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RESIDUAL STRESS MEASUREMENT OF USED MINING DUMP TRUCK FRAME FOR REMANUFACTURING PURPOSES

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Abstract

Remanufacturing the main frame of a mining dump truck can save cost, energy, and materials in heavy equipment industries. It also can reduce CO_2 emissions for environmental preservation to achieve sustainability. However, since the mainframe received a dynamic load during operation, it presumably leaves accumulated residual stresses in the frame. The residual stress, particularly tensile residual stress, stands out as a primary contributing factor to the initiation of cracks, which may ultimately result in failures. In this paper, the residual stress of the used mining dump truck main frame was identified by modeling simulation using FEA (finite element analysis) and actual measurement using a portable x-ray residual stress analyzer with the cos α method. The results showed that the weld area subjected to dynamic loads exhibited the highest tensile residual stress, reaching approximately +772 MPa. This specific region emerges as a critical area demanding attention during the remanufacturing process. The application of PWHT (post-weld heat treatment) at 400 °C for 1 hour effectively reduced residual stress on the weld joint, predominantly tensile residual stress, by more than 80%.

Keywords: *Residual stress, cos α method, mining dump truck, remanufacturing, stress relief*

1. INTRODUCTION

The limited availability of natural resources and awareness of environmental preservation encourages the industry to minimize energy use and implement sustainable production [1]. The circular economy concept helps the industry minimize the use of resources and reduce waste to accomplish sustainability by recovering resources and value from end-of-use products [2]. In a circular economy, the end-of-use products may undergo reuse, recycling, refurbishing, or remanufacturing after their disposal [3]. The remanufacturing is more attractive compared to others because it guarantees the quality of products equal to that of new ones [4].

Remanufacturing, also known as "Reman," is a process that restores used, worn, and retired products or modules to a brand new condition through a salvaging technology [5]-[6]. The process involves disassembly, cleaning, sorting, salvaging or substitution, reassembly, testing, and quality confirmation [1]. In the heavy equipment industry, remanufactured products can save cost, energy, and materials. It also can reduce CO_2 emissions by up to 90% compared with manufacturing raw materials that are suitable for environmental preservation [6].

Off-road mining dump trucks are widely used in open pit mining to transport material from the site to the processing plant. After around 50,000 hours of operation, the mining dump truck will be scrapped and replaced with a new one, as shown in Fig. 1. This condition led to mining dump trucks having the potential to be remanufactured, especially on the significant parts such as the main frame. However, since the mainframe received a bending load during operation, it presumably leaves accumulated residual stresses

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on the frame. Residual stress or locked-in stress refers to stress that may persist in a material after manufacturing, processing, or service conditions, even with no external loading or thermal gradients [7]-[8].


(a)

(b)

Figure 1. (a) off road mining dump truck and (b) used main frame after ±50,000 hours operation (courtesy of PT Komatsu Indonesia)

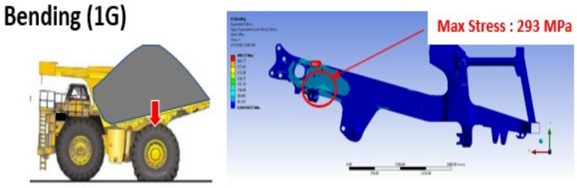
Tensile residual stress is harmful and can lead to failures, especially in areas that are subjected to alternating service loads [8]. Therefore, it is essential to measure the residual stress on the used frame before remanufacturing it. Various techniques have been developed for measuring residual stress, ranging from destructive methods such as hole drilling to non-destructive approaches using x-ray and neutron diffractions, ultrasonication, and magnetic methods [7], [9]. The most widely used approach for measuring residual stress is the hole drilling method due to its simplicity, speed, and applicability in both laboratory settings and actual field conditions [7]. However, this method is destructive and not suitable for remanufacturing purposes. Among other non-destructive methods, the use of X-ray diffraction to measure residual stress has been mature scientifically and in technology [9]. Recent technology of portable x-ray stress analyzer allows us to measure the residual stress without destruction easily and is very efficient for industry [8].

This paper presents the residual stress analysis in used main frame of the mining dump truck, measured by the cos α X-ray diffraction method for remanufacturing purposes. In addition, this paper validates the mechanical stress simulated using ANSYS® software for predicting the high-stress area (critical area) of the main frame. Embracing the objective of understanding the residual stress in the used frame of a mining truck, this study integrates three different aspects of residual stress in a single study, 1) validate determination of residual stress using the cos α X-ray diffraction method; 2) identify critical areas of mining truck frame for remanufacturing purposes; 3) evaluate residual stress and their relaxation using the process of heat treatment.

