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Microstructural analysis of cracked steam drum plate during fabrication process

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Abstract: The understanding of the fracture mechanisms of the thick steel plate cracked during the fabrication is of paramount importance for the improvement of the fabrication process for the pressure-containing vessels like steam drums. This article presented the microstructural analysis of the fractured steam drum plate during the fabrication process. The analysis involved visual inspection, chemical analysis, micrograph study, tensile test, and impact test. Results exhibited that the failure of the steel plate was related to the brittle fracture, initiated from the notch, and propagated in the transverse direction perpendicular to the rolling direction. The formation of martensite was found in the affected area, which lowered the crack resistance of the steel plate. The cold working conditions of the steel plate were induced by the rolling process and subsequently facilitated the fracture propagation. It is advised to conduct a grinding process to remove the notch and the heat affected zone. Warming the steel plate to be significantly above 0ºC is also suggested to be performed prior to the fabrication process.

Keywords: Brittle fracture, crack resistance, microstructure, failure

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1. Introduction

Steam drum is an important part of the power boiler. It can be defined as the large pressure chamber, which is used to accumulate the steam produced in the water tube and separate the mixture of steam and water (Pástor et al., 2020). The steam drum fabrication is complicated, and it is normally composed of several essential processes (Assefinejad et al., 2020). For example, cutting, rolling, welding, and assembling of the steam drum materials. It is also widely known that the performance and reliability of the steam drum is related to the quality of each fabrication process (Han et al., 2006). Thus, the efficient fabrication process of steam drum is of great significance for maintaining the structural integrity and safety of the steam drum.

Technically, a steam drum is a large cylinder with dished end and its thickness can vary depending on the design pressure of its boiler (Saha et al., 2010). It is usually made of low alloy and high strength steel plates rolled to form its shell (Liu et al., 2017). If the rolling stress becomes excessive, the rolled plates may be subjected to unexpected fractures. Besides, both ends of the plates must be beveled by the gas cutting process for circumferential and longitudinal welding joints. The heat during the gas cutting process can adversely affect the microstructure of the steel plates. For instances, the formation of the hard and brittle phase (Chowwanonthapunya & Peeratatsuwan, 2020). This phase contributes to the reduced fabricability of the steel plates by reducing their toughness, which could consequently result in the premature fracture of the plates (Zhang et al., 2020). Obviously, the lack of the fabrication quality can lead to the fracture of the steel plate, which requires extra time and cost for solving the problems. This potentially affects not only the cost overrun but also the overall project delivery time (Niazi & Painting, 2017). To ensure the quality of the steam drum fabrication, the fracture cases of the steel plates during the fabrication should be investigated in detail, particularly the microstructural analysis so that the corrective actions or preventions can be obtained and performed. However, few failure cases related to the drum fabrication have been reported. Hence, it should be important to conduct microstructural investigation on the thick steel plate fractured during the fabrication. Its investigation results undoubtedly become imperative for understanding the fracture mechanisms of steel subjected to the fabrication process. Such understanding leads to the establishment of the appropriate fabrication for the thick pressure-containing vessels like steam drums.

The present work then focused on the metallurgical failure analysis of a 123-mm thick steel plate which was cracked during the fabrication. The visual inspection and microstructural investigation were conducted to obtain the main causes of the failure and failure mechanisms. The significant mechanical properties were also investigated, and their results can be used to gain useful recommendations for improving the steam drum fabrication procedures.

2. Experimental procedure

This investigation was conducted on a 123-mm thick steel plate which was fractured during the rolling process of the steam drum fabrication. The cracked steel plate in as-received condition is shown in Figure 1.

Figure 1. Fractured steel plate in as-received condition.

Table 1. Chemical compositions of the cracked steel plate.

Element	C	Si	Mn	P	S	Cr	Fe
Wt. %	0.35	0.37	1.34	<0.005	<0.005	0.20	Bal.

Chemical compositions of the failed steel plate were analyzed, as given in Table 1. The analysis indicated that the material of the cracked steel plate was SA 299 carbon steel. The temperature during the fabrication was reported to be slightly above 0°C.

