



PRELIMINARY STUDY ON DIFFUSION WELDING OF MARINE GRADES GREY CAST IRON TO LOW CARBON STEEL

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ABSTRACT

Experimental research on joining of grey lamellar graphite cast iron to low carbon steel specimens is being performed under various diffusion welding parameters and variables to examine the effects on their microstructural and mechanical properties. Optimum conditions that produce excellent welding characteristics shall be established, the diffusion process mechanisms observed, the inter-diffusion coefficients and the activation energy of the diffusion system investigated. One of the expected outcomes from this research is to establish the methodology to produce the ultimate weldability of cast iron to steel. This paper updates the progress of this research; the research started with the preparation of the materials and the equipment involved. Base materials used were verified against the inspection/mill certificates by conducting microstructural, compositional and basic mechanical testing. Preliminary studies on diffusion welding experiments were conducted on a few specimens of the materials involved. Although initial few specimens failed to produce credible joints, further investigations on equipment unique characteristics led to making the right adjustments on the parameters and procedures that finally produced good joints on subsequent experiments.

Keywords: bonding, welding parameters, mechanical testing, hot press machine, microstructure, chemical composition.

INTRODUCTION

Recent years have seen drastic curtailment of industrial processes aimed at product cost reduction advancing at an accelerating rate, with the implication of a growing requirement for joining of cast iron to mild steel. At present, joining of cast iron to mild steel is generally performed by mechanical methods, such as bolting, which also adds to product weight, increases the number of process operations, and raises costs. An important contribution to the manufacturing industry could be made possible through a capability in joining of cast iron to mild steel by welding [1].

Grey cast iron has an interconnected nature of graphitic flakes which form a composite that imparts excellent damping capacity and make it ideal for application such as machine base and supports, cylinder blocks and brake components [2]. However, 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 near-weld zone, during and after the welding process. Grey cast iron is inherently brittle and often unable to withstand stresses set up by a cooling weld due to the lack of ductility caused by the coarse graphite flakes. The weldability by fusion welding may be lessened by the formation of hard and brittle microstructures in the heat affected zone (HAZ), consisting of iron carbides and martensites [3].

While welding of cast iron alone remains just as difficult, in the context of cast iron being welded together with dissimilar material such as mild steel having entirely different properties, the fusion welding process is still far from producing an excellent joint acceptable by the industry.

As mentioned in [1], there had been research conducted on the joining of cast iron to mild steel by various fusion welding processes. Fusion welding of cast

iron to mild steel has been previously performed to some extent and also widely researched. However, not much documentation is available on the application of diffusion welding/bonding process for welding of cast iron to mild steel and other marine grade materials.

Diffusion bonding is a solid phase process that avoids many of the welding problems because it reduces the chemical, mechanical and structural heterogeneities associated with fusion welding. Diffusion bonding solves many of the problems that fusion welding methods present in the joining of grey cast iron, especially in dissimilar metals. The presence of carbon in the form of graphite produces important microstructure transformations that do not appear in similar or dissimilar diffusion bonds of others iron alloys [4].

In this research, materials of grey lamellar graphite cast iron and low carbon steel of marine equivalent grades are selected with the objectives of examining the welding characteristics mechanically, metallographically and microstructurally in relation to the variables and mechanisms of the diffusion welding. The research is expected to establish sound formulation, findings, discussion and recommendation on the results of the metallographic examinations and mechanical properties obtained as well as the fundamental aspect of diffusion welding principles and mechanism. The research is not limited to analyze assessment on the welding characteristics and distinctions as compared to the conventional welding; it should also establish the feasibility of the diffusion welding for joining of ship's system components made out of the materials under study. Commercially the research is to be extended for real marine industry application to solve some of the current and future challenges faced by the industry.



METHODOLOGY

MATERIAL AND EXPERIMENTAL

At this initial stage of study, raw material properties were being verified, preliminary studies on diffusion welding were being conducted on a few joining experiments so as to identify equipment characteristics and further verify the welding parameters that were derived from relevant past experiments and the literatures reviewed [2-7].

MATERIALS

Base materials and testing

In this study, samples of the raw materials, namely grey lamellar graphite (GG) cast iron and low carbon steel to be used for the diffusion welding, were first examined and tested of their chemical compositions, microstructures and the basic mechanical properties.

Grey lamellar graphite cast iron

Cast iron, containing lamellar graphite of grade ASTM A 48 class 35 and equivalent to the ISO 250 and EN-GJL-250, is used. Applications for this cast iron include the automotive industry, shipbuilding, engine blocks, cylinder heads, cylinder liners, brake discs, compressor housing, pumps and valves.

