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Evaluation of magnetic particle inspection for optimizing welding quality in back gouging boom structure preparation in heavy machinery

Adhe Aryswan, Apriansyah Sutan Hasibuan, Hendra Butar Butar, Tian Havwini, Mega Gemala
Mechanical Engineering Department, Politeknik Negeri Batam
Batam 29461, Indonesia
Corresponding author: adhearyswan@polibatam.ac.id

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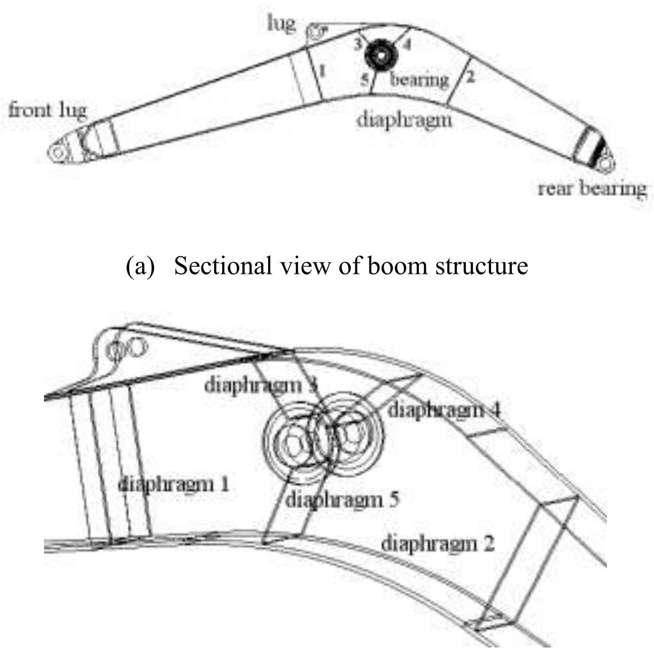
Abstract

This study investigates the effectiveness of Magnetic Particle Inspection (MPI) in optimizing welding preparation for the back gouging of boom structures in hydraulic mining shovels. The primary objective is to evaluate MPI's efficiency in detecting surface and near-surface defects during the pre-welding stage, thereby improving the overall welding quality of boom structures, which play a critical role in supporting heavy loads. MPI is utilized as an initial inspection method prior to Ultrasonic Testing (UT), enabling early detection of potential defects and reducing the likelihood of failures during subsequent UT evaluations. The study reveals the presence of linear and rounded discontinuities that may compromise weld integrity. By applying MPI early in the process, the need for rework during UT is minimized, resulting in cost and time savings. Furthermore, the findings of this study contribute to supporting two key organizational initiatives—People, Quality, Velocity, Cost (PQVC) and Built-in Quality (BIQ)—which aim to enhance both the efficiency and reliability of the welding process.

1. Introduction

The boom of a hydraulic mining shovel (excavator) is a crucial component of the machine. It is a large, heavy-duty arm that extends from the main body of the excavator and supports the lifting arm or dipper shovel. The boom is designed to pivot and move, allowing the excavator to reach and manipulate materials effectively. It is an essential component of the Shovel in hydraulic mining equipment, and ought to be in proper working order without any defect whatsoever[1]. Configuration of a boom structure is illustrated in Fig. 1.



(a) Sectional view of boom structure

(b) Diaphragm arrangement

Fig. 1. Configuration of the boom structure[2]

The welding joint that receives the most loading and movement of the boom needs to be sound to address the stability of the stick and the bucket. The integrity of the joint boom is essential, especially the welding strength, which determines the safety and balance when operating a hydraulic mining shovel[3]. The configuration of the boom structure is illustrated in Fig. 1.

To ensure the structure's integrity, we join the material using a welding process. Welding is one of the significant procedures in fabricating metal structures, which involves parent and filler metal. Arc welding is widely used, and structural steel is mainly welded.[4]. Welds in these structures, particularly in the most load-bearing areas, must have high strength to maintain the integrity of the boom and its connected parts. Welding, especially gas metal arc welding (GMAW), is widely used for joining structural steel, but like any welding process, it is prone to defects. [5]. Some procedures are necessarily conducted to maintain quality assurance; one of them is magnetic particle inspection (MPI).

