery papers and inserted in sand mold. Molten iron alloy with carbon equivalent of 4.40 was poured into the cavities that contained solid 304 stainless steel strips inserts. The chemical composition of final fabricated bimetal ductile cast iron (DI) and 304 stainless steels strips (304SS) are showing in Table I.

TABLE I. CHEMICAL COMPOSITION OF DUCTILE CAST IRON AND 304SS STRIPS, WT%

	C	Si	Mn	P	Cr	Ni	Mg	Mo
DI	3.55	2.51	0.62	0.03	0.08	0.02	0.04	-
304SS	0.03	0.45	1.51	0.03	18.8	8.74	-	0.04

B. Processing

All samples were cut from the bottom parts of solidified bars. Specimens of approximate dimensions 12.5x25.4x25.4 mm^3 were cut for low temperature annealing heat treatment as well as microstructure examination and microhardness measurements. Specimens were heated to 720°C in an electrical heating furnace with heating rate of 8.5°C/min. For ferritizing annealing and to study the effect of holding time at 720°C, specimens are dividied in to two groups. Specimens are holded at 720°C for 60min heating time (group 1) and for 180 min heating time (group 2). All speciemens were subjected to controled furnace cooling to 290°C tempeartue with low cooling rate of 1.67°C/min. Specimens were leter further subjected to furnace cooling to room tempeartue. The heating/cooling sequence is shown in Figure 1.

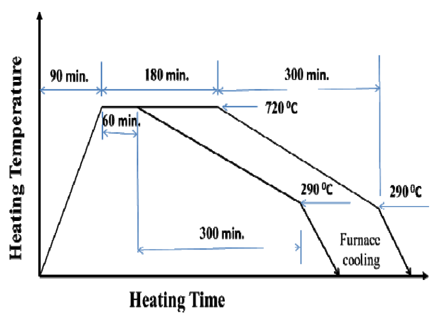

Fig. 1. Schematic illustration showing low temperature annealing heat treatment processes applied for bimetal castings.

C. Material Testing and Characterization

Specimens in both as-cast and heat treated conditions were grinded, polished and etched with a solution of 4% nital. Microstructural observations were performed using an optical microscope connected with advanced digital camera. As-cast and heat treated microstructural changes and interface structures were observed with scanning electron microscope (SEM) with energy dispersive X-ray spectrometry (EDS). Microhardness tests were performed using 0.25kgf loads.

III. RESULTS AND DISCUSSION

A. Microstructure

For higher strength with reasonable ductility, ductile iron region in bimetal ductile iron/304 stainless steel composite, annealing cycle can be varied to produce structures containing variety of percentages of mixed pearlite and ferrite matrices using reduced annealing times in the temperature range of 700°C to 720°C [11, 19]. Figure 2 shows the microstructure of ductile iron region of bimetal casting for as-cast and heat traeted ductile iron for annealing times of 60min and 180min respectively. It is clear that the matrix structure of as-cast ductile iron contains higher percentage of pearlite phases that changed to ductile iron with higher feritte percentage by increasing the holding time. Frrite percent increares with increasing annealing time due to dissociation of cemintite in pearlite phase to iron and carbon.

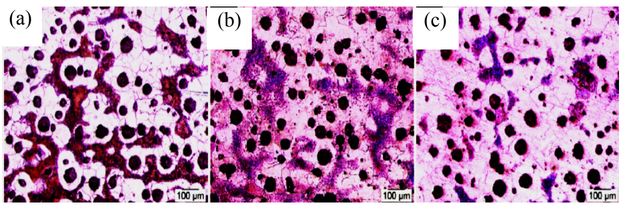

Fig. 2. Microstructure of ductile iron region of bimetal casting for a) as-cast, b) 60min annealing time, c) 180min annealing time.

