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DETERMINING THE EFFECT OF PRE-HEATING ON DIFFERENT MATERIAL WELD JOINT OF P&H-11 CASTING AND MILD STEEL PLATE

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Abstract

Two differently manufactured steel materials are ductile cast iron, Medium Carbon with Mn-Mo alloy steel (P&H-11), and a mild steel combination welded to fabricate a structural component. A typical problem analyzed and discussed related to premature failure under stress and fatigue. It gives guidelines to engineers and fabricators to follow the discipline of pre-heating when they are trying to join two materials with indifferent microstructures especially using hot operations. While the investigation of the heat-affected zone of the plate and casting fillet joint, microhardness was observed at higher sides varying from 400-600 HV, against the recommendation of 350 HV max. The high Hardness at the heat-affected zone has contributed to crack initiation due to high localized stress. Along with microhardness, chemical and microstructural studies were also done to correlate the cause of failure. The effect of higher microhardness has been eliminated through pre-heating during welding. A suitable pre-heating temperature has been established through experimentation for ductile cast iron and mild steel combination of 200 to 250 deg. C was the most optimized and suitable solution.

Keyword: Welding; Ductile cast iron; mild steel; welding; pre-heat; heat affected zone; Microhardness

1. Introduction

The Cast Steel [P&H-11] contains medium carbon with Mn-Mo alloy Steel used for general machinery applications requiring moderate strength, toughness & abrasion resistance. Casting received as annealed or normalized and Tempered to be heat-treated machining condition.

Ductile cast iron has a wide range of applications today for varied applications and products. Ease for manufacturability, heat treatment, and machinability made ductile cast iron more versatile to their application and choice of designers in manufacturing industries, mainly structural welding. Ductile cast iron is also seen most prominently in the application of load-bearing areas due to its resistance to impact and fatigue, higher percentage elongation, and wear resistance. This appreciable behavior of ductile cast iron is due to spherical (round) graphite /nodular structures in the bulk of its material. On the other hand, steel family rolled products-mild steel plates due to their excellent mechanical properties- have become an in-demand material in various industries. It has proved unparalleled weldability and machinability, which has led to an exponential increase in its usage. Easy for alloy-ability, heat treatment, and control of pre-post preparatory process makes mild steel rolled products excellent friend of engineers and designers.

Ductile cast iron has been a significant engineering material for the past 50 years. At that time, it evolved from a complicated material that required the foundry metallurgist's highest skill and strict process control to a commonly used material that could quickly be produced with modern process technology. Yet, for the skilled metallurgist and foundry engineer, it is a material that can be engineered to meet extreme demands regarding mechanical properties and geometrical complexity. It is, therefore, a material that has been in growing use since its discovery [1]. Most of the metal castings have traditionally been cast iron. However, with a greater emphasis on increasing the efficiency of the engine via weight reduction, manufacturers have begun to look for alternative alloys that are lighter than cast iron, which lead the industry to move to aluminum alloys and other nonferrous alloys, such as magnesium which they believe can retaining the necessary strength to withstand the same forces as cast iron [2].

It was found that magnesium has several advantages over aluminum in terms of manufacturability due to its mechanical and physical properties. Revolutions to reduce the average fuel consumption have revived the interest in magnesium. Furthermore, the application of magnesium alloys in automotive has witnessed the developments and successful application of these alloys in an automotive component [3]. It helps to form Nodularity, which provides better ductile properties & strength with better elongation characteristics. The absence of the hardened case in the fillet region and the presence of free graphite and non-spheroidal graphite in the microstructure of the crankshaft made fatigue strength decrease to lead to fatigue initiation and propagation in the weaker region and premature fracture [4]. The comparison of the numerical analysis with the microstructural observations during micro-tensile tests showed a good agreement. The MnS and SiO2 inclusions were responsible for the intensive strain localization and subsequent crack initiation, while the Bi-MnS inclusions were not involved in this process [5]. MnS inclusions are typical non-metallic inclusions commonly occurring in steels. The inclusions significantly influence the mechanical properties of a component in terms of strength, toughness, impact properties, etc. However, the manganese sulfides positively affect material machinability [6]. Adding Pb, Se, and Te was documented to improve the steel machinability. Nevertheless, the elements are neither economical nor environmentally friendly [7].

