ROOT CAUSE ANALYSIS ON MANUFACTURING DEFECTS IN BRASS OXYGEN VALVES

Wan Mohd Haqqi Wan Ahmad[1], Shaiful Rizam Shamsudin[2,*], Siti Hawa Mohamed Salleh[1], Mohd Rafi Adzman[3], Rajaselan Wardan[1] and Mahalaksmi Gunasilan[2]

[1]Faculty of Chemical Engineering Technology, Universiti Malaysia Perlis (UniMAP), 02600 Arau, Perlis, Malaysia.
[2]Faculty of Mechanical Engineering Technology, Universiti Malaysia Perlis (UniMAP), 02600 Arau, Perlis, Malaysia.
[3]Faculty of Electrical Engineering Technology, Universiti Malaysia Perlis (UniMAP), 02600 Arau, Perlis, Malaysia.

*rizam@unimap.edu.my

Abstract. Brass valves are widely used in oxygen gas cylinder systems to regulate pressure and ensure safe operation. The production methods for brass valves include hot forging (700 °C), stress-relieving (300 °C), shot blasting, machining, and selective chrome plating on the external surface. Pneumatic testing at 400 bar has detected more than 10 % of the product production was found to have signs of leakage, and the most severe was when there were visible hairline cracks on the inner wall. Therefore, several tests to investigate valve failure were conducted to identify the root cause of the failure using a series of microscopic methods on the failed sample as well as the as-received brass billet. The study found that hairline cracks in brass valves were most likely caused by internal dross originating from the billet that was not properly removed during the casting process. The presence of dross in the billet manufacturing stage was identified as the primary reason for valve failure. Hot forging and other manufacturing techniques were found to be insufficient to eliminate the formation of dross, leading to a deterioration in the mechanical properties of the valves. In order to overcome this issue, flux can be added to the molten brass to help remove impurities and reduce the formation of dross. As a result, the mechanical properties of the final product deteriorated even though it had gone through the forging process.

Keywords: Brass valve, hot-forging, failure analysis, dross, cracks

---

Article Info

Received 20th January 2023
Accepted 9th April 2023
Published 1st May 2023

ISSN: 1823-7010, eISSN: 2600-7444

Introduction

Copper-zinc alloys, commonly known as brass, are frequently used for their corrosion resistance, non-magnetism, and machinability. The low melting point and good malleability of brass make it easy to fabricate. Its durability, strength, and thermal conductivity make it suitable for valves, fittings, and equipment for containers of explosive gases. The manufacture of brass products involves casting, extrusion, hot forging, and machining [1]. 70 % scrap metal and 30 % pure copper and zinc are melted and mixed to make a 70/30 brass billet.

The production of oxygen gas valves made of brass alloys involves various processes such as casting, extrusion, cold drawing, hot forging, and machining. After chemical examination, billets are heated for hot rolling, and slab milling and cold rolling are used to achieve the necessary size [2]. However, the production of brass-based products can be challenging, as they may suffer from imperfections, defects, low quality, and reliability issues at every level of the production processes [3].

It is critical for designers and plant operators to comprehend valve failure mechanisms in order to optimise valve reliability and drive efficient plant operations while maintaining a safe working environment. The failure of brass valves can be attributed to several manufacturing defects and problems, including the presence of cavities and porosity, surface flaws, and non-metallic contamination [3,5]. For example, improper mold shape, temperature, and composition can cause shrinkage defects in brass casting [4]. Dross or slag in the billet matrix can make the brass brittle and prone to cracking during extrusion [5]. Inhomogeneous stress distribution during hot forging can lead to flash cracking [1,6], while insufficient cooling water can cause surface blackness cracks and lead clustering [7]. Additionally, uneven zinc elements in brass can result in imperfections in forged brass products, leading to brittle γ-phase brass unsuitable for forging [8]. Surface cracking in hot forging brass components can also occur due to excessive working on the surface and too low forging temperature [9].