To ensure the quality of these welds, non-destructive testing (NDT) methods such as Magnetic Particle Inspection (MPI) are essential for detecting surface flaws in ferromagnetic materials. MPI is effective at identifying linear and rounded defects that can significantly affect the welding's performance, particularly before further testing such as Ultrasonic Testing (UT)[6]. This method is beneficial for the detection of linear indications, such as cracks, of which the extent is significantly larger than the depth (L>3W), as well as rounded indications, such as instances of porosity that appear to be round or elliptical and where the extent is at most three times the depth (L<3W).

A project to build a boom structure on a hydraulic mining shovel used an internal engineering specification 1E0099, which specified all the work criteria related to arc welding[7]. However, any welding work cannot be defect-free. Hence, we need repair methods such as gouging.

Thermal gouging is one of the significant processes in welding fabrication. It is characterized by the swift reduction of undesired phases in the solid state by heating a local volume of the material and then expelling the molten metal[8]. Like manual metal arc welding, carbon arc gouging is a conventional process[9].

The most critical area of a boom structure is located at the joint bottom (corner), referring to Park's study [2], as shown in Fig. 2. Hence, back gouging welding needs to be done on the joint bottom area of the welding boom to ensure the structure's integrity and obtain the desired products of the best quality possible.

Fig. 2. Equivalent (von-Mises) stress distribution at boom structure (MPa). [2]

Back gouging removes part of the material on the backside of the previously welded joint. Hence, this treatment helps guarantee the joint root's flow and removes gaps in the earlier root welding. It can even eliminate the metal root pass if a fault could potentially harm the Non-Destructive Test (NDT) operation. Back gouging may help improve the quality of the joint, and since the joint can be rewelded, it is possible to form a joint with the required strength. The preparation after back gouging is essential as it dictates the kind of joints to be fused.

In this study, the focus is on evaluating the effectiveness of MPI in detecting defects in the back gouging process of boom structure welding. Back gouging is crucial for ensuring the quality of the weld by removing part of the backside material and addressing potential faults that may compromise joint strength. This research aims to assess MPI's efficiency in detecting defects during the welding preparation process and improving overall welding quality in hydraulic mining shovel boom structures.

2. Research Methods

The study was conducted at a workshop in Batam, Indonesia, in the Fabrication Boom Area. It was restricted to the boom area's joint bottom, where the MPI inspection was done. The objective was to assess how effectively the MPI process could be included in the joint preparation after back gouging.

2.1. Tools and Consumables

The GMAW process involved using a Lincoln Merit LMC6 wire electrode of 1. Hailed at 32 mm, with a wire type of ER70S-6 weighing 20 kg, the welding power source used was Miller Dimension NT500, while a Miller 70 Series 24V Wire Feeder was used for feeding the wire. The welding gun used in the welding process was Bernard BTB MIG Gun 300 A Rotatable Neck 045. The tools and consumables are also shown in Table 1 for the subsequent MPI process by which the gouged area is inspected.

Table 1. Tool & Consumables for MPI Check

Material	Type
White Contrast Paint	WCP-2 (Magnaflux)
Particle	7 HF (Magnaflux)
Yoke	Parker B-300 (230 V)

2.2. Cleaning before Welding

Before the fit-up, the areas on the boom plate that were to be jointed were first deoxidized through the meticulous removal of all foreign substances, including rust, oil, dust, paint, and other chemicals. This step is crucial to reduce the welding defects resulting from a lack of preparation before the joint. Contaminated surfaces were also treated through a grinding machine called a Wire brush. If rust had developed, a Sandpaper grinding machine (Flap Disc) was used in its place. After grinding, the bevel joint was required to remove all the debris and contaminants from the grinding process using a high-pressure air compressor on the preparation joint.