2. MATERIALS AND METHODS

2.1 Mechanical Stress Modeling using FEA (Finite Element Analysis)

Modeling simulation using FEA (finite element analysis) was conducted to predict the location of the load on the main frame that leads to the existence of residual stresses. This modeling simulation used the ANSYS® program, as shown in Fig. 2.



(a) (b)

Figure 2. Stress modeling simulation with FEA (finite element analysis): (a) loading condition and (b) the results of modelling (courtesy of PT Komatsu Indonesia)

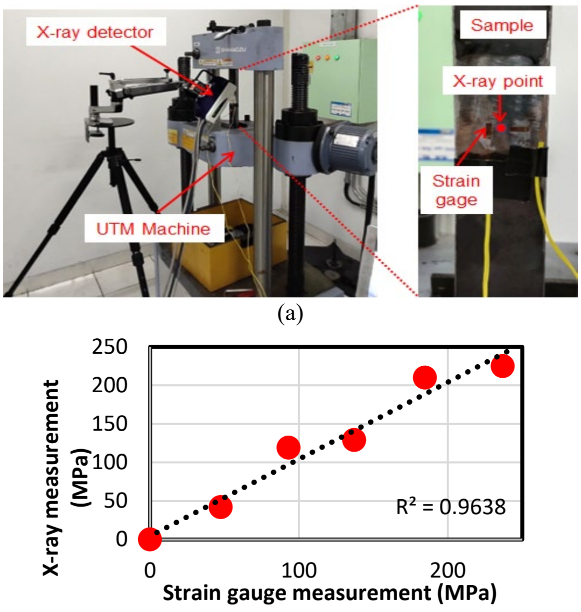
2.2 Calibration of Portable X-ray Residual Stress Analyzer

The study utilized a portable X-ray equipment, PULSTEC μ-X360 residual stress analyzer. Prior to its application, the equipment was calibrated by comparing the measurement result with the actual strain gauge attached to a plate specimen according to ASTM A36 (JIS SS400) with dimensions of 16 mm x 50 mm x 400 mm. The tensile force was driven using a Shimadzu UH-300kN universal testing machine. The schematic is shown in Fig. 3.

2.3 Residual Stress Measurement on Used Frame of Mining Dump Truck

Residual stress measurement was conducted on the main frame of the dump truck, which has been used for ±50,000 hours, as depicted in Fig. 4. As a comparison, residual stress on a new dump truck frame was also measured. The procedure was started by simulating the area under consideration using FEA which will become a reference for measuring the actual residual stress. Further, the actual residual stress was measured using portable

X-ray residual stress analyzer with the cos α method.

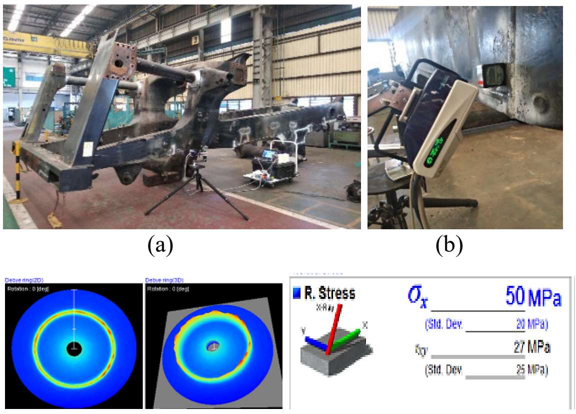


(a)

(b)

Figure 3. (a) the schematic of calibration X-ray residual stress analyzer and (b) comparison result between X-ray and strain gauge

The fundamental principle of residual stress measurement with an X-ray residual stress analyzer relies on the interaction between the X-ray beam wave and the crystal lattice [10]-[11].