The sulfur content and the resulting amount and size of MnS inclusions were extensively studied [8]. Sulfur causes a detrimental effect on steel & a consequential impact with "Hot shortness." The authors also observed internal fracture and decohesion of MnS inclusions during the tensile testing of austenitic steel. As a result, internal cracking occurred, and the authors assumed stress concentration on the inclusions/matrix interface [9]. Low alloyed steels, for example, usually require controlled pre-heat and inter-pass temperatures during welding, slow cooling after welding, and often a final tempering or stress-relieving heat treatment. On the other hand, Austenitic steels should be welded "cold," welds should cool rapidly, and post-weld heat treatments should be avoided wherever possible [10].

Stainless steel of grades 202, 304, 310, and 316 was welded with mild steel by Tungsten Inert Gas (TIG) and Metal Inert Gas (MIG) welding processes. The percentage dilutions of joints were calculated, and the tensile strength of dissimilar metal joints was investigated. The results were compared for different joints made by TIG and MIG welding processes. It was observed that TIG-welded dissimilar metal joints have better physical properties than MIG-welded joints [11]. Better joint efficiency, simple process, low fabrication cost, welding reliability, and efficient metal joining process are essential to produce many engineering and structural components [12]. The coarse grains and intergranular Chromium rich carbides along the grain boundaries in the heat-affected zone are observed during conventional arc welding, which deteriorates the mechanical properties of the joints [13]. The dilution of the weld metal with the two base metals and the different coefficients of thermal expansion are two significant criteria for dissimilar welding of stainless and low-carbon steels [14]. Shielded metal arc welding (SMAW), Tungsten Inert Gas (TIG) welding, and Metal Inert Gas (MIG) welding processes show improved mechanical properties of stainless steel and low carbon joints [15]. TIG welding provides greater control over SMAW and MIG weld processes and higher-quality welds in various metals and alloys. Therefore, it is mainly used to join stainless steel and other metals [16]. It was observed that with an increase in arc current, the Hardness of the mild steel weld joint increased to the optimum level and then decreased. The cooling rate was reduced with an increase in arc current. With an increase in welding arc voltage hardness of the weld joint decreased, and the cooling rate decreased. With the increase in welding travel speed hardness of the weld joint increased, and the cooling rate also increased [17]. Welding is the most common metal joining process. MMAW welding process was used from the early 1930s [18]. In the MMAW process, metal is joined by the application of heat. This heat is produced by establishing an electric arc between flux coated electrode and the base metal. A welding arc is a sustained electrical discharge through an ionized gas. The electric discharge through ionized gas produces high heat, sufficient for melting the metal [19].

From the available literature, work relevant to failure study and countermeasures for premature failures in the case of mild steel & cast iron welded components has yet to be analyzed and found to be a relevant subject for study. Premature welding cracks when ductile cast iron and mild steel welded joints have been made and subjected to application of load and fatigue. A typical problem of premature failure under stress and fatigue has been analyzed and discussed in this work. It gives guidelines to engineers and fabricators to follow the discipline of pre-heating when they are trying to join two materials with indifferent microstructures especially using hot operations.

2. Materials and methods

Fillet joint between Medium Carbon with Mn-Mo alloy steel (P&H-11) grade having quench & tempered with normalizing and mild steel rolled plate (IS2062-E250BR) grade as explained in Figure 1. The failure joint was fillet weld joint welded using the metal active gas welding technique.

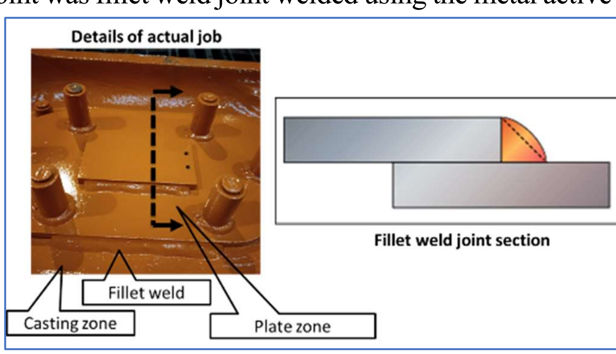

Figure 1. Details of fillet joint considered, with a sectional view.

2.1 Selection of base material

Mild steel, i.e., IS 2062 E250BR, was selected as one of the base materials. This mild steel grade's chemical composition and mechanical properties are reported in [20] and Tables

1 and 2, respectively. This grade of steel plate with a carbon equivalent of 0.40 to 0.42 is normalized without any additional requirement of pre-heating and post-heating to support the strength and quality of weld joints [21].

Another member was Medium Carbon with Mn-Mo alloy steel (P&H-11), also known as P&H 11, having a composition as mentioned in Table 3 and mechanical properties in Table 4.

