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THE IMPORTANT FACTORS FOR STRUCTURE AND MECHANICAL PROPERTIES IN THE REPAIR OF IRON BASE METAL COMPONENT BY THERMAL SPRAY AND WELDING PROCESSES

Raden Dadan Ramdan
Lecturer of Materials Engineering*
Yasya Nur Muhammad
Master Student*
Sihol Christian Lumbantoruan
Master Student*
Irma Pratiwi
Corresponding author
Doctoral Student of Materials Engineering Program*
E-mail: irma031.ip@gmail.com
Bambang Widyanto
Professor
Department of Metallurgical and Materials Engineering
Jenderal Achmad Yani University
Terusan Jend. str., Sudirman, Cimahi, Indonesia, 40525
Aditianto Ramelan
Lecturer of Materials Engineering*
*Department of Materials Science and Engineering
Institut Teknologi Bandung
Ganesa str., 10, Bandung, Indonesia, 40132

Cast iron is widely used in the manufacturing industry due to its high strength and wear resistance properties. However, cast iron's brittle nature results in frequent failure of cracks during formation or use. Among the repair methods that can be used are thermal spray and the welding process. Even though both welding and thermal spray have been implemented for various metal repairs processes, however very limited technical reports as well as scientific papers are found for this topic. Therefore, the optimum condition of metal repair by both processes is still needed to be explored. The present works focus on the comparison between thermal spray and welding method for cast iron repairs purposes. In the experiment of thermal spray process focus has been given in optimizing spraying distance on microstructure and hardness properties. On the other hand, in the welding experimental works focus has been given on the influence of groove design on microstructure and hardness. Each research variable is carried out to obtain optimal crack repair results. It was observed that thermal spray process produces less Heat Affected Zone (HAZ) area compared to the welding process therefore having less critical area. The highest hardness value of thermal spray method is 101.33 shown by 30 cm spraying distance. Meanwhile, the highest hardness value of HAZ area of welding method is 600 HV shown by specimen A. It was obtained that from the present experimental works, thermal spray process produces better results than welding process. However, the value of the specimen hardness produced by the welding and thermal spray method depends on the type of coating material used

***Keywords:** cast iron, repair, thermal spray, welding, spraying distance, microstructure, hardness*

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1. Introduction

Cast-iron components are one of the most popular choices in the manufacturing industry today, due to their good strength, durability, and high wear resistance [1]. Cast iron has the characteristics of being easily formed by casting, a relatively low melting point, and good mechanical properties [2]. Apart from that, it also has ease of machining, good fluidity, good wear resistance, high damping capacity, and excellent heat resistance [3]. Therefore, this material can economically replace steel in a wide variety of applications and industries [4].

Cast-iron components may experience cracks during the service. These cracks are caused by their high carbon content, which results in their brittle nature [3]. Cast iron has a different metallurgical structure from structural steel. It has a matrix with a high carbon phase which is divided into the entire matrix [4]. This phase can be graphite (pure carbon) or Fe_3C (cementite) which has brittle properties [4]. Cracks in components are undesirable and need to be repaired to prevent further damage, which will cost more to repair [5].

Repair methods can include pinning, welding, braze welding, or thermal spray [6]. Welding methods are used for repair, for example, filling cast holes, making a hard coating on tools, thickening worn parts, repairing cracks, and various other repairs [7] Welding in cast iron focused on repair defects formed during casting and specimen joining [8]. More than 80 % of the welding performed on cast iron uses the shielded metal arc welding method, 50 % of which is used to repair new cast iron in foundries [8]. Welding can correct defects of the relatively small size found in cast iron [8]. Also, this repair method is less expensive than other methods. Welding is done by melting the base metal and adding filler metal to the welding area. Metal melting is carried out by applying heat during welding. This can be a problem with cast iron welding because the high carbon content of cast iron ranges from 1.7 % to 6.67 % [9]. The high carbon content can cause the formation of hard carbides during the heating and melting process of cast iron. In cast iron welding, the weld metal must tolerate an increase in carbon content due to the melting of the parent metal [8]. If this does not happen, it can cause defects because the weld metal becomes very hard and brittle followed by the formation of fissures [10]. Therefore, research on the development of cast iron repair methods is relevant.