2.3. Fit-Up Process and Material Use

The bottom plate boom consisted of a first plate-shaped with a bending plate of size R3464 mm, with a material length specification of 2426.9 mm and a width of 750 mm. The second plate, to be connected, had dimensions of 1151.5 mm in length and 513 mm in width. Both materials used had the same composition (equivalent), namely S355 + J2N. The material content is detailed in Table 2.

Table 2. Boom Plate Elemental Composition [2]

Element	Content
Carbon	0.22%
Silicon	0.55%
Manganese	1.60%
Phosphorous	0.035%
Sulfur	0.035%
Copper	0.047%

2.4. Preheating and Welding Process

The bottom boom plate was welded after preheating at a re-dry temperature of 60° C, which only removes the material's moisture content. This process was done in a sequence mentioned in the WPS for the bottom plate joint boom, as shown in Table 3.

Table 3. Welding Procedure Specification (WPS) for Joint Bottom Boom Welding [3]

Description	Root	Filler	Capping
Filler ∅ (mm)	1.32	1.32	1.32
Current (A)	190 – 230	270 – 310	260 – 290
Voltage (V)	22.0 – 26.0	27.5 – 32.0	27.0 – 29.0
Polarity	DCEP	DCEP	DCEP
Wire Speed (m/min)	3.5 – 6.5	7.0 – 9.0	6.5 – 8.5
Travel Speed (mm/sec)	3.3 – 6.3	5.3 – 8.8	5.0 – 8.6
Heat Input (mm/sec)	0.53 – 1.45	0.67 – 1.48	0.65 – 1.33
Welding Position	1G	1G	1G

2.5. Visual Inspection and Cleaning After Gouging

Following welding, a visual inspection was conducted internally and by a quality check, following the acceptance criteria at 1E0099[10] as shown in Table 4, before the back gouging process was carried out. This work was conducted on the actual bottom joint boom structure, as illustrated in Fig. 3. If the visual inspection from the internal team operation and quality was accepted, then the back gouging process was carried out. The back gouging process ensured that the fusion of both sides of the welding could be appropriately blended.

Table 4. Acceptance Criteria for Welding on 1E0099

Defect Name	Remarks	Standard Defect Limit	Stringent Defect Limit
Cracks – Longitudinal, Transverse, Radiating, Crater, Disconnected, Branching		Not Permitted	Not Permitted
Crack – Transverse	Hard Surfacing Welds Only	Permitted	Permitted
Crack – Transverse	Joining Welds	Not Permitted	Not Permitted
Surface Porosity	Minimum diameter to be recordable. Maximum diameter for a single pore. Maximum number of recordable pores in any 300 mm length of weld. Maximum number of recordable pores in any 50 mm of weld length for welds less than 300 mm in length	1 mm (no minimum in clusters) 2 mm 6 1	Not permitted
Internal Gas Pore	Maximum diameter for a single pore	20% nominal weld size, MAX 3 mm	Same as the standard defect limit
Clustered Porosity	Maximum length of cluster in any weld (pores of any diameter, where a cluster is more than two pores with a distance separating them less than or equal to 3 times the diameter of the largest pore).	MAX length = ½ weld bead width (surface). 20% weld volume (cross section) for 25 mm or 10% of weld length (subsurface).	Not permitted at the surface 20% minimal weld size. Max 3 mm (subsurface).
Lack of Fusion	Visual (Breaking the Surface) Subsurface Maximum Height or Width Subsurface Maximum Length for Any Single Discontinuity Maximum Length in Any Weld	Not Permitted 1 mm 25 mm 10% of Weld Length	Not Permitted Not Permitted

