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Effect of post heat treatment on the microstructure and microhardness of diffusion coupled gray cast iron and low carbon steel

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Abstract. Experimental studies carried out on the joining of grey lamellar graphite cast iron to low carbon steel by diffusion welding techniques had successfully produced a few diffusion couples, despite facing some earlier failures. Although faced with some success, analysis on the diffusion couples showed voids and incomplete bond/joint at the interface of the joints while the tensile strength value was found to be low. In furtherance, the diffusion couples were then subjected to a post-weld heat treatment (PWHT) that allowed for further diffusion process to take place to remove the voids and complete the bond/weld. The results revealed microvoids and interface lines at the interfaces of the specimens treated at temperatures of 800^0C, and becoming less visible at 900^0C. At an elevated temperature of 1000^0C, on longer treatment times, apparently these microvoids and interface lines had disappeared, and the bond/weld at the interfaces of the diffusional welded couples seemed to be more complete. Thus, heat treatment time and temperature were found to have a strong influence on the structure, thickness and hardness of the diffusion layer produced.

1. Introduction

Grey cast iron and mild steel/ low carbon steel are two of the most common materials being used by various industries. Grey cast irons have found wide acceptance based on a combination of out-standing castability, excellent machinability, economics, and unique properties [1]. While mild steel/ low carbon steel is commonly used due to its good strength properties and relatively easy to fabricate such as by welding, it is usually used as structural materials.

At present, joining of cast iron to mild steel is generally performed by mechanical methods, such as bolting which adds to product weight, increases the number of process operations, and raises costs. An important contribution would be made to manufacturing industry through a capability being available for joining of cast iron to mild steel by welding [2].

Generally, cast iron which carries a good proportion of carbon, sulphur and phosphorous, is poorly weldable by fusion welding because it tends to crack in the vicinity of the weld zone, both during and after welding process [3]. While fusion welding of cast iron alone remains just as difficult to weld, in the context of cast iron being welded together with dissimilar material such as mild steel/ low carbon steel having entirely different properties such example their thermal expansion coefficients, their welding may result in distortion as well as crack formation[2].

Diffusion welding is a joining process between materials wherein the principal mechanism for joint formation is a solid state diffusion. Coalescence of the faying surface is accomplished through the application of pressure at elevated temperature. There is no melting and only limited macroscopic deformation or relative motion of the parts occurs during welding [4]. Diffusion welding is an attractive joining technique for the manufacture of precision apparatus and complex structures [5]. Diffusion welding is mainly used for joining of difficult to weld materials or when standard fusion welding methods cannot be used [6].

In previous works [7], preliminary studies on experiments conducted on joining of grey cast iron to mild steel/ low carbon steel by diffusion welding method had showed initial failures of few specimens. However, upon investigating and recognizing of each equipment's unique characteristics, some adjustments were made on the parameters and procedures of subsequent experiments that were found to finally produce significant visually good joints of diffusion couples.

Presently, diffusion couples produced are being subjected to the scanning electron microscopy (SEM) metallographic examination and energy dispersive spectrometry (EDS) to check for composition, weight concentration and tensile testing. Despite successful production of the diffusion couples, analysis had revealed voids and incomplete bond/joint at the interface of the joints, while the tensile strength value was found to be low.

Heat treatment allows the change in the microstructure and properties of investigated diffusional welded cast iron within a wide range of parameters [8]. Post heat treatment was found to have a strong influence on the micro-structure and micro-hardness of friction stir processed NiAL Bronze (NAB) alloy [9]. Furthermore heat treatment time and temperature were found to have a strong influence on the structure, thickness, inter-diffusion coefficients, composition and hardness of the diffusion layer of diffusional welded couples produced [10].

In furtherance of this study, the diffusional welded couples produced (although being of low quality in nature) were then subjected to a post weld heat treatment (PWHT) with the objectives, namely: (1) To remove voids and complete the bond/weldment by allowing further diffusion process to take place; (2) To investigate the effects of PWHT on the diffusion layers' microstructure, thickness and hardness values.