2. Literature review and problem statement

The paper [11] explained that in shielded metal arc welding, cast iron is generally considered a complex material to weld due to the thermal welding cycle's effect on iron's metallurgical structure. The thermal process of arc welding results in the metal's temperature near the fusion line being too high, hence experiencing an extremely fast cooling rate. This can cause solid carbides are formed in the zone close to the weld. Thus, there is a tendency to form high carbon martensite in the HAZ (heat affected zone) based on paper [4]. The high carbon content of cast iron leads to the formation of a complex and brittle phase, namely martensite and hard carbide. This phase will be formed in the fusion zone (FZ) and the heat affected zone (HAZ) at the time of welding which shown in paper [3]. This structural transformation reduces flexibility to a very high degree of crack susceptibility to either spontaneous cracking after welding [8]. This proves that welding on cast iron is greatly influenced by heat input. Therefore, it is necessary to pay attention to the heat input in cast iron so that there is no high heating rate and cooling rate to prevent the formation of a martensite phase. One way to adjust the heat input in a weld is to adjust the volume of the weld area. A larger volume of weld area will receive a higher heat input than a smaller volume of the weld area. The volume of the weld area is determined by the groove design used in the weld specimen. Groove design can affect efficiency when welding mainly to avoid fast heating and local cooling which can cause cracking during welding [7]. In addition, groove design avoids overheating and distortion of the weld area [8]. In this research, the shielded metal arc welding method of cast iron welding was carried out with a variable groove design to prevent fissures which are rarely found in other literature. Papers [3, 4, 8, 11] gave interesting insight about welding method for cast iron repair. However, for cast iron, there is other potential option for repair method that is not investigated in those articles, which is thermal spray method.

On the other hand, thermal spray is a method to repair the crack by depositing coating particles onto the substrate surface, which will seal the cracks [12]. This method is one of the most popular methods for restoring dimensional components in the industrial world [13]. Thermal Spray is preferred over replacing components with new spare parts because it is more cost-effective [14]. This method can restore the component dimensions according to the original design. The biggest advantage of thermal spray is that the components will not experience the distortion that occurs in welding. The heating process in this method is only to melt the coating material and does not melt the parent metal [15]. This method is more costly than the welding method because the coating metal is in powder form. Thermal spray requires more process parameters, such as substrate surface preparation, heat treatment before and after thermal spray, and spray distance. If these parameters are not observed properly, it can produce a layer that contains porosity and also the appearance of oxides due to reactions at high temperatures [15]. None of articles [12–14] gave the comparison between thermal spray method and welding method.

From several process parameters, spraying distance is an essential parameter and a simple parameter in the powder thermal spray process. The difference in spraying distance can affect the resulting layer's thickness and oxygen content of the coating. The oxygen content can cause component life to decrease due to decreased wear resistance if oxygen levels are too high [12].

The optimal spraying distance needs to be utilized in order to produce a good coating. Even though both welding and thermal spray have been implemented for various metal repairs processes, however very limited technical reports as well as scientific papers are found for this topic. Therefore, the optimum condition of metal repair by both processes is still needed to be explored. This research is focused on evaluating the mechanical properties of hardness and microstructure of cast iron in the repair area based on the results of powder thermal spray and SMAW welding. In thermal spray, the spraying distance can produce different kinetic energy because the closer the spraying distance, the higher the particles' speed hitting the substrate and produce a thick layer. The increase in kinetic energy due to particle velocity will produce higher residual stresses and make the coating easier to peel off. In SMAW, the groove design can affect the amount of heat input during welding, and the volume of fused metal added [4]. The amount of heat input and the fused metal volume can affect the weld's microstructure and mechanical properties. Based on the description above, each research variable is carried out to obtain optimal crack repair results.

3. The aim and objectives of the study

The aim of the study is to identify the factors influencing the structure and mechanical properties of cast iron in the process of repair using welding and thermal spraying methods. This will allow the development of crack repair methods in cast iron.