Table 1. Chemical composition of base material (IS 2062)

Sl. No.	GRADE	%C MAX	%Si MAX	%Mn MAX	%S MAX	%P MAX	CE
1	E250 BR, Killed	0.23	0.4	1.5	0.045	0.045	0.42

Table 2. Mechanical properties of base material (I.S. 2062B)

Sl. No.	Grade	Y.S (Mpa) Min.	UTS (Mpa) Min.	% Elongation Min.	Hardness (BHN)	Heat Treatment
1	E250 BR, Killed	250	410	23	120-140	Normalized

Note: UTS: Ultimate tensile strength, Y.S.: Yield strength, BHN: Brinell hardness number, Mpa: Mega pascals

Table 3. Chemical composition P&H 11

Element	Specified % content
%C	0.35-0.42
%Si	0.30-0.60
%Mn	1.10-1.50
%P	0.035 max
%S	0.035 max
%Cr	0.025 max
%Ni	0.40 max
%Mo	0.15-0.30 max
%V	0.05 max

Table 4. Mechanical properties of P&H 11 [Normalised Condition]

Properties desired	Specified value
Ultimate tensile strength	617 Mpa min
Yield strength	411Mpa min
% Elongation	15 % min
Hardness (BHN)	241 max

2.2 Selection of weld consumables

The welding wire ER70S-G was used to fulfill the ASME requirement (American society of mechanical engineers- Section II C. SFA 5.18 [22]. For industrial welding products, fabricated structural components of heavy machinery were selected. Heavy earth-moving machinery is used for mining and construction work [23].

2.3 Welding parameters

To have better control of the welding process, qualified welders were employed. Welder qualification was done according to the guidelines of ASME (American society of mechanical engineers) BPVC (boiler pressure vessel code) Section IX, Article III of Section IX [24].

A qualified welding procedure specification (WPS) has been referred for the selection of welding parameters, which is established as per guidelines of ASME (American society of mechanical engineers) - Section IX, Part Q.W., Article II [25]

Three phases digital arc welding machine with a rating of input voltage of 08 ± 10% (50 / 60 Hz) and input of 8.2 kVA power at 60 % duty cycle has been deployed. This gives a rated voltage output of 36 V and an output current of 350 A, and welding parameters are specified in Table 5.

Table 5. Range of welding parameters used for lab trial sample welding.

Sl. No.	Welding Parameter		Value
1	Voltage in Volts		28-34
2	Current in Amps	1 run	280-320
3	The gas flow rate in lpm	Supply gas	20-22
4	Polarity	Fixed - DCEP	DECP
5	Job to nozzle tip distance in mm	Fixed- 15 mm	15/16

3. Observations

The following Methodology for investigation was carried out, and related observations were recorded & discussed.

- Recall of failed part
- Initial observation of crack surface
- A chemical test of cast steel and mild steel section
- Microstructural analysis
- Microhardness study
- Root cause analysis -identification of gap
- Lab trials to study the effect of pre-heating on microhardness traverse and microstructure

3.1 Recall of failed part

Once the component failed in an application, the part was called for failure analysis at the quality control laboratory. Further visual inspection was carried out before nondestructive testing. The crack location in the failed part has been explained in Figure 2.

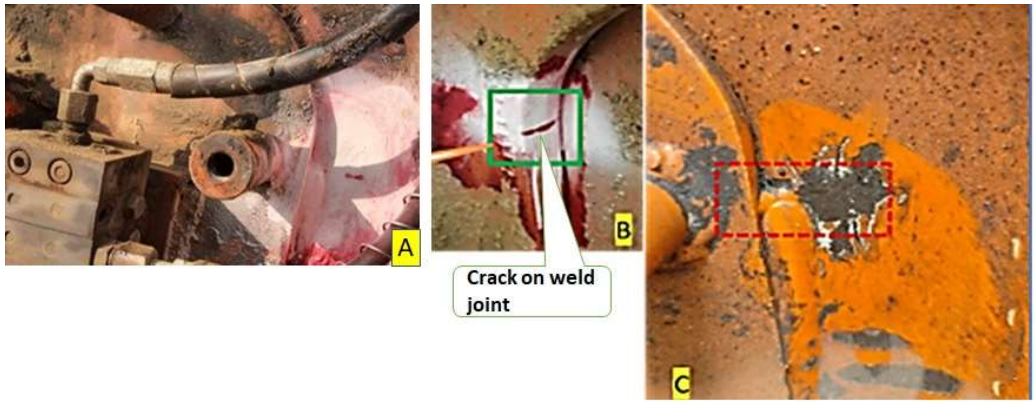

Figure 2. A: Initial crack observation on the welded fillet joint. B: Confirmation of crack by dye penetrant testing. C: Visual inspection of crack location after the cleaning of the joint.