Composition of grey cast iron

The spectral analysis was performed using the equipment SPECTROMAXx to verify the actual chemical composition. It is a desktop spark optical emission spectrometer manufactured by SPECTRO of Germany. The data in Table-1 was compared against the mill or inspection certificate from the supplier.

Table-1. Composition 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

Structure of grey cast iron

The microstructure of the grey cast iron is of pearlitic and ferritic matrix, with free graphites in the shape of flakes. The scanning electron microscopic image (1000x- magnification) of the sample was taken and is shown in Figure-1.

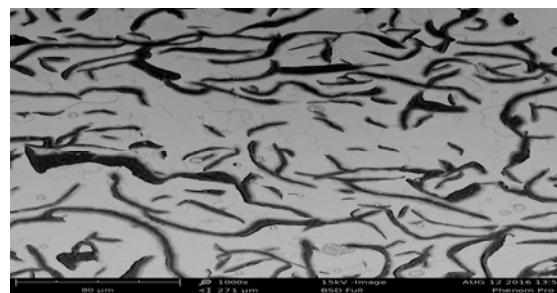


Figure-1. Microstructure of base metal - grey cast iron.

Mechanical properties of grey cast iron

Basic mechanical properties of tensile strength and hardness tests were carried out on the grey cast iron samples. Tensile test specimens were prepared in accordance to the ASTM-E8 standard test methods as shown in Figure-2. The Industrial Series Instron universal testing machine was used for the tensile testing.



Figure-2. Tensile test specimens of grey cast iron and low carbon steel.

The values measured were compared with the mill or inspection certificates and the data obtained is shown in Table-2.

Table-2. Tested mechanical properties of cast iron.

	Tensile Strength (MPa)	Elongation (%)	Hardness (HB)
ASTM A48 C 35	250	-	190

Low carbon steel

Low carbon steel of grade BS 449 grade 250, equivalent to that of ASTM 36 and JIS G 3101 SS 400, is used. This is a structural steel that is commonly used for the construction, buildings, bridges and ship structures.

Composition of low carbon steel

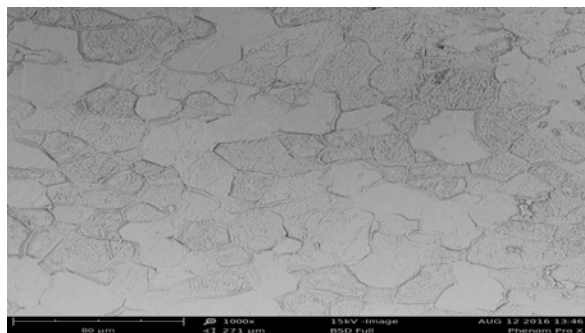
The spectral analysis data for low carbon steel used is as in Table-3 and was compared against the mill or inspection certificate from the supplier.

**Table-3.** Composition 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

Structure of low carbon steel

Low carbon steel consists of perlite and ferrite structures and the sample's microscopic image (1000x-magnification) taken is as shown in Figure-3.

**Figure-3.** Microstructure of base metal- low carbon steel.**Mechanical properties of low carbon steel**

A tested mechanical property of the low carbon steel is shown in Table-4, and the values obtained were compared with the mill or inspection certificates from the supplier.

Table-4. Tested mechanical properties of low carbon steel.

	Tensile Strength (MPa)	Elongation (%)	Hardness (HB)
BS 449 grade 250	408	35	195

EXPERIMENTAL

Initial or 'trial runs' experiments of diffusion welding were conducted at ADTEC, Taiping. Due to unsuccessful outcomes, the subsequent experiments were carried out at SIRIM, Shah Alam.

Experiment at ADTEC Taiping**Equipment**

The diffusion welding equipment used at ADTEC, Taiping is a Korean-made VAC-TEC hot press machine as shown in Figure-4. This is an advanced and computer-operated machine, where vacuum, pressure and heating systems being set and controlled through a programming process on the control panel. The heating system used is of the induction type.

**Figure-4.** Hot press machine ADTEC, Taiping**Specimen preparation**

The materials were cut in a lathe into cylindrical specimens of size $\phi 48 \times 50$ mm. The specimen ends to be joined were polished on 600 and 800 grits abrasive paper and cleaned with alcohol to remove any loose grit, dirt and grease or other contaminants.

Welding parameters

Welding parameters were selected based on best conditions of past relevant experiments and literatures reviewed [2-7]. Two joints were conducted at ADTEC, Taiping, using the welding conditions as shown in Table-5. Heating rate was set at 15 °C/minute.

Table-5. Diffusion welding parameters.

