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The effect of graphite shape on vacuum-free diffusion bonding of ST37 steel and nodular cast iron

In this study, a low carbon steel (ST37) and tow kinds of ductile cast iron with different nodularities, were diffusion bonded at the temperature 850 °C for 10 hours and then cooled in the furnace to investigate the effect of the graphite nodularity in the ductile cast iron on the diffusion bonding of dissimilar iron alloys and carbon diffusion. After diffusion bonding, microstructure analysis including metallographic examinations and image analysis, and also mechanical properties including micro-hardness measurements of interface region of the couples were made. The microstructure of the steel near the interfaces of couples consisted of pearlite, but the amount of that is different in two couples. As a result, from the microstructure observations, the carbon diffusion to the steel from the ductile cast iron with 10 % nodularity is higher than that with 90 % nodularity, and a good bonding along the interfaces is formed.

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1 Introduction

Diffusion bonding (DB) is a solid-state bonding method. It is a joining process wherein the principal mechanism for join formation is solid state diffusion without any fusing the parts to avoid its harmful effects on the joints. In this method two similar or dissimilar materials are brought into contact at a temperature below the melting points of the particular materials under a pressure far below the yielding strengths of the materials for a time long enough to form a sound bond [1-4].

Mechanical and micro-structural properties such as grain size, present phases, recrystallization temperatures are the other important parameters of the method [3, 5, 6]. Orhan et al. [6] showed that pressure and grain boundary diffusion were the most effective ones amongst all the parameters. As bonding does not involve melting or gross macroscopic interface distortion, the microstructure of the bond region is similar to that of regions remote from the joint and has parent metal properties [7].

The method is suitable especially for the materials which cannot be bonded with conventional or melting welding methods. The disadvantages are the difficulty in joining large parts and performing destructive test methods [8-11].

Cast irons are used in machine constructions as structural materials but joining these materials with the conventional welding methods is problematic and difficult [12]. Particularly cast irons crack, when we have to use fusion bonding methods to joining them, due to the brittleness. Consequently, it seems that diffusion bonding is a proper method for bonding these materials [12, 13].

But, when one of the diffusion bonding materials is ductile cast iron, the percent of ductile cast iron (DI) nodularity seems to be very important in diffusion and the bond that form in the interface.

In the present study, carbon diffusion and the resulting bond of a low carbon steel (ST37) and two DI with different nodularities were tested to investigate the effect of that on the bonding and diffusion and it was seen that the shape and nodularity percent of the graphite in irons had an important effect on diffusion bonding.

2 Materials and method

In the experiments, two kinds of DI, one with 10% and another with 90% nodularity, and also a low carbon steel (ST37) were used. The chemical composition of the specimens used for diffusion bonding, are given in **Table 1**. The microstructures of the materials prior to bonding process (etched with nital 2%) can be seen in **Figure 1**.

For performing the diffusion bonding (DB) process, the specimens were cut to plates with 10 mm × 10 mm × 5 mm dimensions. Prior to diffusion bonding, surfaces of each specimens were prepared using 1200 mesh SiC grinding

Table 1: Chemical composition of specimens used in diffusion bonding

Alloy	Chemical composition, wt %									
	Fe	C	Si	Mn	Cu	Cr	Ni	Al	P	S
DI with 10 % nodularity	bal.	3.23	2.88	0.193	0.174	0.054	0.038	0.002	0.033	0.042
DI with 90 % nodularity	bal.	3.6	2.45	0.196	0.365	0.089	0.036	0.006	0.026	0.028
ST37 Steel	bal.	0.098	0.125	0.430	0.019	0.007	0.036	0.000	0.029	0.023