Structure of interface region of as-cast and annealed bimetal casting are shown in Figures 3 and 4. Four layers interface in ductile iron/304 stainless steel bimetal casting are performed (see Figure 3a)). From stainless steel side, layer1 (austenite+carbide), layer 2 (ferrite+carbides), layer 3 (pearlite+carbide) and layer 4 (pearlite+ledeburite) are formed due to the diffusion of C, Cr and Ni from higher concentration sides to lower concentration ones (see Figure 5). Unlike the interface of gray iron/stainless steel bimetal casting [16] that contains a martensite layer, the current interface of ductile iron/stainless steel bimetal casting contains a pearlite layer. Low temperature annealing of ductile iron/304 stainless steel bimetal casting significantly effects on layer1, layer 2, and layer 3, for 60min. and 180min annealing time (see Figure 3b), 3c) and Figure 4 at higher magnification). Layer 4 is not affected by low temperature annealing. The annealing processes of ductile cast iron are mainly depended on the amount and type of carbides in matrix structure. Eutectic cementite in layer 4 needs a relatively higher temperature and longer time to be dissolved [11].

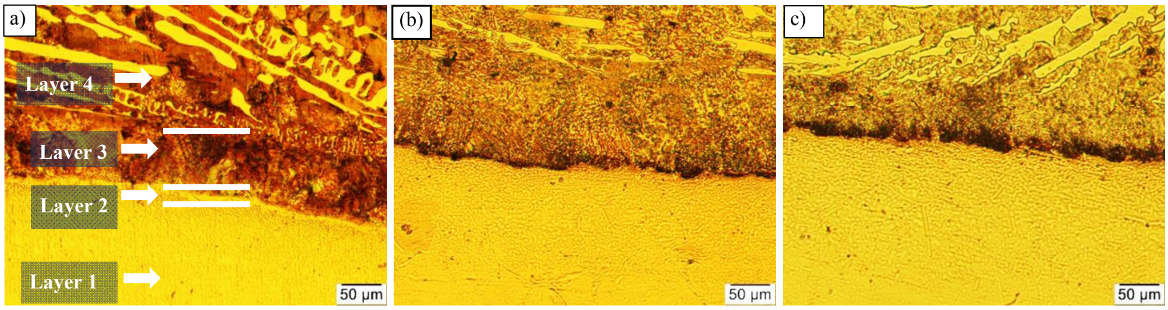

Fig. 3. Microstructure of interface region of bimetal casting for a) as-cast, b) 60min annealing time, c) 180min annealing time.

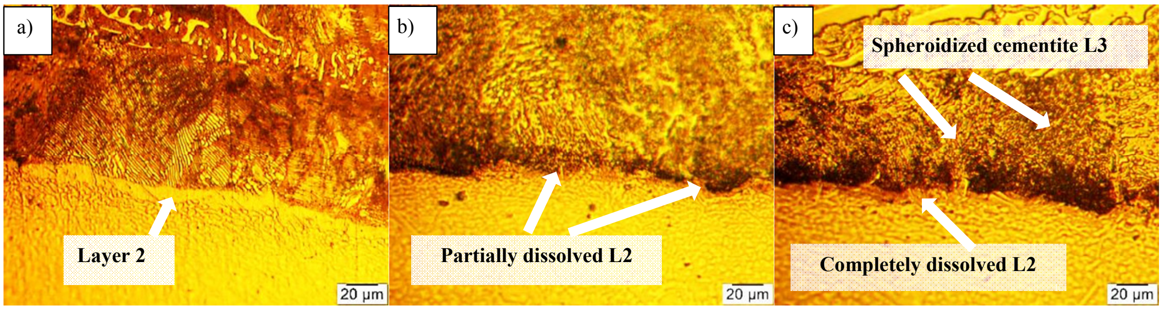

Fig. 4. Differences in annealed interface microstructures: a) as-cast, b) 60min annealing time, c) 180min annealing time.

Layer 2 (ferrite+carbides) partially dissolved and changed to discontinuous layer after 60min annealing time (see Figure 4). By increasing the annealing time to 180min, layer 2 completely dissolved. Pearlite morphology in layer 3 changed to be of spheroidal shape instead of the lamellar one that was presented in as-cast bimetal interface microstructure. Subcritical anneal that convert pearlite to ferrite by heating and holding single metal ductile iron at 705°C to 720°C [11] does not have the same effect in bimetal casting layer 3. Whereas, the current layer (layer 3) has a carbon content of 1.28%wt that considered as being hypereutectoid steel contains pearlite and some secondary cementite. Referring to previous research work [20] and by applying 720°C annealing temperature and maximum 180min annealing time, the microstructure of the typical lamella pearlite that performed in as-cast bimetal microstructure will be changed to spheroidized cementite pearlite. The percent of lamella pearlite that changed to spheroidal often increases by increasing annealing time.