Visual inspection was initially performed by naked eyes and a moveable enlarging lens. Samples for the microstructural investigation were prepared from the failed steel plate adjacent to the actual fracture. The microstructure of unaffected areas of the fractured steel plate were also studied and employed for a comparison with those of the fracture areas. To conduct the microstructural analysis, mounted samples were ground on SiC paper down to 800 grade emery paper and then followed by polishing them with a diamond polishing paste of 1 µm. The polished surface of specimens was etched with 2% nital solution. As-polished samples were investigated by an optical microscope. Tensile test and Charpy impact test were also conducted to provide useful information for the investigation of the cracked steam drum plate.

3. Results

3.1. Visual examination

Figure 2 (a) shows the as-received fractured steel plate. It is obvious that the fracture initiated and propagated in the longitudinal direction of the rolled plate, as indicated by “B” and red arrows. The result from examination displayed no gross deformation, necking and thinning of the plate adjacent to the fracture, meaning that the steel plate underwent brittle fracture during the rolling process. It is evident that the edge of the failed steel plate was beveled by the gas cutting process, which was prepared for the circumferential weld joint. It is also obvious that there was a thickness transition in the edge of the plate, which prepared for the head part of the drum.

As indicated by A in Figure 2(a), the fracture initiation site was observed between the rolling marks, and it obviously appeared on the outer surface of the slope transition prepared for joining with the thinner steel plate. The enlarged view of the initiation site of this fracture in Figure 2(a) was shown in Figure 2(b). As pointed by the arrow, the fracture origin site was observed. The notch was found along the edge of the lower surface. Figure 2(c) exhibited the fracture propagation which obviously proceeded from the fracture initiation site in the longitudinal axis perpendicular to the rolling direction.

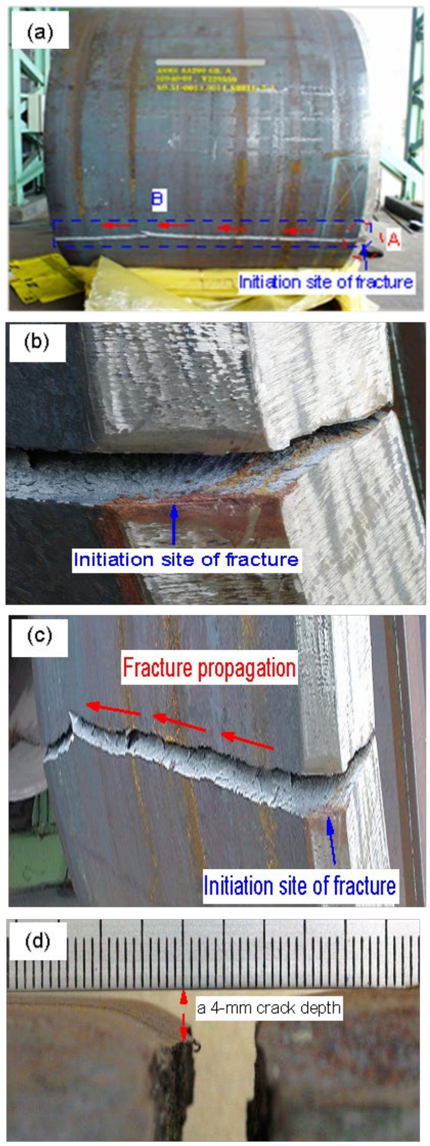

Figure 2. (a) The as-received fractured steel plate, showing fracture initiation site (A) and the propagation direction (B and red arrows), (b) the enlarged view of the fracture initiation site, (c) the fracture propagation and (d) the depth of the crack.

Figure 2 (d) provided the details of the notch depth, which was estimated to be 4 mm. The fracture surface of the failed steel plate was shown in Figure 3 (a).