Standard quality inspection techniques, including pneumatic testing, visual inspections, non-destructive tests like radiography and ultrasonic tests, chemical analysis, and mechanical testing, are used to ensure the safety and quality of oxygen brass valves [3,10]. The as-received brass valves in this case had never been utilized in operation by any users, but during pneumatic testing at a pressure lower than 400 bar, a 10 % from specific manufacturing batch was found leaked, and personnel responsible for quality assurance discovered a hairline crack in the female thread area during their inspection. Subsequent radiography testing confirmed the presence of multiple cracks on the valve body. The brass valves were produced using hot forging (700 °C), pressure relief (300 °C), shot blasting, milling, and selective chrome plating. The chemical compositions of the brass valve body were determined by optical emission spectroscopy (OES), as displayed in Table 1.

Table 1: Nominal chemical composition of the specimen (wt.%)

Cu	Mn	Pb	Sn	Fe	Ni	Si	Al	Zn
58.4	1.12	1.10	0.39	0.37	0.14	0.01	<0.001	Bal.

Brass valves are typically replaced when they begin to exhibit signs of failure due to their low cost [1]. In operational environments, it is crucial to prevent oxygen gas leaks from brass valves to ensure the safety of those in the vicinity [10]. A hairline crack in the valve female thread area detected during the inspection is likely to be the cause of the failure of the pneumatic test suggesting a material problem.

This study aimed to identify the objective evidence presented by the failed components the root cause of hairline cracks in brass valves and suggest corrective or preventive measures to improve quality control during production. The study was limited to the examination of failed samples and received brass billets in a laboratory setting, with a narrow scope of samples. The study did not account for variations in real-world manufacturing conditions, economic feasibility, or the impact of impurities on valve performance in different industrial applications.

Materials and Methods

A visual inspection of a failed brass valve's as-received condition was documented using a digital single-lens reflex (DSLR) camera (D3100, Nikon), as shown in Figure 1. The failed oxygen valve sent in for failure analysis was a brass valve with chrome plating, as shown in Figure 1(a). The brass valve was bisected using a diamond cutter at the slowest speed (200 rpm) to ensure that no external residual stress was applied to the brass valve, as shown in Figure 1(b).

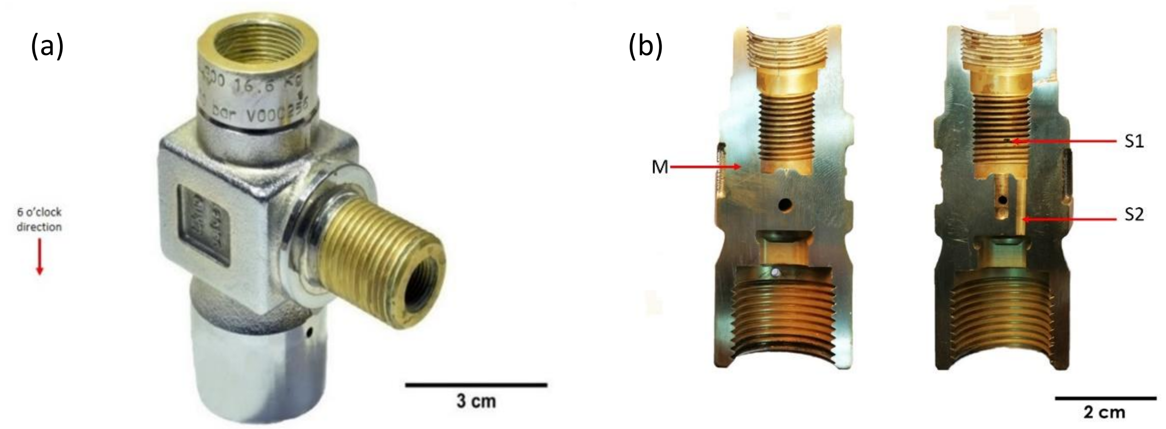


Figure 1: Camera photograph of (a) as-received, and (b) bisected brass oxygen valve.

A stereomicroscope was used to perform a close-up examination of the cracks at the S1 and S2 locations shown in Figure 1(b). The bisected sample was then ground with SiC grit paper of varying grit sizes, including 180, 240, 320, 440, 800, and 1200, before being polished with diamond solution to 6 µm. The as-polished sample was observed using a metallurgical microscope (BX41, Olympus). The metallurgical microscope observations provided further insights into the nature of the defects at the location labeled M in Figure 1(b) to identify the presence of defects such as cracks, voids, and porosities. Additionally, metallographic observations on as-polished billet samples were conducted at random specified locations for comparison purposes. To study the existence of fine cracks, inclusions, pinholes, and/or any microstructural abnormalities in greater detail, the valve metal matrix was repolished using 1 µm diamond solution and 0.3 µm alumina suspensions. The repolishing of the valve metal matrix with diamond and alumina suspensions enabled a more thorough examination of the microstructural abnormalities. To facilitate comparison, a metallographic analysis was conducted on the original brass billet to identify any indications of dross and cracks.