Defect Name	Remarks	Standard Defect Limit	Stringent Defect Limit
Lack of Penetration (For Partial Penetration Welds Only)	Maximum Reduced Penetration	10% of Nominal Weld Size Not to Exceed 1 mm	Not Permitted
	Maximum Allowed Total Length of Reduced Penetration	25 mm or 10% of Weld Length	
Undercut	Maximum Depth Measured from Plate Surface – Any Length	0.5 mm	5% of plate thickness, MAX 0.5 mm
	Weld toes at the melted corner may have a scalloped appearance, which is not to be labeled as undercut		
Excess Weld Metal – Groove Weld Reinforcement (Convexity)	Any Length Weld Face Width 20 mm	2.0 mm	Same as standard defect limit
	Weld Face Width Over 20 mm but less than 30 mm	3.0 mm	
	Weld Face width 30 mm and Over	4.0 mm	
	Conformance to Design – Excess Reinforcement may be left oversized (within defect limitations plus 2 mm) without repair, provided the toe angles are greater than or equal to 90° and the excess does not interfere with satisfactory end use of the component (i.e., distortion, Fit-up interference, etc.) A documented Deviation process shall be used, and Corrective Action pursued to eliminate further deviations.		
Elongated Cavities (Subsurface)	Maximum Height of Width	3 mm	20% nominal weld size, MAX 2 mm
	Maximum Length for Any Single Discontinuity	25 mm	25 mm
	Maximum Length in Any Weld	10% of Weld Length	
Wormholes (Subsurface)	Maximum Height or Width	3 mm	20% nominal weld size, MAX 2 mm
	Maximum Length for any local affected area	25 mm	25 mm
	Maximum Length in any Weld	10% of Weld Length	
Shrinkage Cavities	Maximum Diameter or Depth	1 mm	25% of the weld seam length
	Maximum Length in Any Weld	25 mm, or 10% of Weld Length	5% of plate thickness, MAX 0.5 mm
Slag, Flux, or Oxide Inclusions	Maximum Height of Width	1 mm	20% nominal weld size, MAX 2 mm
	Maximum Length for Any Single Discontinuity	25 mm	25 mm
	Maximum Length in Any Weld	10% of Weld Length	
Metallic Inclusion		Not permitted	Not permitted

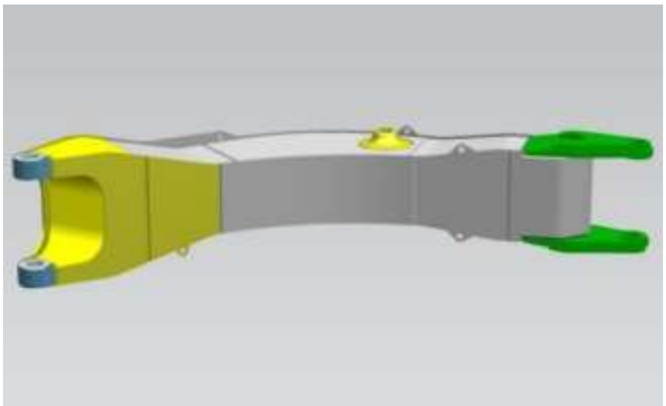


Fig. 3. *Actual Bottom Joint Boom Structure*

After the back gouging process was completed, the grinding on the welded pot preparation was ensured to be completely clean of residual discharge resulting from the previous back gouging process. This step is crucial to ensuring that the subsequent back-welding process can produce good fusion and that there are no weld defects left behind at the root of the previous welding.

2.6. Magnetic Particle Test

Before the MPI inspection, the yoke used must undergo a magnetic lift calibration test, where it is expected to lift at least 10 lb (4). After that, the conclusions regarding the appropriateness and readiness of the yoke to calibrate have been made. The surface to be inspected must be cleaned. This includes washing the surface of the test piece with a detergent solution to remove dirt, grease, oil, sand, rust, and scale.

Subsequently, the White Contrast Paint (WCP) is applied on the surface of the back gouging preparation. This application must be carried to the extent of at least 1 inch (25mm) of the base metal to observe the proper contrast. A yoke is then placed on the part or region to be tested, and wet particles are distributed uniformly on the said surface. When applying the magnetic particle, it is essential to be alert to any signs showing that it is in the process of working.