3.1.1 observation of visual inspection are:

- Welding visual: No visual defect observed.
- Welding size: As per drawing specification
- Welding length: As per the drawing specification

Hence, no visual defect is observed in failed part; all the checkpoints were as per the drawing. Further to visual inspection, the nondestructive examination was carried out to understand the cause of failure. The observation of destructive testing is explained in Figure 3.

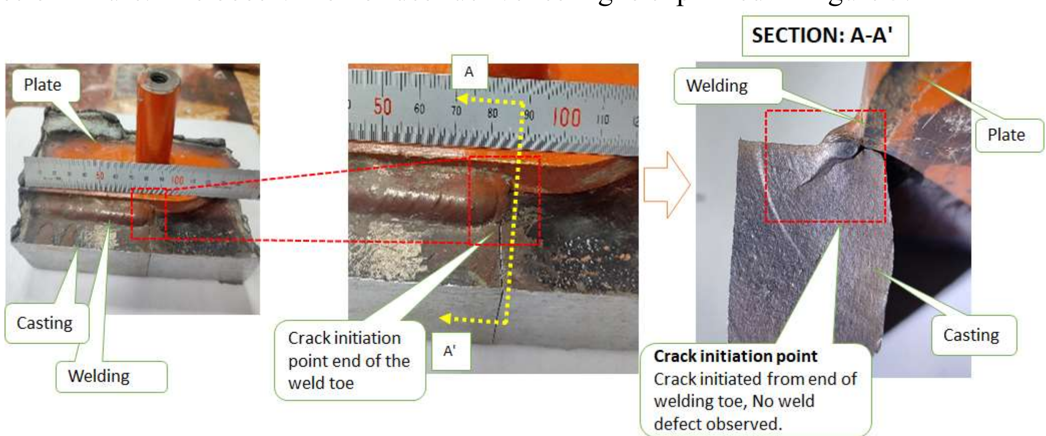

Figure 3. Observation of destructive testing. A: A small section of the failed part. B: Sectioning of the crack zone. C: Fracture surface investigation of crack zone section

The job has been cut along the crack line for destructive testing to visualize the crack surface. Weld fusion at root and toe found OK. But the crack surface indicates that the crack has initiated from the toe of the welding, although there was adequate root penetration during welding. It suggests that there might be some nonconformities in the base material for which this part could not withstand with expected working stress and failed prematurely. A further Macro-surface investigation was done for the fracture surface to analyze the case of failure. Details of fracture surface investigation are explained in Figure 4.

Figure 4 shows crack was initiated from the welding toe & propagated to Base Metal through heat affected zone. Most of the circumference of the casting indicates that fatigue cracks initiated from Welding Toe & propagated accordingly. The single crack initiation region indicates that the force acting on the casting in the application was unidirectional.

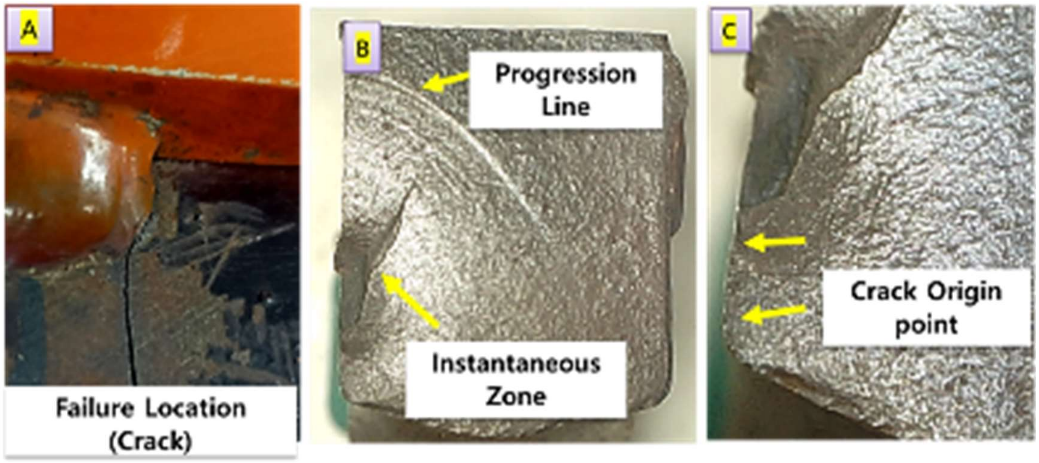

Figure 4. Details of fracture surface investigation were explained. A: Crack location marking on fillet joint. B: Identification of Instantaneous zone and progression line. C: Identifying crack origin point.