2. Material and method

2.1 Material

Types, grades, composition and the mechanical properties of the parent materials used in this study are as shown in Table-1 and Table-2.

Table-1.Chemical composition and mechanical properties of grey cast iron

	Chemical Composition (wt%)				
	C	**Si**	**Mn**	**P**	**S**
Grey Cast Iron (ASTM A48C 35)	3.43	2.21	0.62	0.073	0.069
	Tensile Strength (MPa)	**Elongation (%))**		**Hardness (HB)**	
	250	-		175	

Table-2.Chemical composition and mechanical properties of low carbon steel

	Chemical Composition (wt%)				
	C	**Si**	**Mn**	**P**	**S**
BS 449 grade 250	0.19	0.10	0.46	0.011	0.031
	Tensile Strength (MPa)		**Elongation (%)**	**Hardness (HB)**	
	408		35	195	

2.2 Method

With regards to the preliminary study [7], to date, five diffusion couples of grey cast iron to low carbon steel have been successfully produced by diffusion welding techniques. The equipment and the processes used to produce these diffusion couples were also described in the previous paper [7].

In the following study before conducting post weld heat treatment, few of these diffusion couples were then subjected to a scanning electron microscopy (SEM) metallographic examination and energy dispersive spectrometry (EDS) for a composition and weight concentration analysis and a tensile testing. For the tensile testing, the subsize test specimen was prepared as per ASTM standard's E8M-11. Room temperature tensile testing was carried out using a computer controlled Instron testing machine with a crosshead velocity of 0.15mm/minute.

A post weld heat treatment was conducted on a few specimens of the diffusion couples. The main parameters/variables that constitute the PWHT are temperature and time, and performed under atmospheric pressure. The temperatures selected are based on optimum recommended temperatures for diffusion welding process of the appropriate materials as this treatment is meant to allow for further diffusion process to take place. Hence the temperatures and times being chosen were 800^0C, 900^0C, 1000^0C and 2, 4, 8 hours respectively.

An apparatus was designed for the PWHT; the heating system is done through radiation consisting of a coil resistance furnace as the heat source, with appropriate switches and the instrumentation needed to set measure and monitor the desired treatment temperature and time.

After completing the PWHT, the specimens were then prepared for a metallographic examination. Photographs of the prepared metallographic specimens, in the vicinity of diffusion zones, along the bonding interface were then taken by optical microscope (OM). The metallographic specimens were also used for hardness testing. In this test, the micro-hardness tester of the Vickers hardness testing machine was employed. The hardness was measured across the bonding interface.

3. Results and discussion

3.1 Before PWHT

Figure-1 shows one of the successfully joined diffusion couples. The micrographs of few samples exhibit fairly good bonding along the interface of the welded joint with microvoids still present. Figure-2 shows one of the micrographs. From the micrographs, diffusion layer was observed on the low carbon steel side while on the cast iron side close to the interface, partial dissolution of graphite flakes was visible. From the energy dispersive spectrometry (EDS) results, as per Figure-3 and Table-3, a rapid diffusion of carbon occurs from the cast iron to the low carbon steel. From the tensile test, the strength value observed was indeed very low and the fracture was brittle in nature and suspected the joint/weld was incomplete. Figure-4 shows one of the fractured specimens.