To achieve this aim, the following objectives are accomplished:

– to investigate the effect of spraying distance during thermal spray on the mechanical properties of hardness and microstructure of cast iron in the repair area;

– to find out the effect of groove design of welding on the mechanical properties of hardness and microstructure of cast iron in the repair area.

4. Materials and methods

The base metal studied in this research was nodular cast iron grades 80-60-30 that had been certified with

ASTM A476-70 standards. Specimens for thermal spray and welding were grooved by milling. The crack repair was simulated in the groove area filled with filler metal by powder thermal spray and shield metal arc welding.

Thermal spray specimens machined to the dimensions of 40 mm x 40 mm x 40 mm and prepared design single V groove 45 °C in the form of a trapezoidal prism with a groove height of 2 mm. Prior to the thermal spray process, specimens were subjected to coarsening of the surface using the sand blasting method. This process was carried out to make a profile (roughness) on the specimen surface in order to form a good bond between the coating material and the specimen surface. The coating material used was Nickel-based alloy Eutalloy 10224 (NiTec) and the thermal spray tool used was SuperJet-S-Eutalloy. The specimens were preheated at 200 °C. The variation of the spraying distance was applied to the specimens with a distance of 20 cm, 30 cm and 40 cm.

Welding specimens machined to the dimensions of 70 mm x 60 mm x 13 cm and prepared design single V groove 45° in the form of a trapezoidal prism and a triangular prism with a groove height of 6 mm. The filler metal used in SMAW welding was CIN-1. The specimens were preheated at 250 °C for normalization after groove preparation and were given post weld heat treatment of 450 °C for 30 minutes for stress relief. Welding was carried out with a SMAW welding machine at a welding current of 110 A and a welding voltage of 220 V. Variations in the groove design applied to the specimen was a trapezoidal prism with a width of 7 mm, a trapezoidal prism with a width of 5 mm and a triangular prism with a width of 5 mm. The groove design width can be seen in Fig. 1–3.

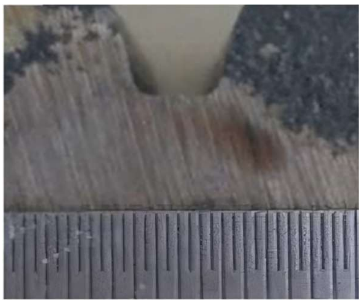


Fig. 1. Groove design trapezoidal prism with a width of 7 mm

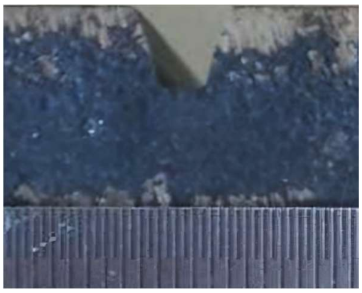


Fig. 2. Groove design trapezoidal prism with a width of 5 mm

To find out the heat input, equation (1) was used:

$$HI = \eta \frac{V \times I}{v}, \tag{1}$$

where HI – heat input; η – efficiency; V – voltage; I – current; v – welding speed.

Fig. 3. Groove design triangular prism with a width of 5 mm

Several characterizations were performed after the process, including microstructure observation, hardness measurement and elemental composition characterization. Microstructure observations were carried out using an Olympus BX53M optical microscope. Homogeneous in sample microstructure was assumed during the observation. Specimen hardness measurements were carried out using the Zwick Roll Indentec machine. Observation of the chemical element composition used an Optical Emission Spectrometry tool. General to detail microstructure observation was performed by optical microscope method. The focus was given to the metallurgical features at the groove area. In the welding results, the microstructure was focused on the HAZ area, while the thermal spray results were focused on the quality of the structure of the layer thickness and the number of defects. This observation was supported by a hardness test to determine the changes of hardness values before and after repair on specimens. The welding specimens were subjected to a microvickers hardness test with a pyramid diamond indenter and a load of 0.5 kgf. Thermal spray specimens were subjected to a Rockwell hardness test with a load of 100 kgf.

For welding method, the wider the welding groove, the easier the weld metal filler penetrates to the groove. Wider welding groove also creates wider surface area which results higher heat input. For thermal spray method, the farther the spraying distance, the higher possibility of splat experience early solidify. However, when the spraying distance is too close, the splat can bounce back making the coating hard to build up.