Further, a metallography analysis of the crack surface was carried out. Casting- heat affected zone -Weld zone- heat affected zone -Plate zones were studied as specified in Figure 5.

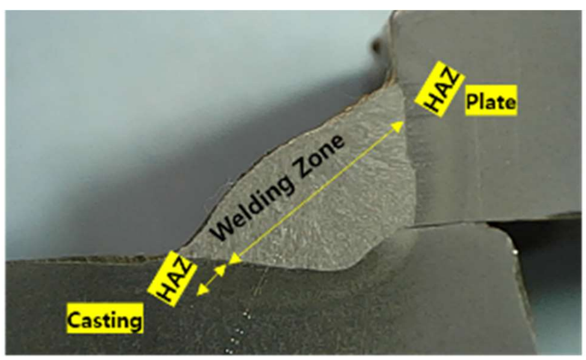

Figure 5. Zones considered for metallography analysis of crack surface

The microstructure study from welding to the casting zone has been explained in Figure 6.

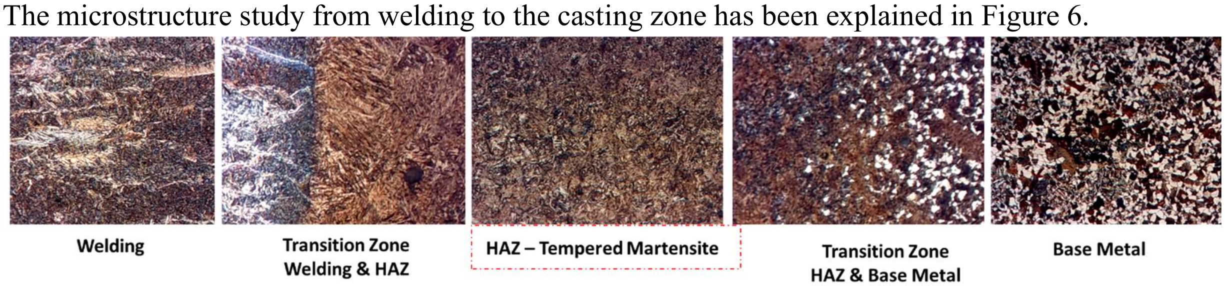

Figure 6. Microstructure study from welding to casting zone.

Observation of microstructure study welding to casting:

- Fig 6A: Welding is free from any non-metallic inclusion. The bainitic structure was seen: OK

- Fig 6B: Mixture of bainite with fine-tempered martensitic structure visible. Not OK
- Fig 6C: Fine-tempered martensite observed. Indicating highly hardened microstructure. : Not OK. Considered most detrimental.
- Fig 6D: Fine tempered martensite with pearlite and ferritic mixture: Not OK
- Fig 6E: Normalized. Pearlite and ferrite mixture was visible. OK

The microstructure study from welding to plate zone has been explained in Figure 7.

Figure 7. Microstructure study from welding to plate zone

Observation of microstructure study welding to plate zone

- Fig 7A: Columnar grains Welding was free from any non-metallic inclusion. : OK
- Fig 7B: Columnar grains with low carbon bainitic structure. OK
- Fig 7C: Low carbon bainitic coarse grain heat affected zone: OK
- Fig 7D: Low carbon bainitic and ferrite-pearlite mixture: OK
- Fig 7E: Normalized. Perlite and ferrite mixture is visible: OK

The chemical composition of the failed P&H, 11 cast iron, was verified and found within specification as specified in Table 6. Hence, no nonconformities were found in the chemical composition of failed sample casting.

Table 6: Chemical Composition observations for the failed to-cast P&H 11 grade

Parameters	%C	%Si	%Mn	%P	%S	%Cr	%Mo	%Ni
Specification	0.35 ~ 0.42	0.30 ~ 0.60	1.10 ~ 1.50	Max 0.035	Max 0.035	Max 0.25	0.15~ 0.30	Max 0.40
Actual	0.375	0.52	1.17	0.007	0.011	0.12	0.17	0.031

Further metallographic and chemical analysis of the failed sample microhardness study of the crack zone has been carried out. The hardness test was carried out in the following two directions viz:

- Welding – heat affected zone – Base metal (Casting side @P&H-11 grade)
- Welding – heat affected zone – Base metal (Mild steel plate side)

Welding – heat affected zone – Base metal (casting side) microhardness examination has been explained in Figure 8. The Hardness at the heat-affected zone was observed at the higher side, which varies from 407-571 HV.