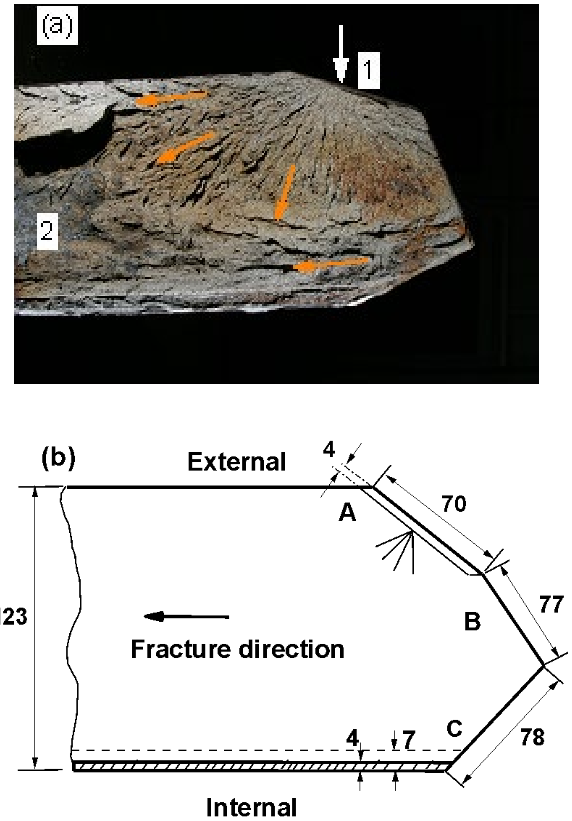

Figure 3. (a) The fracture surface and (b) the sketch of the fracture surface with the dimension on the beveled surface.

The observation on the fracture surface from Figure 3(a) provided the location of the crack origin taking place on the outer beveled surface. The chevron patterns as the distinguishing marks of the brittle fracture were clearly seen (Sowards et al., 2012; Li et al., 2013). Technically, these marks can indicate the crack propagation direction. The apex of these marks normally points toward the crack origin (Hazra & Singh, 2021; Rao & Eischen, 2016). Thus, the fracture should be originated from Area 1 and propagated toward Area 2, as given by the arrow in Figure 3(a). To clearly understand the fracture, the sketch of the fracture surface with dimensions on the beveled surface was given in Figure 3(b). The shaded area indicates the 4-mm width shear lip after fracture and the dash line means the 7-mm width unfractured area.

3.2. Microstructure examination

As mentioned, the edge of the failed steel plate, as seen in the edge "A" of Figure 3(b), was subjected to the heat from the gas cutting process for the circumferential weld joint. Thus, it should be vital to investigate the microstructure in the heat affected area and compare its results with those of the unaffected area. Figure 4 showed the micrograph of the mid-wall of the failed steel plate, where no significant thermal degradation was anticipated.

Figure 4. Microstructure examination conducted at the mid-wall of the failed steel plate.

Microstructure examination at the mid-wall of the failed plate clearly exhibited the ferrite/pearlite banded structure. This kind of structure is usually found in the hot rolled steels and it can be described as a microstructure which composes of alternate layers of pro-eutectoid ferrite and perlite in comparison to irregular distribution of these microstructural constituents (Peeratatsuwan & Chowwanonthapunya, 2020).

The microstructure of the edge "A" investigated from the external surface to the mid-wall plate was shown in Figure 5(a)-(b) and the microstructure transformation was obviously observed, indicating that these areas was heat-affected from the gas cutting process. Technically, the gas cutting process provides the preheat flame, which can raise the edge of the steel plate to about 980°C so that the steel at the edge can be oxidized and then blown away (Adedayo, 2011).

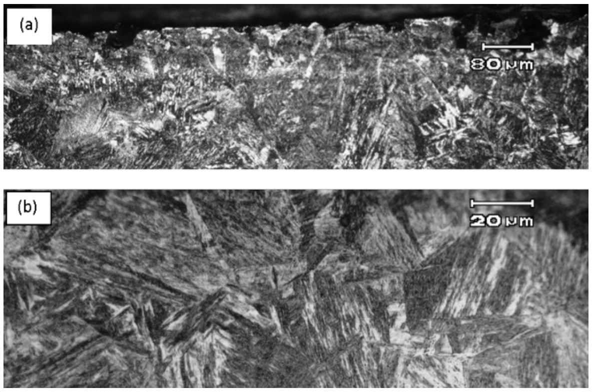

Figure 5. (a) Microstructure alternation found from the edge "A" of Figure 3(b) and (b) the higher magnification of the altered microstructure taken at the edge "A."