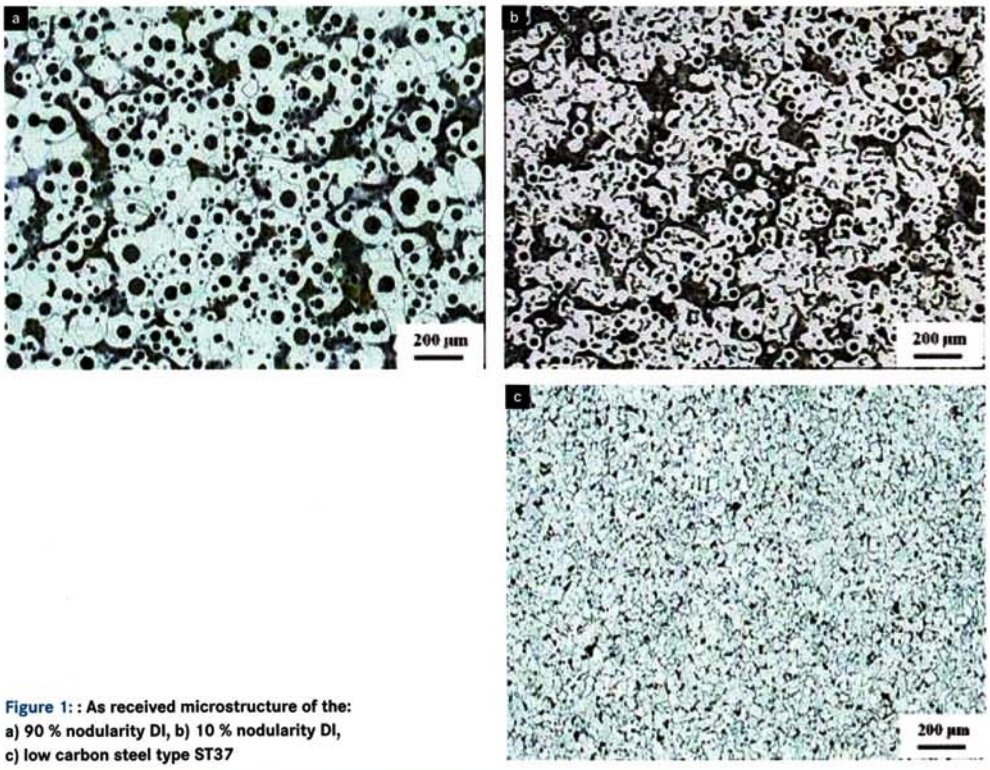

Figure 1: : As received microstructure of the: a) 90 % nodularity DI, b) 10 % nodularity DI, c) low carbon steel type ST37

paper for achieve predetermined degree of roughness. Then, the specimens were degreased in an ultrasonic bath that contained acetone. Following, the diffusion bonding couple was made by putting the specimens on each other from the 10 mm × 10 mm surfaces, just after removing from the ultrasonic bath. Then the couple was welded by brazing around the interface to be fixed and preventing the diffusion of the oxygen. Afterwards, the DB couple was coated by Carbostop C4EW (Acheson France) to minimize the effects of the furnace atmosphere. Finally, the DB couple was put in the furnace under 15 MPa pressure at the temperature of 850 °C for 10 hr, and then cooled to room temperature in the furnace to complete the bonding process. 12 samples have been made and jointed.

After bonding, the bonded specimen was cut transversely through the bond and surfaces were polished by 60-1200 grinding paper and then, samples were polished with diamond powders with 1 µm diameter. Phase identification was achieved after etching in 2 % nital. Then by using an optical microscope (Olympus BX41M-LED) equipped with a digital camera, any variations in the microstructure examined and delineated. Also, for determining the percent of the phases, image analyzing process was performed.

For hardness measurements, also the same techniques were used to prepare the specimens. Micro-hardness measurements were made using a Vickers hardness machine at a load of 100 g for 10 seconds on polished samples. A mean of five measurements was made for each report.

3 Results and discussions

The microstructures of the as received alloys are shown in Figure 1. Figure 1a is the microstructure of the DI with 90% nodularity. Figure 1b is the microstructure of the DI with 10 % nodularity with the high amount of graphite flakes. It is indicated that the microstructures of the irons are graphite