Surface morphology and microelemental analysis of the valve metal matrix were conducted using a scanning electron microscope (SEM) (JSM-6490LA, JOEL) and energy dispersive spectroscopy (EDS), respectively. The SEM analysis was conducted to identify any fatigue striation morphology present on the fractured surface. The EDS analysis, on the other hand, was conducted to determine the microelemental composition of the valve metal matrix and identify the presence of any inclusions or impurities.

Results and Discussion

Figure 2 depicts the results of a visual inspection of the brass oxygen valve sample, which provided valuable information about the condition of the valve. Upon close examination, it was found that there were vertical hairline cracks present on the female thread shallow zone of the valve wall, as indicated by the red arrows in Figure 2(a). In addition, there was an unequivocally opening crack detected in the deeper wall zone that propagated at an angle of 45° (Figure 2(b)). These cracks could have been caused by stress concentration due to the threading process or by the application of excessive torque during the installation of the pneumatic test cock/ insert.

Furthermore, a hairline crack was also detected on the exterior body at the chrome-plated area, which suggested that the crack had extended across the valve wall (Figure 2(c)). This observation highlights the importance of inspecting the entire valve structure, as defects in one area can often lead to more significant issues elsewhere. The presence of these cracks indicates that the valve had been subjected to excessive stress, likely due to the high-pressure environment in which it operated. Taken together, these findings indicate that the applied air pressure during the pneumatic test was able to escape via the tiny openings in the cracks. This not only compromised the integrity of the valve but also posed a significant safety risk, as leaks in oxygen valves can be highly dangerous.

Upon bisecting the valve sample, it was discovered that a portion of the valve wall structure was easily detached, indicating that the crack had fully severed the solid bulk structure of the valve wall. Upon closer inspection of the fracture surface, a progressive crack was found to have initiated on the outer side of the valve wall and grown inward, as evidenced by the red arrow in Figure 2(d). The presence of this progressive crack raised the possibility of two potential causes: a forging crack or metal fatigue. However, since the valve had not yet been put into service, the argument for a forging crack was more convincing. This was because the cracking patterns resembled fatigue striations that were expected to be produced from the inward mechanical stress progressively generated during the forging process. Therefore, the possibility of failure due to metal fatigue could be ruled out. This argument was further supported by the valve's design, which featured a curvy shape that could serve as a starting point or stress riser for the appearance of cracking during forging. However, in order to ensure a thorough investigation, evidence or indications to refute the presence of fatigue failure were also explored through SEM observation at points E1, E2, and E3. These points will be described in greater detail below. Overall, the investigation revealed that the progressive crack observed on the valve wall was likely caused by a forging crack rather than metal fatigue.