Figure-1.Jointed diffusion couple

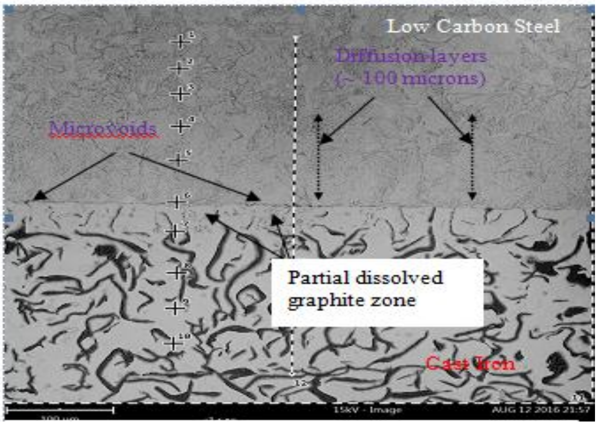


Figure-2.SEM Microphotograph of a diffusion couple (500x)

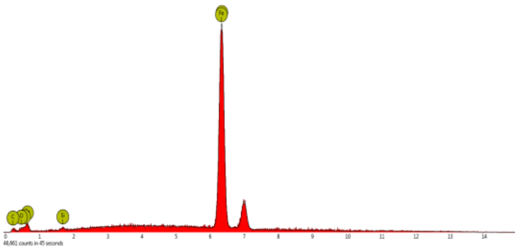


Figure-3.EDS graphic in interface region point 6, of Figure-2.

Table-3. EDS Composition and Weight Concentration at point 6, of Figure-2.

Element	Weight Concentration
Iron	96.5
Oxygen	0.7
Carbon	2.5
Silicon	0.3

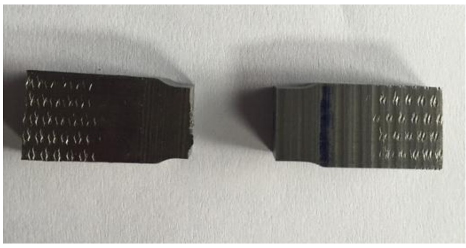


Figure-4.View of a fractured diffusion couple

3.2 After PWHT

3.2.1. Microstructure of diffusion layer. OM microphotographs of the diffusion zone of the diffusion couples between cast iron and low carbon steel after PWHT are as shown in Figure-5 and Figure-6. These photographs show the microstructures of the diffusion layer after a series of heat treatments, conducted under a combination of temperature of 800^{0}C, 900^{0}C and 1000^{0}C, and time at 2 hours, 4 hours and 8 hours respectively. Figure-7 shows the typical analysis of the interfaces and the diffusion layers of the heat treated diffusion couples.

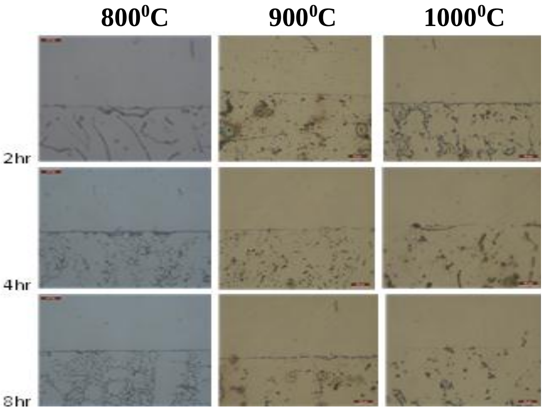


Figure-5.OM microphotographs of specimens after PWHT, before etching (500x)