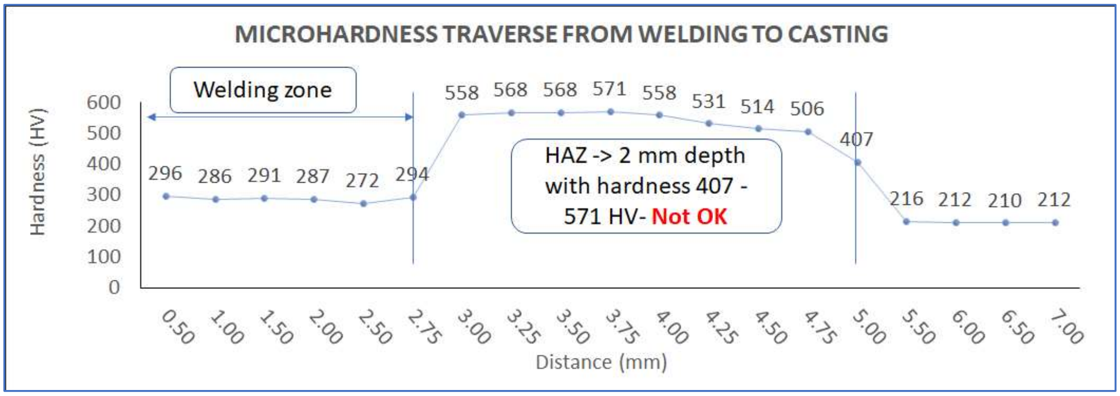

Figure 8. Welding – heat affected zone – Base metal (casting side) microhardness examination

Welding – heat affected zone – Base metal (mild steel side) microhardness examination has been explained in Figure 9. Hardness values were observed well within 300HV. No non-conformities were observed on the base metal (Mild steel) side.

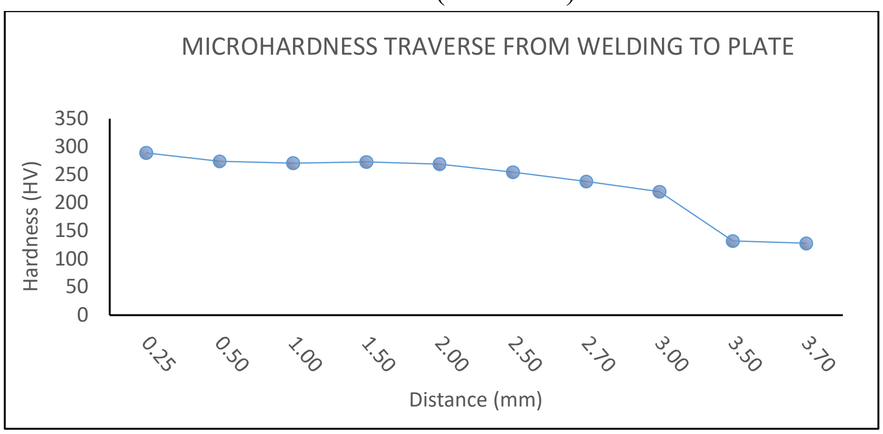

Figure 9. Welding – heat affected zone – Base metal (mild steel side) microhardness examination

Based on the above Observation, finding the hardness variation with or without heating is essential.

3.2 Comparison study of various pre-heating temperatures:

To study the effect of pre-heating following analyses are carried out. It will give better clarity on how Hardness is affected by slower cooling.

- Without pre-heating
- Pre-heating with 150-200 deg C
- Pre-heating over 200 deg C

Without pre-heating, microhardness observations have been explained in Figure 10.