Specimen Joint No.	Vacuum Pressure (Torr)	Welding Pressure (MPa)	Welding Temperature (°C)	Welding Time (Min)
1	10^{-4}	10	800	15
2	10^{-4}	10	900	30

Procedure

The specimens were positioned in the hot press machine as shown in Figure-4. The specimens were set between the pressing axes of the graphite rods in such a way that the polishing scratches together with the brushing mark directions on each of the mating surfaces were mutually perpendicular. The chamber was then evacuated; firstly, half an hour by rotary pump, then switched over to the diffusion pump for another one hour of vacuuming. Using an automatic controller, the desired welding pressure, temperature, hold time and heating rate were programmed. Immediately after the load was applied, heating was started with a heating rate of 15°C/minute. The load was maintained constant until the end of the hold time and then allowed to reduce by itself.

At completion of the cycle the specimen was allowed to cool to less than 100 °C before removing the vacuum. This was to avoid oxidation which may take place at higher temperatures if the vacuum was removed.



Figure-5 shows a schematic diagram for the diffusion welding process.

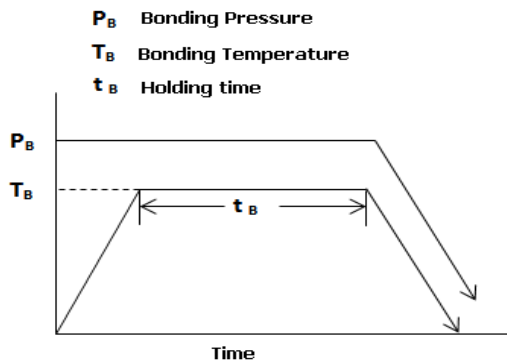


Figure-5. Schematic diagram for the diffusion welding/bonding process.

Experiment at SIRIM, Shah Alam

Equipment

The diffusion welding equipment used at SIRIM, Shah Alam is a hot press machine by JICA of Japan, as shown in Figure-6 below. This machine used to be equipped with automatic controller and programming devices but due to its aging condition, vacuum, pressure and heating are manually operated, adjusted and controlled throughout the experiments. The vacuum system of diffusion pump is not adjustable; it automatically creates a vacuum pressure of 10^{-6} Torr. The heating system used is of the induction type.



Figure-6. Hot press machine SIRIM, Shah Alam

Specimen preparation

The materials were cut on a lathe machine into cylindrical specimens of size $\phi 25 \times 20$ mm. The specimen ends to be joined were polished on 600 and 800 grits abrasive paper and cleaned with alcohol to remove any loose grit, dirt and grease or other contaminants.

Welding parameters

Welding parameters were selected based on the best conditions of past experiments and literatures reviewed [2-7]. Three joints were conducted at SIRIM,

Shah Alam using the welding conditions as shown in Table-6. Heating rate was set at $15^\circ\text{C}/\text{minute}$.

Table-6. Diffusion welding parameters.

Specimen Joint Nos.	Vacuum Pressure (Torr)	Welding Pressure (MPa)	Welding Temperature ($^\circ\text{C}$)	Welding Time (Min)
1	10^{-6}	10	1100	60
2	10^{-6}	10	950	60
3	10^{-6}	10	900	60

Procedure

The specimens were positioned in the hot press machine as shown in Figure-6. The specimens were set between the pressing axes of the graphite rods. The chamber was then evacuated; firstly, with rotary pump, then switched over to the diffusion pump for further vacuuming. The vacuum for the diffusion pump was not adjustable. Heating was started once the vacuum was reached. The temperature was regulated by adjusting the current and voltage manually for every few minutes such as to maintain a heating rate of $15^\circ\text{C}/\text{minute}$. The load/pressure was then applied once the required temperature was reached. The load was also gradually and manually adjusted to the desired values. Both temperature and pressure were then maintained at the desired values by adjusting and controlling manually the regulators throughout the welding period.

At the end of the hold time both pressure and heating were stopped and the temperature was allowed to reduce by itself. The specimen was allowed to cool to less than 100°C before removing the vacuum to avoid oxidation.

RESULTS AND DISCUSSION

Experiment at ADTEC, Taiping

Two joints were welded as per welding conditions in Table-5, however both failed to result in any bonding. The following Figure-7 shows the unjointed surfaces of the joint specimen no.1.



Figure-7. Unjointed specimens of grey cast iron and low carbon steel ($T_w=900^\circ\text{C}$, $t_w=30\text{min}$, $P_w=10\text{MPa}$).



Related literature reviews [2-7] had shown evidence of good bonding results for specimens of diffusion welding carried out based on conditions specified.