5. Result of investigation two repair methods for cast iron

5. 1. The effect of spraying distance during thermal spray on the mechanical properties of hardness and microstructure of cast iron in the repair area

5. 1. 1. Specification of base metal

The test results of the chemical composition of cast iron specimens for welding and thermal spray are shown in Table 1. Based on the ASM Properties and Selection volume 1, the chemical composition of the specimens is the composition of nodular cast iron. To ascertain the type of cast iron, the microstructure of the specimen was observed as shown in Fig. 4.

In the microstructure there is nodular graphite which is characteristic of nodular cast iron. In addition to nodular graphite, the microstructure shows the presence of pearlite and ferrite phases.

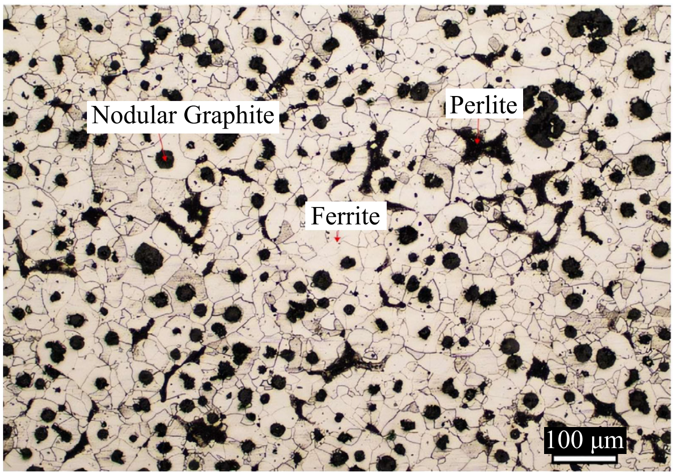


Fig. 4. The microstructure of the base metals

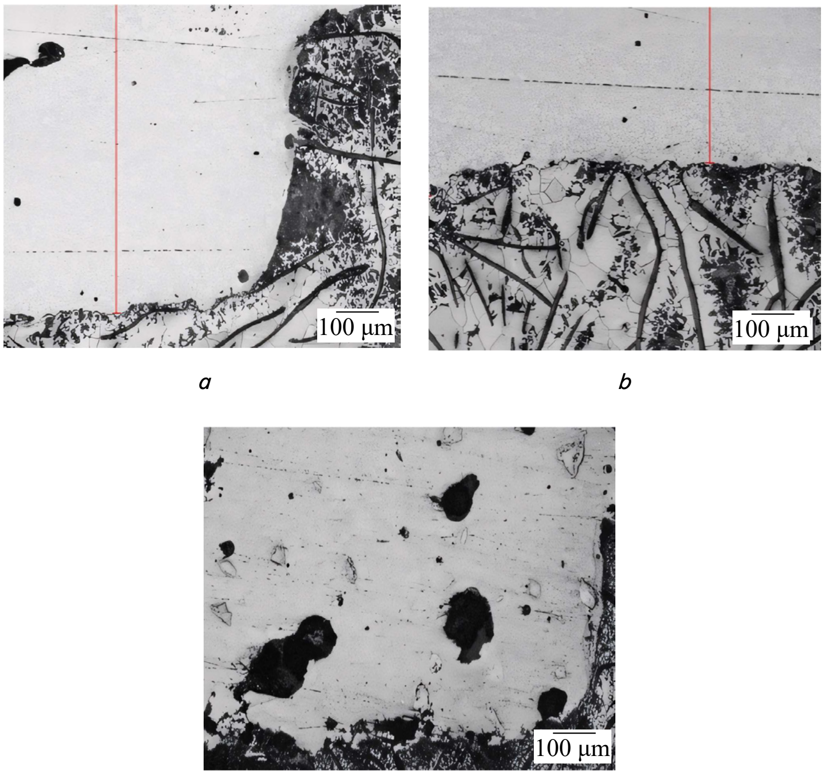
Table 1

Chemical elemental composition of the specimen

C (w %)	Si (w %)	S (w %)	P (w %)	Mn (w %)	Ni (w %)	Cr (w %)
3.10828	2.64532	0.00809	0.01014	0.25652	0.03314	0.276
Mo (w %)	V (w %)	Cu (w %)	W (w %)	Ti (w %)	Sn (w %)	Al (w %)
0.0147	0.00411	0.02154	0.00067	0.013	0.00197	0.018
Pb (w %)	Sb (w %)	Nb (w %)	Mg (w %)	Zn (w %)	Fe (w %)	–
0.00058	0.00044	0.00099	0.04684	0.00554	93.5332	–