Distance	Hardness (HV)
0.50	272
1.00	285
1.50	294
2.00	296
2.50	292
2.80	601
3.00	595
3.20	588
3.40	546
3.60	549
3.80	421
4.00	423
4.20	379
4.40	351
4.60	324
4.80	280
5.00	246
6.50	242
7.00	238

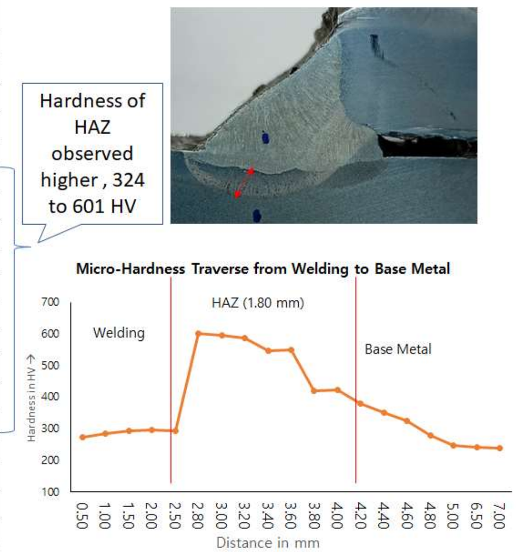

Figure 10. Without pre-haeting welded sample - micro hardness observations

The analysis was carried out to understand the effect of no pre-heating on the part. The job needed to be pre-heated and welded. Micro-Hardness results show a high hardness value in the heat-affected zone area, resulting in the formation of tempered martensite, an unstable microstructure with high microhardness.

With pre-heating at 150 to 200 deg. C, microhardness observations have been explained in Figure 11. The analysis was carried out to understand the effect of less pre-heating on the part. The job was not pre-heated below the recommended pre-heat temperature and welded. The microhardness results show a high hardness value in the heat-affected zone area, resulting in the formation of tempered martensite, an unstable microstructure with higher microhardness in heat affected zone.

After Pre-heating	
Distance	Hardness (HV)
0.50	272
1.00	238
2.00	246
2.50	244
2.70	578
2.90	540
3.10	409
3.30	423
3.50	454
3.70	413
3.90	421
4.20	340
4.40	338
4.70	302
5.00	241
5.20	228
7.00	220

Hardness of HAZ observed higher , 421 to 578 HV

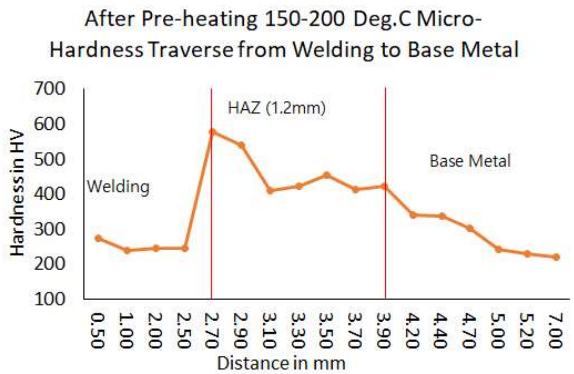

Figure 11. With 150-200 deg. C pre-haeting welded sample - micro hardness observations

With pre-heating at 200 to 250 deg. C, microhardness observations have been explained in Figure 12. The hardness value reduced and recorded were within normal limits.

Distance	Hardness (HV)
0.50	252
1.00	256
1.50	254
2.00	266
3.00	268
3.50	**302**
3.70	**377**
3.90	**360**
4.10	**339**
4.30	**323**
4.50	**319**
4.70	**315**
4.90	**309**
5.10	**313**
5.30	**307**
5.50	**293**
5.70	274
5.90	276
6.20	229