(a) (b)

(c) (d)

Figure 4. Residual stress measurement on a used frame using portable x-ray residual stress analyzer (a) set-up of measuring equipment (b) measurement residual stress on weld joint (c) Debeye ring (d) residual stress value

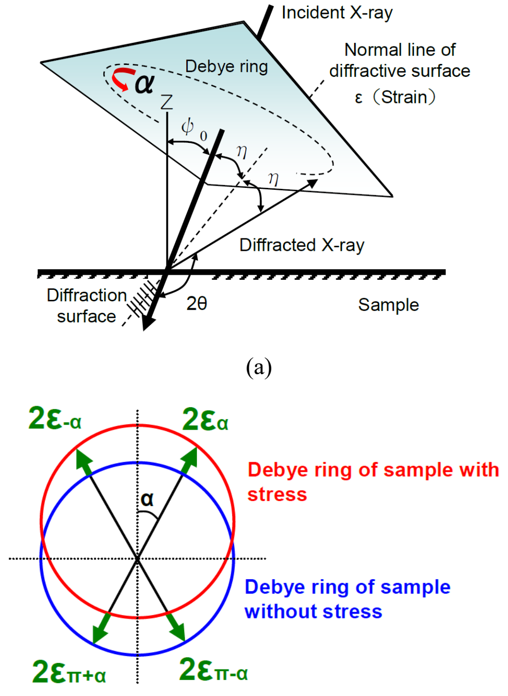
The stress is then determined from the measured lattice strain using the theory of elasticity [11]. As has been mentioned previously, in this work, the residual stress within the main frame was assessed using a PULSTEC μ-X360 X-ray residual stress analyzer employing the cos α method.

The cos α method for residual stress measurement was first proposed by Taira et al. in 1978 [12]. The underlying principle of this cos α method is explained as follows. When an X-ray beam is directed at polycrystalline materials, it generates diffracted X-rays in the form of a cone and circular diffraction pattern, known as the Debye-Scherrer (D-S) ring, which provides insights into lattice strain [13]. The whole Debye ring was captured on a two-dimensional detector, as shown in Fig. 5 [11]. Subsequently, the strain εα where α = 0-360° at the Debye ring can be utilized to estimate the residual stress following formula Eq. (1), Eq. (2), and Eq. (3) [14].

$$\varepsilon_{\alpha 1}=\frac{1}{2}\{(\varepsilon_{\alpha}-\varepsilon_{\pi+\alpha})+(\varepsilon_{-\alpha}-\varepsilon_{\pi-\alpha})\} \quad (1)$$

$$\varepsilon_{\alpha 2}=\frac{1}{2}\{(\varepsilon_{\alpha}-\varepsilon_{\pi+\alpha})-(\varepsilon_{-\alpha}-\varepsilon_{\pi-\alpha})\} \quad (2)$$

$$\sigma_x=-\frac{E}{1+v}\frac{1}{sin2\eta}\frac{1}{sin2\Psi_0}\left(\frac{\partial\varepsilon\alpha_1}{\partial cosa}\right) \quad (3)$$



(a)

(b)

Figure 5. Schematic diagram of the cos α method, (a) the formation of Debeye ring (b) comparison of Debeye ring with stress and without stress. (reprinted with permission from PULSTEC)

3. Result and Discussion

3.1 Residual Stress Result on Used Frame

Modeling simulation with FEA (finite element analysis) shows several points that have stress due to loading during operation. These points become a reference for measuring the actual residual stress as well as to confirm the results of the modeling simulation. Simulation results found 7 areas on the main frame that have potential high stress, as shown in Fig. 6.

Based on this simulation, the actual residual stress in the main frame area was subsequently measured with a portable X-ray residual stress analyzer. The cos α method measures many points at the D-S ring and has been effectively used in determining residual stress. Several research confirm that the residual stress measurement using the cos α method gives the same accuracy as the sin2 ψ method and is more efficient since a single X-ray incidence obtains the diffraction angles [14]-[16].

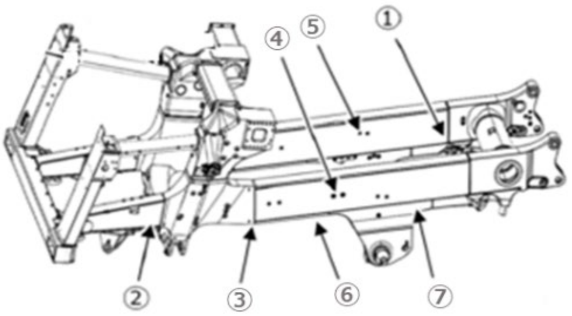


Figure 6. Illustration of stress location on the off-road dump truck main frame (courtesy of PT Komatsu Indonesia)

Figure 7 shows the result of residual stress measurement on the dump truck frame. The residual stress occurred in both compressive residual stress (-) and tensile residual stress (+). Tensile residual stress (+) mainly occurred on locations ①, ④, ⑤, and ⑦, which indicate the location of high load during operation. The highest tensile residual stress recorded on the used frame is +772 MPa.