Investigation into the failure of the joining process revealed that one of the possible causes was related to the characteristics and configuration of the hot press equipment in use that may have resulted in insufficient heating. In relation to the induction heating system used, the computerized setting of temperatures and the actual temperatures at the interface of the joints could have a big variation.

Experiment at SIRIM, Shah Alam

Specimen No. 1 was supposedly to be welded as per the condition in Table- 6. However, during welding, from the indicator of the equipment in use it was observed that the specimens had already melted and deformed while being heated at a temperature of about 1080°C, before pressure and holding time could be applied.

The following Figure-8 shows the melted specimen's No.1, with welding conditions as per Table-6 above.

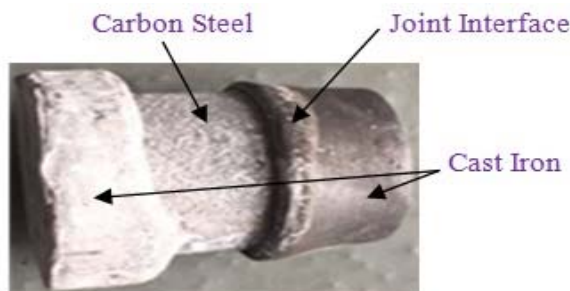


Figure-8. Melted specimens No.1, of grey cast iron and low carbon steel ($T_w=1100\text{ }^{\circ}\text{C}$, $t_w=60\text{min}$, $P_w=10\text{MPa}$).

Cast iron had melted but not the low carbon steel as the former has a lower melting temperature, about 1147 °C, while the latter's is about 1500 °C. As the joining process was done in a very high vacuum environment (10^{-6} Torr), that could have lowered a great deal of the melting temperature. Due to the equipment's condition, the vacuum system was not able to be regulated. However, based on the literatures reviewed, the cast iron should not have melted at that condition, and it is suggested that the equipment characteristics, the thermocouple and parameters, which were generally manually set and controlled, could have caused the variation and inaccuracy.

From the lesson learned of the above unsuccessful bonding, the second specimen's experiment was conducted at a lower temperature, while other parameters were maintained as per Table-6. Finally a visually good joint was obtained as per Figure-9 below.

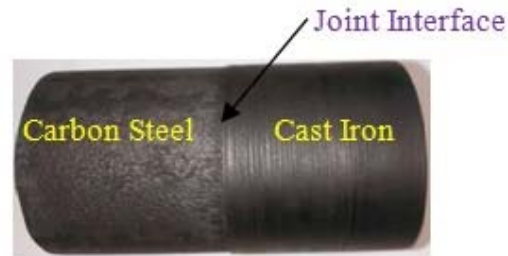


Figure-9. Jointed specimens No. 2, of grey cast iron and low carbon steel ($T_w=950\text{ }^{\circ}\text{C}$, $t_w=60\text{min}$, $P_w=10\text{MPa}$).

Subsequent to the successful joint obtained, a third experiment was conducted, with slightly lower temperature than the specimen No.2, while other parameters were kept constant as with welding conditions in Table-6. Figure-10 shows the jointed specimens No.3.



Figure-10. Jointed specimens No. 3, of grey cast iron and low carbon steel ($T_w=900\text{ }^{\circ}\text{C}$, $t_w=60\text{min}$, $P_w=10\text{MPa}$).

From visual examinations of the above joints, Figure-9 and Figure-10, no surface imperfections were discovered and the welded parts look intact and strong. Further microstructural examination and/or mechanical test will be conducted to verify the quality of the joints.

CONCLUSIONS

The experiments and related testing carried out on the performance of diffusion welding of grey cast iron to low carbon steel joints had resulted in the initial failures of few samples. However, subsequent experiments and testing had managed to produce good joints that proves the viability of diffusion welding of marine grades grey cast iron to low carbon steel. This initial positive development is a good indication that grey cast iron and low carbon steel has good prospects to be welded by diffusion welding.

Upon completion of the preliminary study, the results obtained shall be gathered and verified with data gathered from the literature reviews. This finding shall become the basis in conducting of a full study on diffusion welding of grey cast iron to low carbon steel. The main welding variables to be focused on are namely, welding temperature, welding time, and welding pressure. Due to the large number of possible combinations of the welding conditions, the actual number of welding conditions to be performed will be decided based on the Taguchi's Design of Experiments.



Amongst microstructural examination to be considered are namely, Optical Microscopic, Scanning Electron Microscopic (SEM), EDS/EDX/WDX, XRD and EPMA, while mechanical testing would involve tensile strength, charpy impact, bending and hardness tests.

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