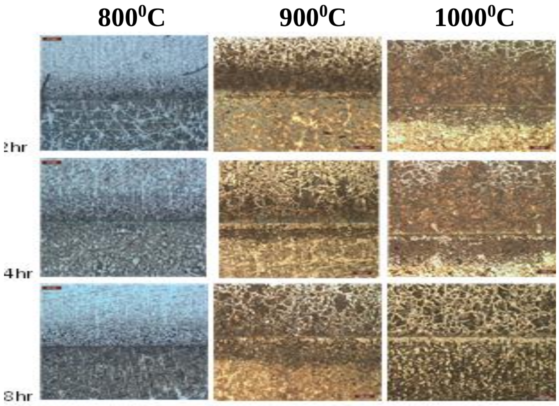
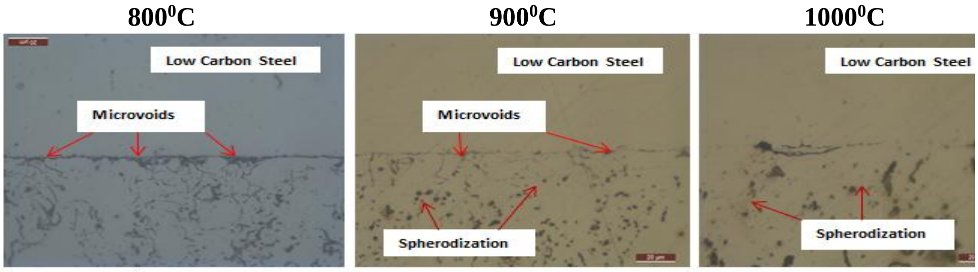
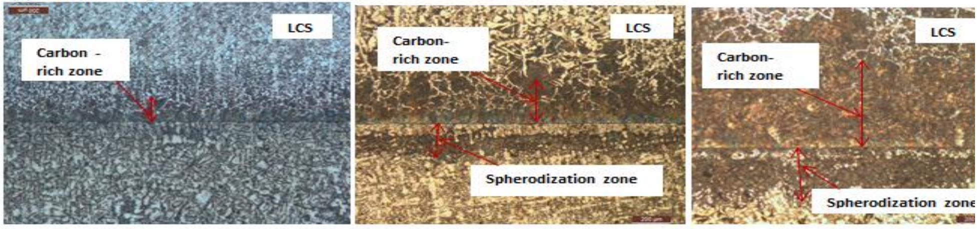


Figure-6.OM microphotographs of specimens after PWHT, after etching (50x)



(a) Before Etching



(b) After Etching

Figure-7.OM microphotographs' typical analysis of the interfaces and the diffusion layers of specimens treated at 800^0C, 900^0C and 1000^0C for 4 hours.

From the observations carried out on the micrographs of all the specimens (Figure-5 and Figure-6), the following inferences apply to all the PWHT diffusion couples:

1) Microvoids and interface lines are very much visible at the interfaces of the specimens treated at temperature of 800^0C, and becoming less visible at 900^0C, while at 1000^0C with longer treatment time, not only they almost disappear but the bond/weld also seems to be more complete. This phenomenon of elimination of the interfacial defects (voids) and the original interface at higher diffusion temperatures were also observed in the diffusion bonding of cast iron to medium carbon steel [11].
2) Further diffusion process has taken place with the increase of the diffusion layer thickness corresponding with increase of PWHT times and temperatures.
3) Spheroidization or dissolution of graphite flakes is observed on the cast iron sides close to the interface of specimens treated at 900^0C and 1000^0C but is not observed on specimens treated at 800^0C. This spherodization phenomenon was also observed by the researchers [1], in their study on the effect of high heating and cooling rate on interface of diffusion bonded gray cast iron to medium carbon steel.
4) A rapid diffusion of carbon and silicon from the grey cast iron to the low carbon steel are expected to take place.
5) As a result of the above, diffusion layers of spheroidization zone and carbon rich zone have formed near the interface of cast iron and low carbon steel sides respectively on specimens treated at 900^0C and 1000^0C, while at 800^0C only carbon rich zone has formed. For all specimens, these diffusion layers thicknesses increase with the increase of PWHT times and temperatures.

3.2.2. Thickness of diffusion layer. As stated above, examination of the microstructures in the microphotographs indicated that further diffusion process has taken place during PWHT and the increase of the diffusion layers thickness formed in each specimen of the diffusion couple, were very much influenced by the heat treatment temperature and time.

Changes in thickness with respect to time as observed from the microphotographs are shown in Figure-8, as time dependence of diffusion layer thickness produced for all diffusion couples.