5. 1. 2. Microstructure of thermal spray specimen

Fig. 5 shows the microstructure of thermal spray specimen. The repaired specimens do not have HAZ areas.



a *b*

c

Fig. 5. Principal signature: *a* – microstructure of the thermal spray specimens spraying distance 20 cm; *b* – spraying distance 30 cm; *c* – spraying distance 40 cm

5. 1. 3. Hardness test of thermal spray specimen

The thermal spray coating did not have a significant difference in hardness values along with the difference in spraying distance which can be seen on Table 2.

Table 2

Data on the hardness of thermal spray specimens

Spraying distance (cm)	Base metal average magnification value (HRB)	Filler metal average magnification value (HRB)
20	49.81	91.26
30	47.73	101.33
40	49.93	99.77

The thermal spray coating has a higher hardness than the base metal.

5. 2. The effect of groove design of welding on the mechanical properties of hardness and microstructure of cast iron in the repair area

5. 2. 1. Heat input calculation

Table 3 shows groove design data and heat input of welding specimens. The heat input can be calculated using equation (1). From equation (1) it can be seen the relationship between the volume of the weld area and the heat input. The volume of the weld area affects the welding speed. With the same welding travel speed for each specimen, the welding time required for a groove design with a larger volume takes longer. The longer the welding time, the slower the welding speed. Heat input is inversely proportional to welding speed. From Table 3 it can be seen that specimen B with a larger volume of weld area received a higher heat input than other specimens.

Table 3

Welding specimen data

Specimen	Single V 45° groove design shape	Specimen volume (cm^3)	Groove volume (cm^3)	Heat input (J/mm)
A	Trapezoidal prism with a width of 5 mm	561,6	18,3	19.755
B	Trapezoidal prism with a width of 7 mm	577,2	22,2	20.594
C	Triangular prism with a width of 5 mm	553,8	8,52	16.133

The variation in groove design resulted in differences in the volume of the weld area in each specimen. The volume of the weld area is influenced by the shape and dimensions of the groove design for each specimen. Specimen B has the largest volume of weld area and specimen C has the smallest volume of the weld area. The difference in volume causes a difference in heat input when welding. When compared the volume of the weld area with the volume of specimens in each specimen, each specimen A, B and C has a ratio of 1:31, 1:26, and 1:65.

5. 2. 2. Heat affected Zone (HAZ) width

Fig. 6 shows the macrostructure of the welding area. There are 3 welding areas, namely the heat affected zone, weld metal and base metal. From the macro structure image, the HAZ width of each specimen can be measured by the line comparison method. Table 4 shows the macro HAZ width calculation data for each specimen. From Table 4 it can be seen that the specimen that received the greatest heat input had the largest HAZ width. Microstructure, Fig. 6 shows the width of the HAZ area in each specimen is different. The HAZ area is indicated by a darker-colored structure.

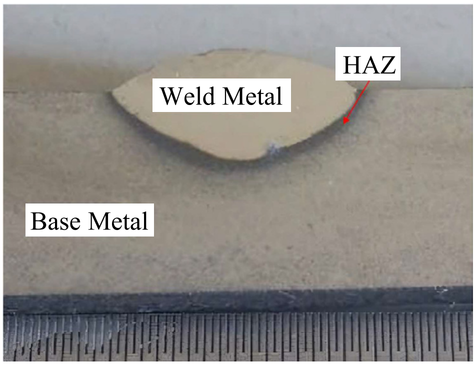


Fig. 6. The macrostructure of the welding result area

Table 4

HAZ width data

Specimen	Average HAZ width (mm)
A	0.382±0.024
B	0.754±0.053
C	0.511±0.034

In terms of macrostructure and microstructure, specimen B has the largest HAZ width with the greatest heat input value as well. There is an anomaly in specimen C which has a larger HAZ width than specimen A with smaller heat input. This occurs because the volume ratio between the weld area and the specimen is greater than that of specimen A, which causes the main metal to melt more.