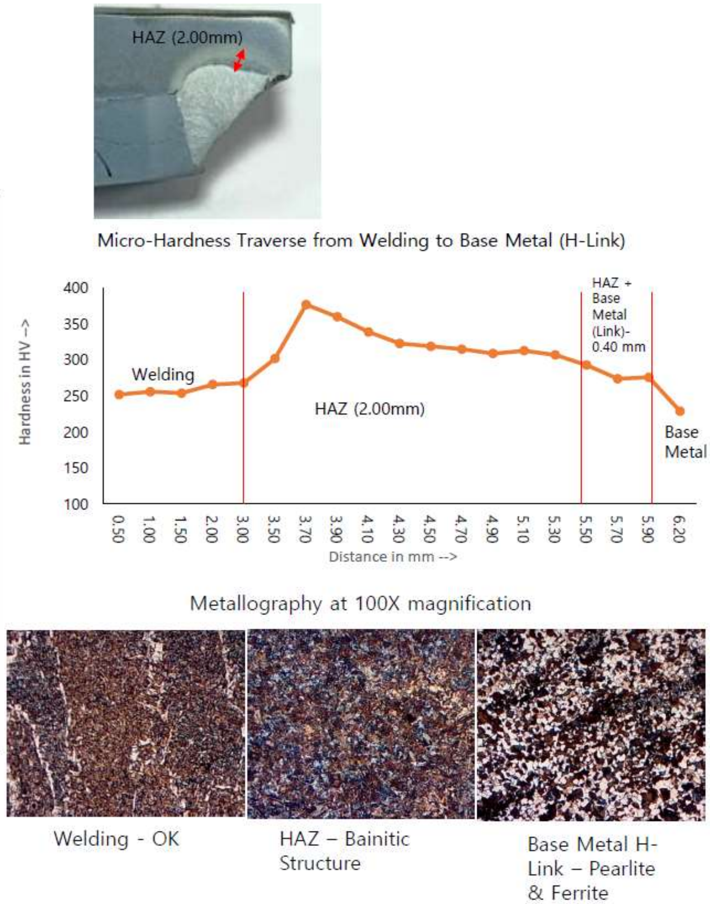

Figure 12. With 200-250 deg. C pre-haeting welded sample - micro hardness observations

4. Results and discussion

No visual defect is observed in failed part, and weld fusion at the root and toe was found OK. But the crack surface indicates that the crack has initiated from the toe. Figure 4 shows crack was initiated from the welding toe & propagated to Base Metal through heat affected zone. Observation of Microstructure study for welding to casting, as explained in Fig 6, has shown non-conformity with respect to microstructure.

A mixture of bainite with fine-tempered martensitic structure is visible, as seen in Fig 6B. Fine-tempered martensite was observed, indicating highly hardened microstructure. as shown in Fig 6C, and fine-tempered martensite with pearlite and ferritic mixture, as seen in Fig 6D.

The chemical composition of the failed P&H, 11 cast iron, was found within specification. In the failed sample, the Hardness at the heat-affected zone was observed at the higher side, which varies from 407-571 HV. The high Hardness at the heat-affected zone would increase strength and low ductility. The microstructure and Hardness produced in any ferritic steel heat-affected zone (HEAT-AFFECTED ZONE) depend on the cooling rate through the transformation temperature range of the steel/iron in question. This high hardness value indicates the less cooling time after welding.

A low heat balance led to rapid cooling as the weld deposited was small in relation to the parent material, and the parent material acted as a heat sink. The toughness can be low in microstructures that have arisen from rapid cooling rates. Finally, it forms crack-susceptible microstructures with poor toughness. This high Hardness might have contributed to the crack due to high localized stress.

The job was not pre-heated and welded in the comparative study for analyzing the effect of pre-heating on the welding of stated grades of material. Micro-Hardness results show a high hardness value in the heat-affected zone area, resulting in the formation of tempered martensite, an unstable microstructure with high microhardness. With pre-heating at 150 to 200 deg. C, microhardness results show a high hardness value in the heat-affected zone area, resulting in the formation of tempered martensite, an unstable microstructure with higher microhardness in heat affected zone. With pre-heating at 200 to 250 deg. C, microhardness observations have been explained in Figure 12, and the hardness value recorded was within the standard limit.

From overall observation, it was inferred that welding Medium Carbon with Mn-Mo alloy steel (P&H-11) with mild steel affects the microstructure and will result in premature failures. To avoid the same, it is recommended to adopt a suitable pre-heating temperature technique during welding.

5. Conclusion

Two differently manufactured steel materials, ductile cast iron, and mild steel combination, welded in the form to manufacture a structural component, have been studied to establish the cause of failure and to suggest suitable measures to avoid failures in the application.

a) While the investigation of the heat-affected zone (heat-affected zone) of the plate and casting fillet joint, microhardness was observed at higher sides varying from 400-600 HV, against the recommendation of 350 HV max.
b) Microstructure for welding to casting zone has shown non-conformity with microstructure in welding done for two materials without pre-heating.
c) In the failed sample, the Hardness at the heat-affected zone was observed at the higher side, which varies from 407-571 HV.
d) The high microhardness of the heat-affected zone has contributed to the crack.
e) When welding of stated samples without pre-heating, microhardness shows a high hardness value in the heat-affected zone area, resulting in the formation of tempered martensite, an unstable microstructure contributing to high microhardness.
f) With pre-heating at 150 to 200 deg. C, microhardness results show a high hardness value in the heat-affected zone area, resulting from the formation of tempered martensite, an unstable microstructure with higher heat-affected zone microhardness.
g) With pre-heating at 200 to 250 deg. C, microhardness observations have been found within normal limits.

From overall observation, it was inferred that welding ductile cast iron with mild steel affects the microstructure and will result in premature failures. To avoid the same, it is recommended to adopt a suitable pre-heating temperature technique during welding.

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