Low temperature annealing of ductile iron / 304 stainless steel does not show a significant effect on the microstructure of layer 4 (pearlite+ledeburite). Eutectic cementite and/ or primary cementite usually need relatively higher temperatures and longer time to dissolve to ferrite and graphite. In order to heat treat ductile iron with carbides present, full annealing by heating and holding at 900°C to 925°C for minimum 2h and longer for heavier sections followed by controlled furnace cooling should be applied [11].

The structural changes occurring in the transition zone of ductile cast iron/stainless steel bimetals result from diffusion and redistribution of elements in the solid phase. It is well known that many reactions and processes important in the treatment of materials rely on the transfer of mass within a specific solid or from a liquid or another solid phase. The diffusion is a material transport by atomic motion. Figure 6 shows the interface of C, Cr and Ni distribution for studied as-cast and annealed ductile cast iron/stainless steel bimetal casting. It is clear that low temperature annealing at 720^{o}C has a significant effect on carbon diffusion in the transition zone between ductile cast iron and 304 stainless steel bimetal casting. By increasing annealing time from 60 to 180mins the diffusion rate of carbon from ductile cast iron side to 304 stainless steel side increases. On the other hand, the low temperature annealing does not show a significant effect on the diffusion of Cr and Ni from stainless steel side to ductile iron side.

There are two models for atomic motion in metallic materials. One mechanism involves the interchange of an atom from a normal lattice position to an adjacent vacant lattice site or vacancy and the other (model of diffusion) involves atoms that migrate from an interstitial position to a neighboring one that is empty. This latter mechanism fits the inter diffusion of carbon, nitrogen, and oxygen, as they have atoms small enough to fit into the interstitial positions. This can explain the significant effect of low annealing temperature on carbon atom form ductile iron side to stainless steel side. Layer 1 (austenite+carbide) in 304 stainless steel microstructure of bimetal casting for as-cast and low temperature annealing (720^{o}C for 60 and 180min, furnace cooling) is shown in Figure 7. It is clear that low temperature annealing has a significant effect on the structure and thickness of layer 1. Like the previous research on gray iron/stainless steel [18, 21], layer 1 thickness increases by increasing annealing time. Carbon interstitially diffused in austenite, which migrates from the whole volume of γ phase and after saturation to the grain boundaries and in connection with Cr vacancy diffusion from near border grain areas, $Cr_{23}C_6$ chromium carbides are achieved [21]. Besides the presence of this border carbides, they occur in the central areas of austenite grains. Layer 1 is easy to difine using nital etching metallographic specimens that appear explicitly in those areas due to decreasing of the corrosion resistance of containing $Cr_{23}C_6$.

B. Hardness

Hardness of interface layers of as-cast and annealed ductile cast iron/stainless steel bimetal casting is shown in Figure 8. It is clear that annealing at 720°C for 60 and 180min increases the hardness of layer 1 and decreases the hardness of layer 3 and layer 4. The relativelly high diffusion of C from ductile iron side to stainless steel side is the reason of these changes in hardeness measerments of bimetal interface.

IV. CONCLUSION

Casting and low temperature annealing heat treatment at 720°C of bimetallic castings of ductile cast iron and 304 stainless steel were investigated, which led to the following conclusions:

- Good coherent interfaces with multi-layers (4 layers) with different interfacial microstructure bimetal castings are produced.
- Three layers of interface structure are obtained after 180min annealing time due to the complete dissolving of the thin layer 2 (ferrite+multi carbides).
- Low temperature annealing shows a significant effect on the diffusion of C and slightly effect on the diffusion of Cr and Ni.
- In layer 1, C (carbon) interstitially diffused in austenite in whole volume of γ phase and after saturation migrates to the grain boundaries and in connection with chromium vacancy diffusion from near border grains areas.
- Plearlite phase of layer 3 for as-cast condition is transformed to spheroidal one by low tempeature annealing at 720°C. The percentage of spheroidal cementite increases by increasing the anneaaling time.
- Annealing at 720°C for both 60 and 180min increases the hardness of layer 1 and decreases the hardness of layer 3 and layer 4 due to the significant carbon deffussion .