Comparing the residual stress measurements result with the modeling analysis result, it was observed that the weld joint area subjected to substantial dynamic loads during the application experiences tensile residual stress.

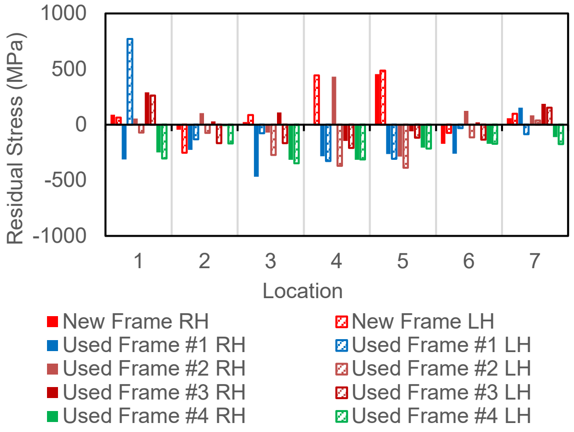


Figure 7. Residual stress on dump truck frame

Tensile residual stress stands out as a prominent factor contributing to the initiation of welding cracks, which can ultimately result in failures [8],[17]. Because of that, this weld joint area was identified as a critical zone necessitating residual stress relief treatment as part of the remanufacturing process and is explained as stress relief in the following session.

3.2 Residual Stress Relief

The standard methods for eliminating residual stress of welded joints on big structures include shot peening, VSR (vibration stress relief), and PWHT (post-weld heat treatment) [17]-[18]. Compared with other methods, PWHT has a higher stress relief rate and better efficiency [17],[19]-[20].

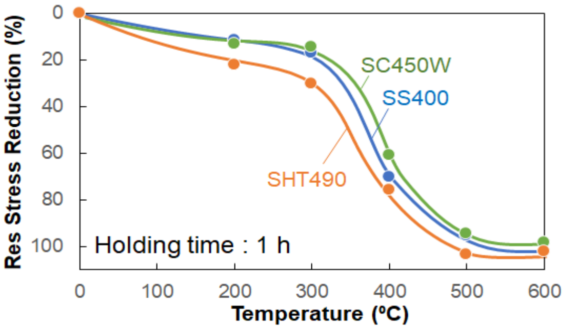


Figure 8. Residual stress relief by heat treatment at various temperatures and holding time for 1 hour

Because of that, residual stress relief experiments with the PWHT process were carried out by making a test piece of welded joints with the same material and weld construction as the main frame structure of the dump truck. The findings are presented in Fig. 8 and Fig. 9.