Fig. 7 shows the microstructure of the welding results.

In Fig. 7, the HAZ area is shown in a darker color than the weld metal and base metal areas.

5. 2. 3. Hardness test

Fig. 9 shows the hardness value of the welding results in each welding area. From this Fig. 9, it can be seen that the HAZ area in each specimen has a very high hardness. As observed in Fig. 8, there is an acicular or needle-like structure and a black round structure in the microstructure of the HAZ area.

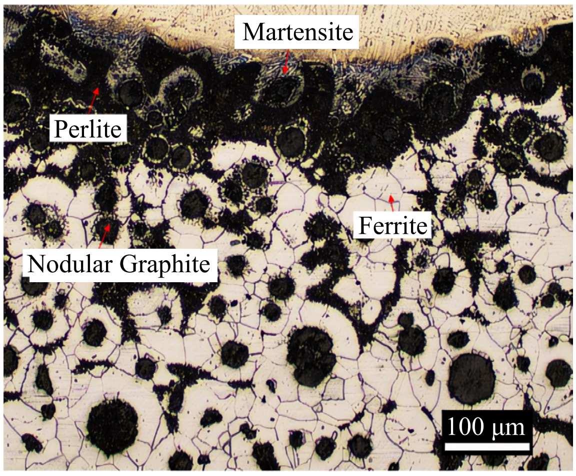


Fig. 8. The microstructure of the HAZ area

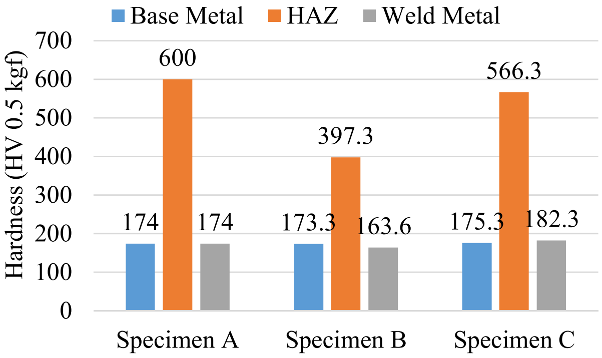
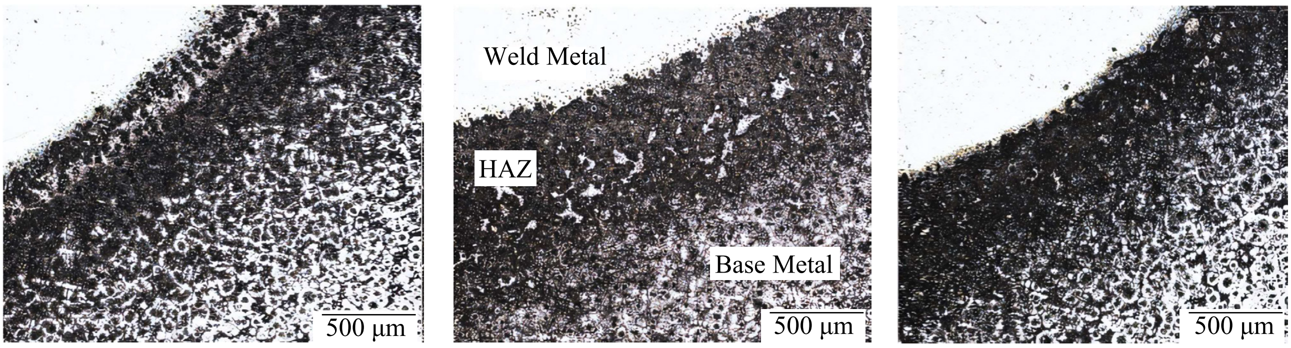