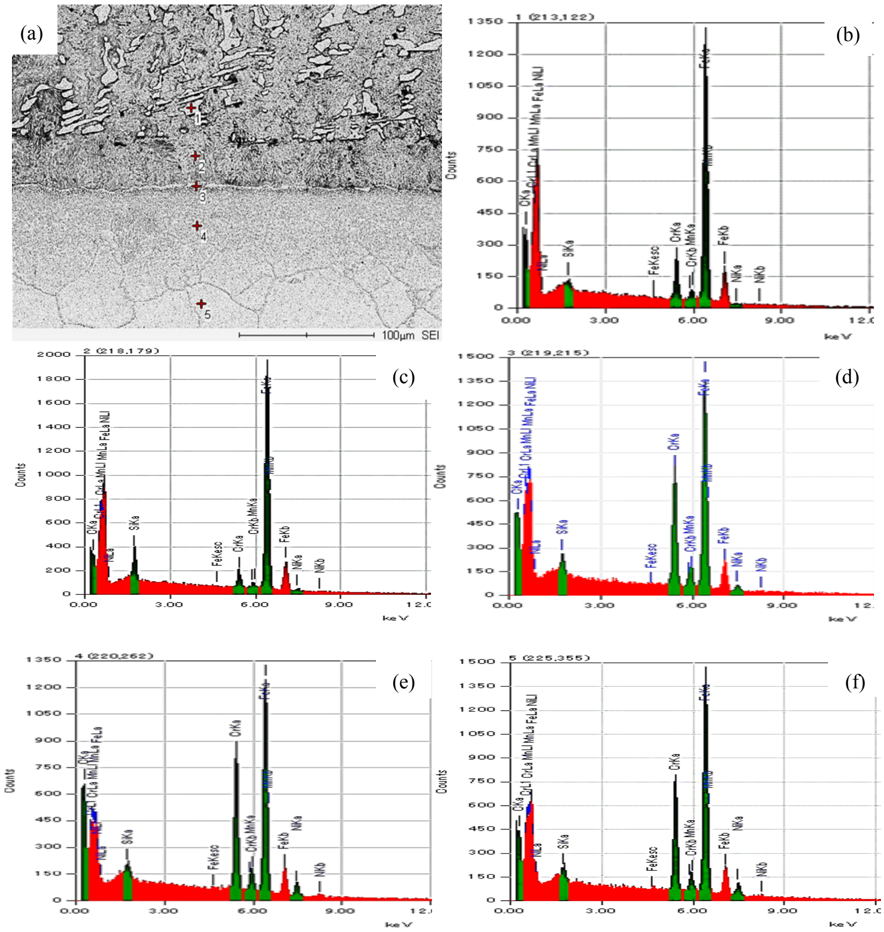

Fig. 5. EDS analysis for interface layers of as-cast ductile cast iron/stainless steel bimetal casting, a) as-cast interface microstructure, b), c), d), e) and f) are the point 1, 2, 3, 4 and 5 EDS analyses respectively.