Obviously, the preheat temperature is above the transformation temperature, resulting in the transformation of ferrite/pearlite into austenite. After cutting, the steel plate is subjected to the natural cooling process, the cooling rate of which determines the final microstructure. The near surface region of the edge “A” was directly affected from the heat of the thermal gas cutting process and after the cutting process, this area underwent the rapid cooling rate because it directly contacted with the cold air, the temperature of which was just slightly above 0°C. The 123-mm thick steel plate, considered as a thick plate, also facilitated the faster heat dissipation by heat conduction. Thus, the final microstructure of this region after cooling was mostly related to the formation of martensite, as depicted in Figure 5(a)-(b). The finding in this section pointed out that heat generated from the gas cutting process facilitated the transformation of austenite and the rapid cooling at the metal/air interface was responsible for the martensite formation, which is hard and brittle in nature. The presence of such brittle phase promoted the brittleness and resulted in the residual stress accumulation (Barbosa et al., 2006). Both can reduce the crack resistance in the near surface region of the edge “A,” which would potentially lead to the premature fracture of the failed steel plate.

3.3. Mechanical property examination

To obtain useful information about the fabrication of this steel plate, a tensile test and Charpy impact test were conducted. Tensile test was conducted according to ASTM A370-21 (ASTM A370-21, 2021). and round specimens for tensile test were prepared from the inner, the mid-wall, and external part of unaffected areas of the failed steel plate. Their diameter was 12.5 +/- 0.2 mm and gauge length were 50+/- 0.1 mm. The averaged properties obtained from tensile test and the standard values of properties were given in Figure 6. Results of testing revealed that the steel plate has complied with the standard requirement of mechanical properties. However, the yield strength value of all tensile test specimens was significantly higher than that specified in the standard requirement.

Technically, steel can be hardened when it is subjected to the mechanical forming process (Krishna et al., 2015). This steel plate was pre-bended and rolled for the fabrication of the steam drum. Hence, the increased yield strength would be resulted from the pre-bending and rolling process. The lowered difference between the ultimate tensile and yield strength can be seen from Figure 6. As indicated in this figure, the lowest difference value of the ultimate tensile and yield strength was 68 MPa, but that of the lowest ultimate tensile and yield strength in standard was 240 MPa. This finding means that as crack initiated after yielding, it required just slightly more applied stress to propagate in the transverse direction perpendicular to the rolling direction of the steel plate. Besides, it is suggested that combination of cold working, residual stress, and the brittleness at the dished edge of the plate would accelerate the fracture propagation of the fracture occurring in the failed steel plate.

A Charpy V-notch test was conducted to measure the toughness of materials which related to their fracture toughness. specimens for this test were prepared from the steel plate at the mid-wall of the plate. The dimension of specimens was 55 X 10 X 10 mm, and the test was performed as per ASTM E23-18 (ASTM E23-18,2018).

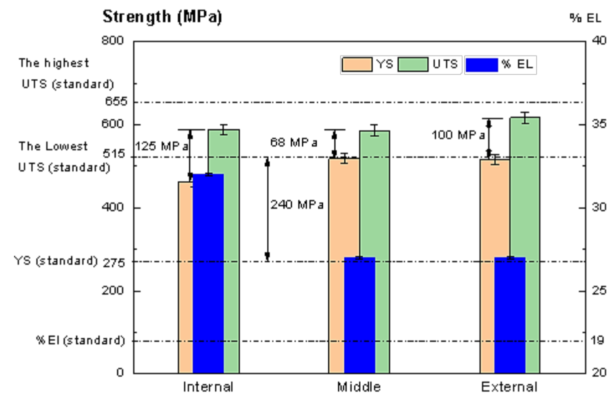

Figure 6. Yield strength (YS), ultimate tensile strength (UTS), and % Elongation (%EL) obtained from tensile test.