They were retrieved from the process improvement of the boom structure, where the problem of no fusion in the root back welding area at the bottom joint of the boom occurred. The data were collected on the boom structure's BSN 263, 264, 265, 266, 267, and 268. The information is of paramount importance in determining the efficiency of the MPI process in detecting defects and the solidity of the welded structure.

3. Results and Discussion.

This study evaluated the effectiveness of Magnetic Particle Inspection (MPI) in detecting welding defects during the back gouging process for boom structures. Data were collected from six Body Serial Numbers (263-268) to compare Defects Per Unit (DPU). The welding process followed the Welding Procedure Specification (WPS), but suboptimal root penetration was observed due to gaps between the plates, as shown in Fig. 4 and Table 5. Factors such as insufficient backing ceramic, inadequate preheating, and poor joint design contributed to these defects.

Fig. 4. Welding Seam Before Back Gouging

Table 5. Gap Measuring Results

263	264	265	266	267	268
3 mm	2 mm	2 mm	3 mm	4 mm	4 mm

This finding was attributed to several factors, including the lack of process improvement to add backing ceramic to root preparation, insufficient skills or expertise among welders, joint design with a root face that is too thick, preheating before welding that does not reach the corresponding hot spot WPS, and gaps or root openings that are too wide.

Fig. 5 shows that the correct back gouging process yielded good gouging results and uniform grooves. Before conducting the magnetic particle test, as shown in Fig. 6, the joint preparation had to be cleaned of all contamination following the back gouging process.

Fig. 5. Welding Seam After Back Gouging Process

Fig. 6. Welding Seam After MPI Checking

Linear indications, caused by surface roughness, contamination, and suboptimal welding parameters, were found across samples, as illustrated in Fig. 7. These indications can occur due to several factors, including suboptimal material cleanliness before welding, which can cause a lack of fusion; using a voltage that is too low, which can also lead to a lack of fusion; and the need for a faster travel speed[11].

Fig. 7. Linear Indication

Rounded indications, attributed to porosity and gas flow issues, were less frequent, but still present (Fig. 8). These indications could occur due to porosity during the root process and are caused by several factors, including joint preparation contaminated by water, paint, grease, oil, and other substances; the use of electrodes that are too humid and a lack of preheating before the welding process; strong air or wind gusts that interfere with the flow of shielding gas; gas flow that is too high, causing turbulence and drawing air out; and gas flow that is too low, not providing enough protection for the weld crater[12].

Fig. 8. Rounded Indication

The following Fig. 9 presents the Chart Data Defect per Unit (DPU) obtained after the inspection and the built-in Quality (BIQ) process. From this data, it is known that the number of defects found in the sample is higher in the form of linear indications than rounded indications. The DPU data highlight Body Serial Number 265 as having the highest defect rate.

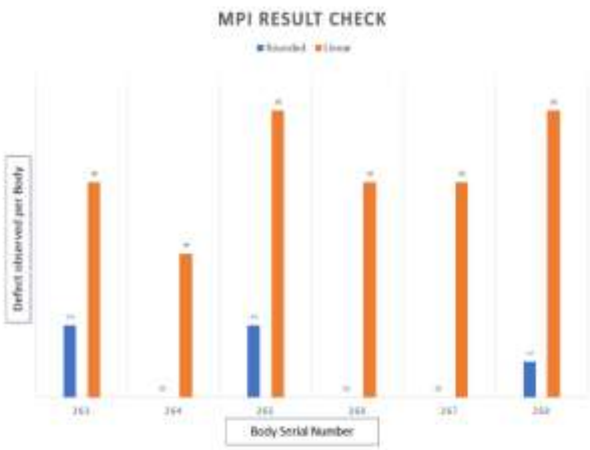


Fig. 9. Chart Data Defect per Unit (DPU)

4. Conclusions.

In conclusion, this study confirms that Magnetic Particle Inspection (MPI) is an effective quality control step before Ultrasonic Testing (UT). By detecting linear and rounded defects early in the welding process, MPI consistently reduced defect rates by 10%, leading to a 15% reduction in rework costs. The integration of MPI with programs such as People, Quality, Velocity, Cost (PQVC), and Built-In Quality (BIQ) resulted in improved welding accuracy and efficiency. These findings align with the research objectives, confirming that MPI plays a critical role in enhancing the overall quality and cost-effectiveness of welding processes in heavy machinery manufacturing.