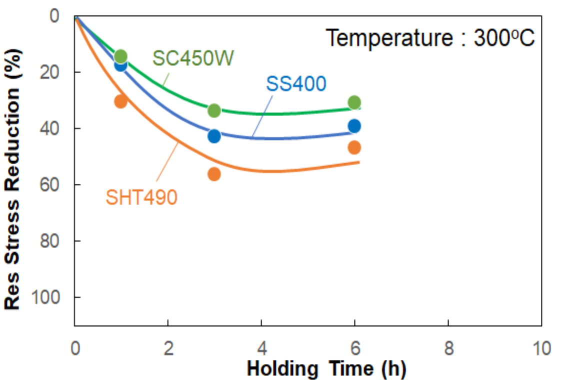
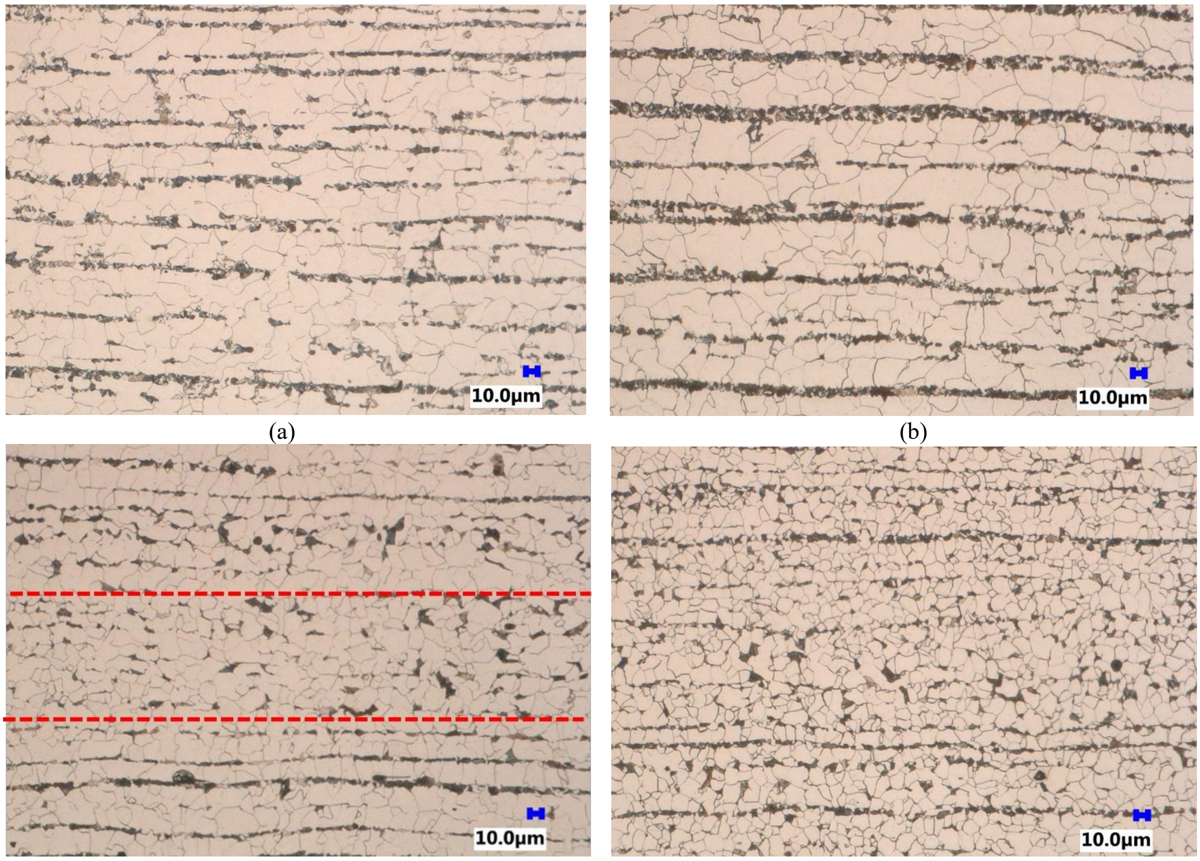


Figure 9. Residual stress relief by heat treatment under various holding times at temperature of 300 °C

As depicted in Fig. 8, residual stress in the weld joint was annihilated after PWHT at temperature above 400 °C. Regarding the influence of holding time, Fig. 9 indicates that the reduction in residual tensile stress becomes insignificant beyond 3 hours.

Microstructure observation was further carried out to reveal the effect of the PWHT process on the base material and the outcomes are presented in Fig. 10. As depicted in the figure, the microstructure does not change at 400 °C, partially recrystallize at 500 °C, and fully recrystallize at 600 °C. Comparing these microstructures with the graphs in Fig. 8 and Fig. 9 confirms that the PWHT process at 400 °C for 1 hour is effective in reducing residual stress in the weld joint without altering the microstructure.



(a) (b) (c) (d)

Figure 10. Microstructure comparation of frame (plate) before and after heat treatment for tensile residual stress removal. (a) before PWHT, (b) after PWHT at 400 °C for 1 hour, (c) after PWHT at 500 °C for 1 hour shows partial recrystallization at area between dotted line, (d) after PWHT at 600 °C for 1 hour shows material have full recrystallization

On actual structures, this comprehensive residual stress relief process was performed using a large furnace at PWHT facilities, PT Komatsu Indonesia, as shown in Fig. 11.

(a) (b)

Figure 11. Residual stress relief process for main frame structure at PWHT facilities, PT Komatsu Indonesia (a) the furnace and (b) the main frame in the furnace

4. CONCLUSION

Residual stress in the main frame of the mining dump truck can be identified using the cos α x-ray diffraction method. In this work, the highest tensile residual stress of around +772 MPa occurred in the weld joint area, which was then identified as the critical area that must get attention during the remanufacturing process. Post-weld heat treatment at 400 °C for 1 hour was proven to be effective in reducing residual stress in the weld joint.

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