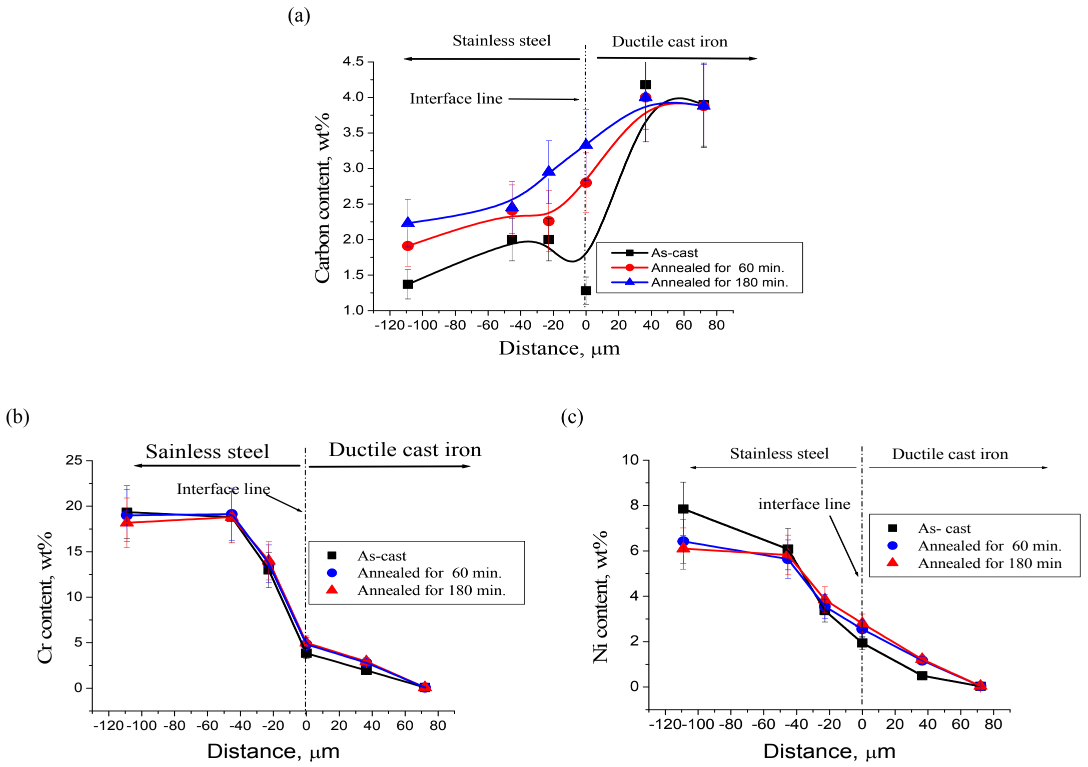

Fig. 6. Interface C, Cr and Ni distribution for as-cast and annealed ductile cast iron/stainless steel bimetal casting; a) C%; b) Cr% c) Ni%.

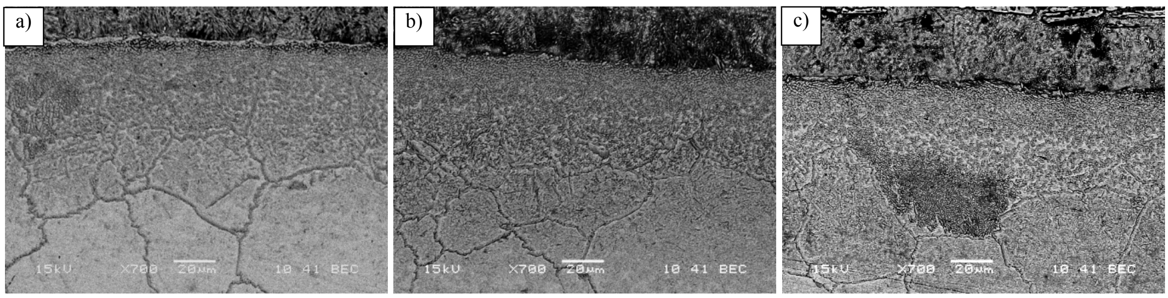

Fig. 7. Stainless steel region of bimetal casting for a) as-cast; b) 60min annealing time and 760°C annealing temperature and c) 180min annealing time and 760°C annealing temperature.

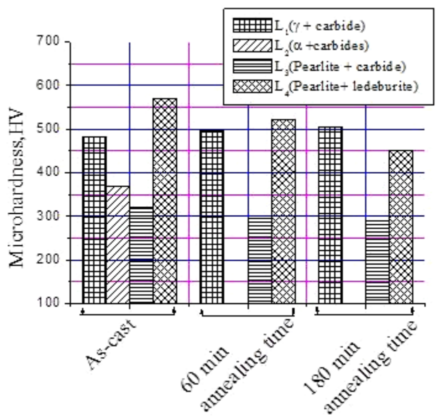

Fig. 8. Hardness measurments of interface layers of as-cast, annealed for 60min and annealed for 180min bimetal casting.

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