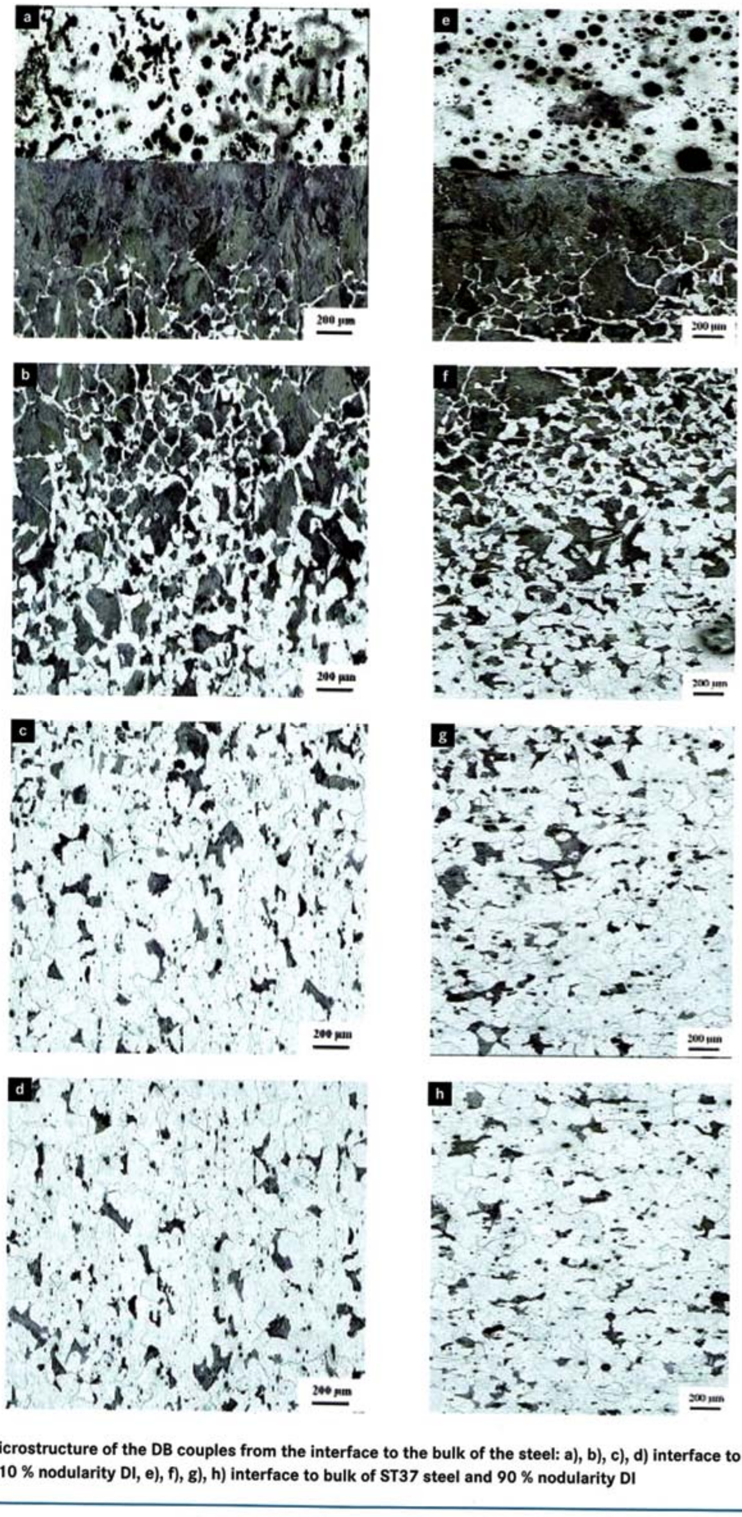

Figure 2: The microstructure of the DB couples from the interface to the bulk of the steel: a), b), c), d) interface to bulk of ST37 steel and 10 % nodularity DI, e), f), g), h) interface to bulk of ST37 steel and 90 % nodularity DI

nodules and flakes with some pearlite islands in a ferritic matrix. Figure 1c shows the microstructure of the low carbon steel before the DB process. It shows a full ferritic matrix with a few pearlitic regions.

Figure 2 shows the microstructures of the diffusion bonded couples, from interface to the bulk of the low carbon steel. It can be seen that in both couples, the microstructure of the steel at the interface is fully pearlitic, and the amount of that is reduced by increasing the distance from interface. It showed the carbon diffusion from the DI to the steel by passing from the interface. But, according to the graphite shapes, the carbon diffusion distance in both couples is different.

For investigating the pearlite percent in microstructures in different distances from the interfaces, we use an image analyzer software (MIP). **Figure 3** shows the pearlite amount profile in the steel, from the interface to the bulk in both couples. It can be seen that, at the distances from the interface to about 50 µm, the amount of pearlite in DB couple between the steel and 10% nodularity DI, is higher than that in the DB couple between the steel and 90% nodularity DI. This phenomenon is due to the graphite shapes in both ductile cast irons.

Figure 4 shows the stress concentrated areas as elastic circular regions with a radius r_e at the tips of the graphite flakes, schematically [14]. It is clear from the figure that stresses concentrations around and at the tips of the graphite flakes are much more severe than around graphite nodules. As a result, total free energy in the DI with 90% nodularity is much less than that in the DI with 10% nodularity. Since the reason for diffusion is the tendency to decrease the free energy [15], carbon diffusion from the 10% nodularity DI is more than that from the 90% nodularity DI.