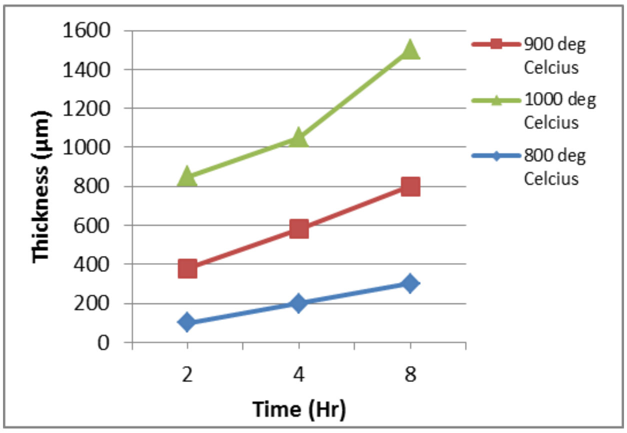


Figure-8. Time dependence of diffusion layer thickness

Some essential characteristics which could be derived from this form of time relationship of diffusion layer thickness are as follow:

1) A steady increase in thickness is observed as diffusion times consecutively increase from 2 to 8 hours was registered for all diffusions of 800^{0}C, 900^{0}C and 1000^{0}C temperatures.
2) A linear form of correlation between diffusion layer thickness and time could be deduced especially for 800^{0}C and 900^{0}C treatments.

The effect of heat treatment temperature on the diffusion layer produced was partly clearly displayed in the time related graph as mentioned above. Figure-9 shows directly the temperature dependence of the diffusion layer thickness, for all diffusion couple specimens.

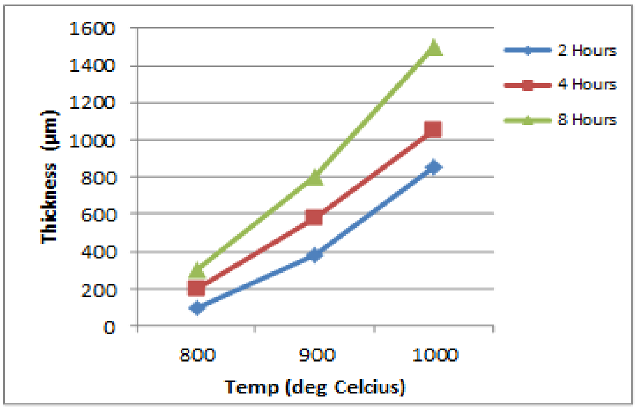


Figure-9. Temperature dependence of diffusion layer thickness

In this form, a further temperature role could be:

1) For all specimens, as the temperature rise from 800^{0}C to 1000^{0}C, a steady increase in diffusion layer thickness was observed.
2) A near quadratic form of correlation between diffusion layer thickness and temperature could be deduced especially for 8 hours treatment.

3.2.3. Microhardness across diffusion layer. Figure-10 (a), (b) and (c) show micro Vickers hardness gradients across the bonding interface of grey cast iron and low carbon steel diffusion couples after 2, 4 and 8 hours at 800^{0}C, 900^{0}C and 1000^{0}C annealing heat treatment; of which microstructures are shown in the Figure-5 and Figure-6 and the related characteristics are as described above.

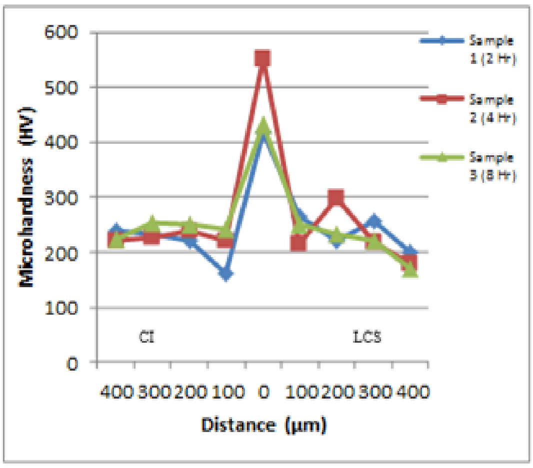


Figure-10(a). Microharness profile across the interface of diffusion couples after PWHT (800^{0}C).