Fig. 9. The hardness values of the base metal, HAZ, and weld metal areas

The HAZ area is an area affected by heat when welding so that the area can experience recrystallization due to heating.



a *b* *c*

Fig. 7. Principal signature: *a* – the microstructure of the welding results specimen A; *b* – specimen B; *c* – specimen C

6. Discussion of the investigation two repair methods for cast iron

The variation in groove design resulted in differences in the volume of the weld area in each specimen. A large volume comparison between the weld area and the specimen will have a very large effect on the welding result. This effect can be in the form of a faster cooling rate in the specimen with a larger volume ratio because the heat will be easier to spread and propagate throughout the specimen. In addition, specimens with a larger volume ratio will cause more base metal melting. This can affect the area of the HAZ and the weld metal that is formed.

From the macro structure image, the HAZ width of each specimen can be measured by the line comparison method. Table 3 shows the macro HAZ width calculation data for each specimen. From Table 3 it can be seen that the specimen that received the greatest heat input had the largest HAZ width. Microstructure, Fig. 7 shows the width of the HAZ area in each specimen is different. The HAZ area is indicated by a darker-colored structure. In terms of macrostructure and microstructure, specimen B has the largest HAZ width with the greatest heat input value as well. There is an anomaly in specimen C which has a larger HAZ width than specimen A with smaller heat input. This occurs because the volume ratio between the weld area and the specimen is greater than that of specimen A, which causes the main metal to melt more.

HAZ width is influenced by the value of the heat input. The greater the heat input value, the greater the heat energy produced. The heat energy can affect the microstructure morphology or phase changes in the HAZ area of the welding result. The amount of heat energy causes the formation of a heat affected area in the welding area so that it affects the resulting HAZ width. The greater the heat energy received by the specimen, the greater its effect on the welding area. In addition, the heat input can affect the heating rate during welding. The slower the heating rate, the larger the melting of the parent metal and the larger the HAZ area formed.

In Fig. 7, the HAZ area is shown in a darker color than the weld metal and base metal areas. When compared with the results of thermal spray in Fig. 5, the repaired specimens do not have HAZ areas. This happens because the thermal spray process is relatively shorter and the heating given does not melt the parent metal. The formation of a larger HAZ width on the result of welding is certainly a special note to be optimized. Good defect repair results in welding are specimens that have fewer HAZ areas or HAZ areas that do not produce a brittle phase.

In addition to the difference in the HAZ area, from Fig. 5, 6 it can be seen that there are porosity defects that exist between the HAZ area and the weld metal. In the thermal spray specimens shown in Fig. 4, the porosity is more visible than the welding specimens. Porosity is indicated by a black round shape. The porosity formed on the results of the thermal spray shows that the spraying distance used is not ideal. The porosity that is formed can be caused by the spraying distance is too far. The spraying distance can be related to the presence of particles that do not have time to melt and the speed of impact of the coating particles. If these two things happen, the presence of porosity is expected to increase. In Fig. 5, it can be seen that specimens with a spraying distance of 40 cm have more porosity than specimens with a spraying distance of 20 cm and 30 cm. Research [16] showed the specimens of thermal spray results with a greater number of porosity in the specimens with a spraying distance of 40 cm. the increase in the amount of porosity at different spraying distances was due to the low particle collision speed and the increase in the number of unmelted particles.

Fig. 9 shows the hardness value of the welding results in each welding area. From this Fig. 9, it can be seen that the HAZ area in each specimen has a very high hardness. As observed in Fig. 8, there is an acicular or needle-like structure and a black round structure in the microstructure of the HAZ area in research [3] showed that the black HAZ area is the pearlite phase and the martensite phase which has an acicular or needle-like structure. The martensite phase has a very high hardness above 500 HV [3]. It can be ascertained that the high hardness in the HAZ area indicates that as the result of the welding, martensite hard carbide was formed. The hardness of the weld metal follows the initial hardness of the filler metal type CIN-1 which has a hardness value of 140–160 HV. In base metal, all specimens have relatively the same hardness after welding and are not much different from the initial hardness of 170 HV. There is no significant difference in the area of base metal and weld metal for each specimen. When compared with the hardness value of the thermal spray specimens, the thermal spray coating did not have a significant difference in hardness values along with the difference in spraying distance. The thermal spray coating has a higher hardness than the base metal. This happens because the coating material has higher mechanical properties. Besides being able to repair cracks by filling the crack area with a coating material, thermal spray can also improve the mechanical properties of hardness on the surface. In addition, the results of the thermal spray did not form a HAZ area because it did not experience melting of the base metal as in the welding process.