References.

[1] H. Maury, J. Wilches, D. Illera, V. Pugliese, J. Mesa, and H. Gómez, "Failure assessment of a weld-cracked mining excavator boom," *Eng Fail Anal*, vol. 90, pp. 47–63, Aug. 2018, doi: 10.1016/j.engfailanal.2018.03.022.

[2] S.-C. Park, "Design of Excavator Boom Structure Based on Fatigue Strength of Weldment(II)," *Journal of Welding and Joining*, vol. 29, no. 4, pp. 61–66, Aug. 2011, doi: 10.5781/kwjs.2011.29.4.423.

[3] S. M. Bošnjak, M. A. Arsić, N. Đ. Zrnić, M. P. Rakin, and M. P. Pantelić, "Bucket wheel excavator: Integrity assessment of the bucket wheel boom tie-rod welded joint," *Eng Fail Anal*, vol. 18, no. 1, pp. 212–222, Jan. 2011, doi: 10.1016/j.engfailanal.2010.09.001.

[4] M. Tümer, C. Schneider-Bröskamp, and N. Enzinger, "Fusion welding of ultra-high strength structural steels – A review," *J Manuf Process*, vol. 82, pp. 203–229, Oct. 2022, doi: 10.1016/j.jmapro.2022.07.049.

[5] H. Liu and Y. Hu, "Welding," in *Encyclopedia of Materials: Metals and Alloys*, Elsevier, 2022, pp. 39–65. doi: 10.1016/B978-0-12-819726-4.00143-5.

[6] C. MacLeod and Y. Javadi, "Advanced nondestructive evaluation for welded joints," in *Welding of Metallic Materials*, Elsevier, 2023, pp. 431–461. doi: 10.1016/B978-0-323-90552-7.00017-1.

[7] Y. Hadi Ilhamda, Mutiarani, and I. Wijayanti, "Pengaruh Variasi Sudut Pengelasan Menggunakan Welding Carriage Terhadap Weld Bead Pada Pengelasan GMAW," *Jurnal Teknologi dan Riset Terapan (JATRA)*, vol. 5, no. 2, pp. 2685–4910, 2023, doi: 10.30871/jatra.v5i2.6591.

[8] H. Huang *et al.*, "Experimental and numerical investigation of a gouging heat source model and gouging/welding residual stress and deformation," *J Manuf Process*, vol. 110, pp. 101–113, Jan. 2024, doi: 10.1016/j.jmapro.2023.12.056.

[9] G. Y. Koga, T. Ferreira, A. P. de Bribean Guerra, D. Cunha, J. G. G. Wiezel, and C. Bolfarini, "Air carbon arc gouging of austenitic stainless steels prior to arc welding – opportunities and risks," *J Mater Process Technol*, vol. 303, p. 117524, May 2022, doi: 10.1016/j.jmatprotec.2022.117524.

[10] A. Fajrin, R. Sutrisno, L. Giat, and J. Putra, "NDT Testing with Visual Testing Method in the Inside Upper Frame 6015 Area with GMAW Welding Based on 1E0099," *Journal of Mechanical Engineering, Science, and Innovation*, vol. 4, no. 1, pp. 17–26, 2024, doi: 10.31284/j.jmesi.2024.v4i1.5125.

[11] P. Moore and G. Booth, "Welding problems and defects," in *The Welding Engineer□s Guide to Fracture and Fatigue*, Elsevier, 2015, pp. 23–36. doi: 10.1533/9781782423911.1.23.

[12] F. Yusof and M. F. Jamaluddin, "Welding Defects and Implications on Welded Assemblies," in *Comprehensive Materials Processing*, Elsevier, 2014, pp. 125–134. doi: 10.1016/B978-0-08-096532-1.00605-1.