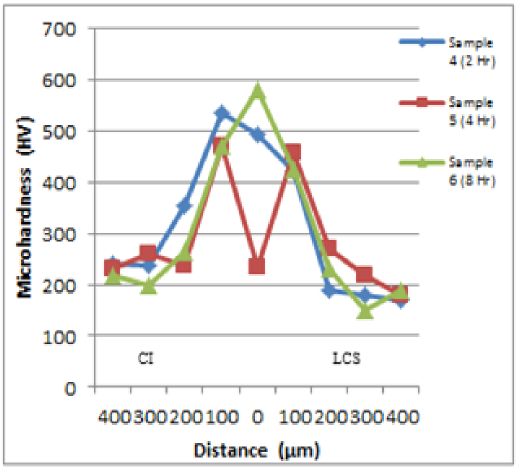


Figure-10(b). Microharness profile across the interface of diffusion couples after PWHT (900^{0}C).

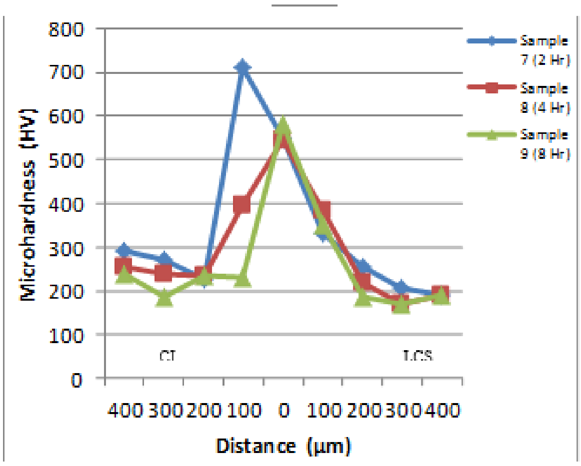


Figure-10(c). Microharness profile across the interface of diffusion couples after PWHT (1000^{0}C).

From these hardness test results Figure-10 (a), (b) and (c), a few specific comments can be deduced:

1) The hardness of the diffusion layer produced in all diffusion couple's specimens is much higher than the hardness of the respective base metals at all treatment time and temperatures.
2) The maximum hardness was observed close to the interface on the both sides of cast iron and low carbon steel. This corresponds to the area of diffusion layers of spheroidization zone and carbon rich zone, especially for 900^{0}C and 1000^{0}C treatments.
3) The above high hardness value can be related to the presence of high amount carbides. According to the researchers [12], increasing hardness value is due to higher the temperature and longer times available for carbon to diffuse.

4. Conclusion

A few diffusion couples of grey cast iron and low carbon steel were successfully produced by diffusion welding techniques after earlier failures. The micrographs examination of few samples of these diffusion couples exhibit fairly good bonding along the interface of the welded joint with microvoids still present. The strength value observed was indeed very low and the fracture was brittle in nature and it is suspected that the joint/weld was incomplete.

Specimens of these successful diffusional welded joints (despite being of low quality joint) were then being subjected to post heat treatment to allow further diffusion process to take place in the diffusion couples.

From the results and the discussions of the metallographic examinations and hardness testing of the specimens after post heat treatment as described above, some conclusions could be derived as follow:

(1) Temperature was observed as the main variable that controls the bond formation and it is necessary to have diffusion above the A3 temperature to eliminate the interfacial voids and for the bond interface to disappear as well for a complete bond.

(2) Heat treatment time and temperature were found to have a strong influence on the structure, thickness, composition and hardness of the produced diffusion layer.

(3) New phase or phases may have been formed in the diffusion layers. The natures of these phases are yet to be determined but they could be assumed to have the following properties: high hardness.

(4) Graphite flakes act as a source of carbon to the austenitic matrix that surrounds it. Their dissolution instigates the break-up and spheroidization.

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