The HAZ area is an area affected by heat when welding so that the area can experience recrystallization due to heating. The recrystallization is affected by the cooling rate. Heat flow from the weld area to the base metal area causes a temperature gradient so that a fairly fast cooling rate occurs in the HAZ area. The fast-cooling rate of cast iron tends to produce a martensite phase in the HAZ area. The martensite phase is a brittle phase so it can cause the area to become more brittle and allow cracks to form after the welding process. If there is a martensite phase in the HAZ area, there will be a very different hardness gradient between the weld metal and the base metal. A significant difference in hardness in the HAZ area can cause the welded cast iron component to fail due to the uneven operating load received as a result of significantly different hardness values. The ideal welding result is shown in specimens that have hardness values that do not differ significantly between weld metal, HAZ, and base metal.

From the experimental results with the welding method, of course, it still has to be evaluated and developed, especially in groove design. A good groove design is that groove design results in a balanced heating and cooling rate and less heat input. In addition, other process parameters are needed to support the process of achieving optimization in welding, such as the provision of pre-heat treatment and post weld heat treatment. Pre heat treatment can reduce the temperature gradient so that the cooling rate in the HAZ area is not high and avoids the formation of a masrtensite phase due to high cooling rates. PWHT is required to increase the ductility of the heat affected zone, improve the machinability of the weld metal and HAZ, break down the cementite formed during welding, convert martensite to a less brittle microstructure (troostite), and eliminate residual stress in the welding area [4]. A research [10] conducted by adding the PWHT process parameters to the welding of cast iron and the martensite phase produced in the dissolved HAZ area into a non-brittle pearlite and ferrite phase so that the hardness in the HAZ decreased. Multi-pass welding can also be applied to cast iron welding to avoid fast cooling rates.

In the thermal spray method, more variations in the size of the spray distance with a small distance range are needed in order to get good coating results and no porosity is formed in the repair area. To prevent the formation of porosity, other process parameters are needed, such as the thermal spray method, the substrate preparation method, and the type of coating material. The thermal spray method affects the presence of porosity because each method has different technical requirements, resulting in different coating qualities. The preparation method needs to be considered to ensure the cleanliness of the substrate surface from impurities as well as ensuring mechanical bonding is formed based on the level of roughness of the surface. In addition, the type of eraser material also has an influence on the formation of porosity because each material has a different flowability and speed for different solidification.

When compared between the welding method and the thermal spray method for repairing cast iron cracks, the thermal spray method provides better quality results than the welding method. This is shown from the microstructure and hardness value. From the microstructure, the thermal spray method does not form HAZ areas which have a brittle martensite phase. The hardness value in thermal spray does not produce a significant difference in hardness values. The thermal spray method is suitable for repairing cracks of a relatively small size. The welding method can repair cracks of a relatively larger size due to the metal melting process. In terms of the cost required, the thermal spray method is more expensive than the welding method. However, there was still room for improvement at this technology. The variation of some thermal spray parameters can determine the optimum methods for cast iron repair.

7. Conclusions

1. In thermal spray processes, the optimized spray distance produces different coating qualities. It was observed that the greater the spraying distance the greater amount of porosity. Thermal spray process produces less HAZ (0 mm) area compared to the welding process (0,754 ± 0,053 mm on specimen B) therefore having less critical area.

2. The value of the specimen hardness produced by the welding and thermal spray method depends on the type of coating material used. In addition, martensite phases were observed in the HAZ after welding, thereby the hardness in the HAZ area are significantly higher than the base metal and weld metal which reach 600 HV on specimen A. For optimum welding condition, it was also suggested for having optimum groove design that significantly produce different heat input during welding.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data cannot be made available for reasons disclosed in the data availability statement.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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