Hardness variations of the bonded specimens, from the interface to the bulk of the steel (ST37) in both couples are given in **Figure 5**. The hardness is lower at the steel that is bonded with the 90% nodularity DI, than that at the bonded steel with the 10% nodularity DI due to the C diffusion that is more from the graphite flakes than that from the graphite nodules. It shows that the carbon diffusion in the steel with 10% nodularity have longer distances, as indicated in Figure 3.

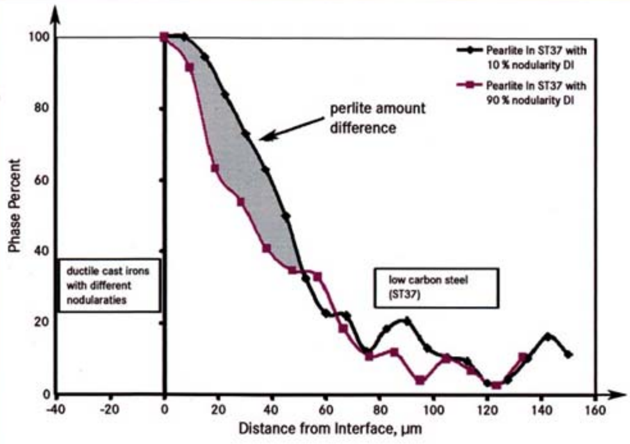

Figure 3: **Profile of the pearlite percent (average values) in the steel (ST37) in DB with both 10 % and 90 % nodularity ductile cast irons**

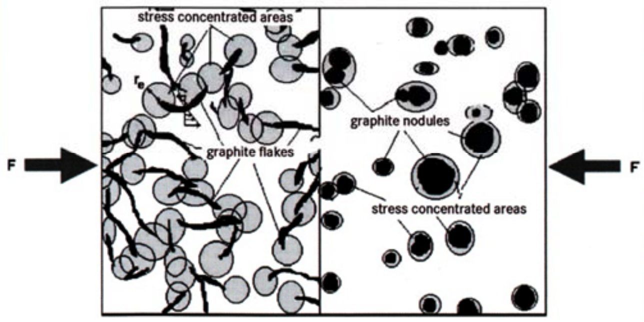

Figure 4: **Schematic illustration of stress concentration areas around the different graphite shapes**

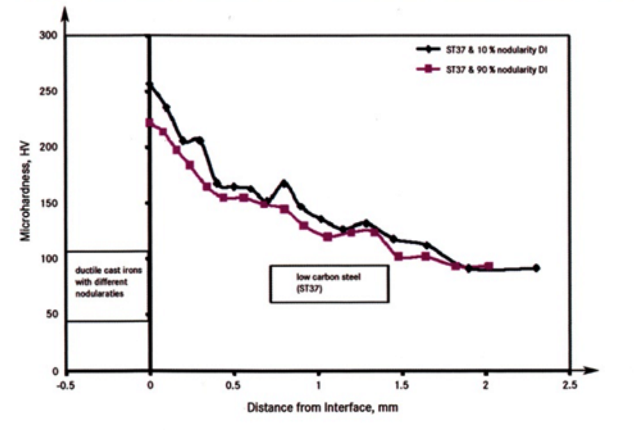

Figure 5: **Microhardness profile of the steel (ST37), from the interface to the bulk**

4 Conclusions

There are several factors that affect the DB process. The major factors are materials micro-structures, temperature, external stresses, different conditions of contact surfaces like surface roughness and cleaning.
It was determined that:

1. diffusion bonding can be performed under these conditions;
2. mechanical properties can be changed by this DB process.
3. the shape and kind of the graphite affected diffusion bonding behavior of the cast irons.
4. It was showed that graphite flakes increased the diffusion distances out of the region where they are.
5. The irregular shapes of the graphite and second phases can be the stress raiser points inside the material and increase the diffusion.

It can be planned to investigate the DB process on alloys with more different micro-structure properties, especially ferrous alloys. Also the graphite shape, size and their distribution in the micro-structure can be investigate with more details by using advanced equipments like SEM or TEM and even AFM in determination new phases and comparison them with previous one. Also, the adhesion properties of the bonding, mechanical bonding of parts after DB process and corrosion properties variations of the parts before and after the DB processes are investigable

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