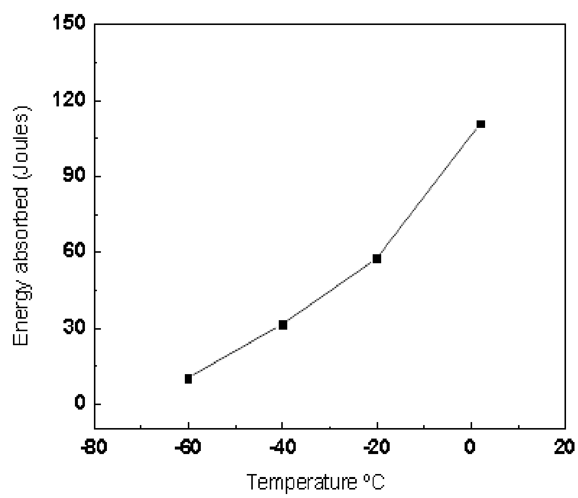

Figure 7. Absorbed energy from the impact test.

Figure 7 showed the results of Charpy V-notch test conducted on specimens prepared from the failed steel plate (unaffected area). It was clearly seen that the absorbed energy showed acceptable results for a pressure vessel used in operation with the temperature from 0 to -40 °C. However, as temperature became lower, the absorbed energy of specimens significantly decreased. Thus, this finding may suggest that the thick steel plate should be warmed up to significantly above 0°C so that the absorbed energy of steel can be recovered, and the better fracture toughness of steel can be obtained, particularly when it the steel plate encounters the forming stress in the plain strain condition.

4. Discussion and suggestions

The schematics diagram used to explain the failure mechanisms of the failed steel plate is provided in Figure 8. SA 299 carbon steel plate was prepared for the steam drum fabrication. The edge of the plate was subjected to the gas cutting process for the weld joint preparation. The thermal gas cutting caused not only the formation of a 4-mm depth notch but also the microstructure change. The edge "A" from Figure 3(b) underwent the transformation of ferrite-pearlite into austenite during heating and the rapid cooling at the edge "A" and the cold air facilitated the formation of martensite, as clearly seen from. Besides, the residual stress in the steel may also be accumulated in the steel.

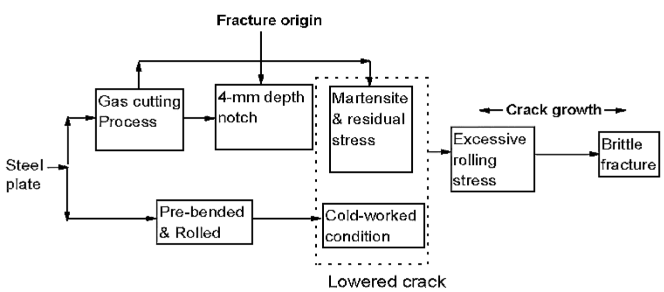

Figure 8. The schematic diagram illustrates the mechanisms of failure occurring in the failed steel plate.

The rolling process can produce cold-worked conditions to the steel plate. All potentially reduced the crack resistance of the steel plate. During fabrication, steel plate experienced rolling stress, which was excessive. The notch would function as the stress concentration and then became the crack origin. The excessive forming stress accelerated the crack propagation through the degraded crack resistance steel plate, finally causing the brittle fracture as clearly observed from Figure 2 and 3. Based on the results of this investigation, the recommendations, it is advised to remove the notch by grinding. Grinding the notch removed not only the stress concentration effect but also the heat affected area. The results from the Charpy impact test provided the fact that warming up the steel plate to be markedly above 0°C is useful to improve the toughness of the steel plate.

5. Conclusions

The microstructure analysis of the failed steam drum plate was already conducted. The visual inspection revealed that the steam drum plate experienced a brittle fracture. The fracture origin was found at the notch located on the outer beveled surface of the steel plate. The gas cutting process potentially caused the notch which then became the fracture origin. The rapid cooling after the cutting process promoted the formation of martensite and the accumulation of the residual stress in this area. The pre-bending process also induced the cold working conditions in the steel. All favored the brittleness of the steel plate, accelerating the crack propagation. Mechanical grinding to remove the notch and the heat affected area from the steel plate was suggested to be performed prior to the rolling process. Warming the steel plate to be above 0°C is also recommended for the improvement of the steel toughness during fabrication.

Conflict of interest

The authors have no conflict of interest to declare.

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