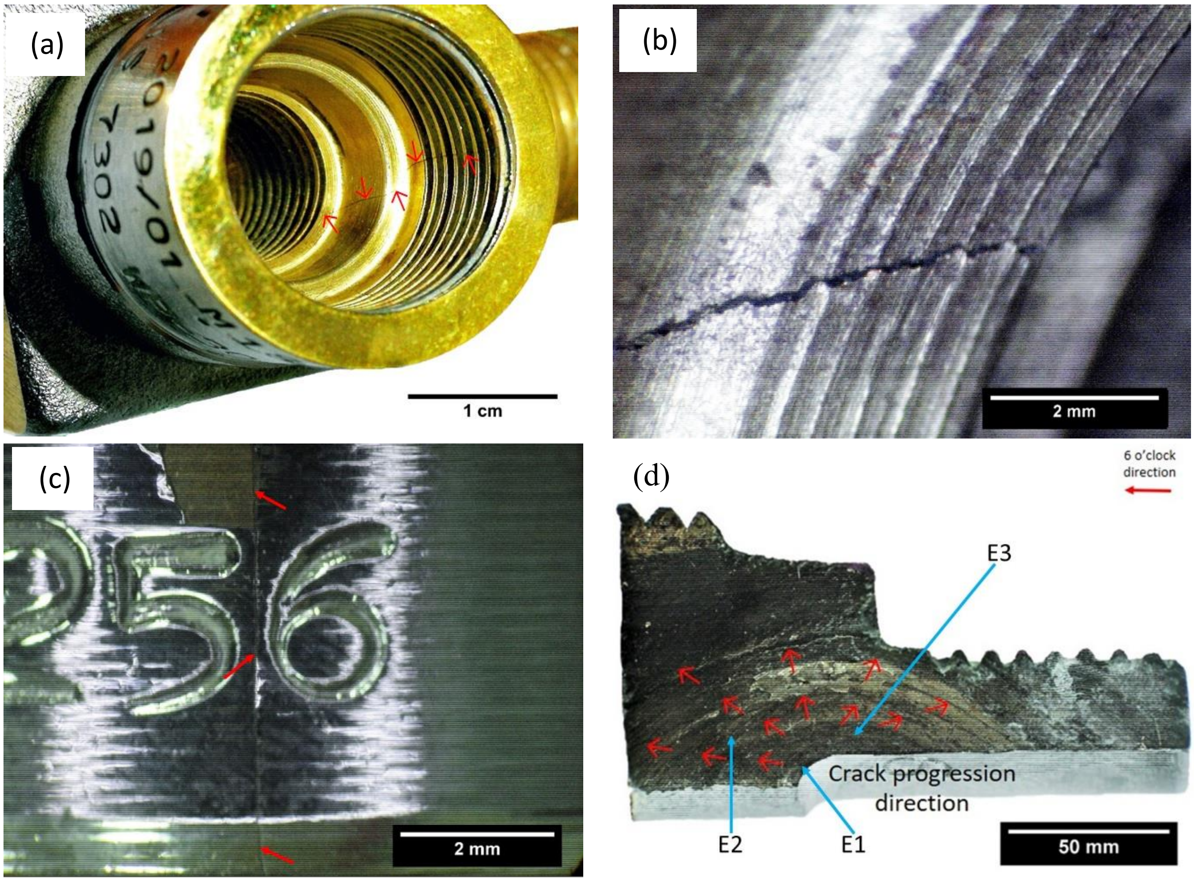


Figure 2: Visual inspection photographs demonstrate the defective marks on the (a) shallow and (b) deeper female thread walls zone, (c) the external body at the chrome-plated area, and (d) the fractured surface on the detached valve body section

Figure 3 shows a stereoscopic micrograph that illustrates the behavior of crack propagation at locations S1 and S2 (refer to Figure 1(b)). Upon close examination of the thread area at the S1 location, it was observed that there were indications of chipped fractures that had been detached from the thread structure (Figure 3(a)). Another similar sign of the nearby crack appearance was also detected, but it had not yet detached away from the thread structure. This circumstance demonstrated that the brass valve appeared to be made of a material that was prone to breakage easily. In addition, Figure 3(b) depicts a digitally enlarged stereomicroscope image of the cracked region in the S2 location (refer to Figure 1(b)). The observations indicated that the S2 region had branching cracks and chipped breaks. This branch crack showed that the valve was under excessive pressure. Meanwhile, the existence of chipped cracks indicated that the valve's material was less ductile, implying that the material still had some degree of ductility, but it was reduced due to the nature of the brass material. The combination of these findings suggests that the brass valve had been subjected to excessive stress, likely due to the high-pressure environment in which it operated. This is consistent with the presence of the cracks observed in earlier inspections.

The image presented in Figure 4 displays the observation made through a metallurgical microscope on the as-polished sample at location M (as depicted in Figure 1(b)). The low magnification view of the sample revealed that there were multidirectional cracks present in the brass matrix as shown in Figure 4(a). Furthermore, it was noted that the polishing process used during this stage left behind some stain or dirt that was challenging to remove. Upon observing the as-polished sample on the billet, intermetallic solid inclusions, impurities, pinholes, and fine cavities were identified in the brass matrix (Figure 4(b)). However, there was no evidence of cracks present in the studied billet matrix. It was noted that the microstructural imperfections in the form of dross in the billet were visible at low magnification. Dross is produced when molten metal is exposed to air and can have a detrimental effect on the mechanical properties of the metal. As a result, even a small amount of stress can cause the valve material to crack or fracture due to the presence of these dross imperfections.

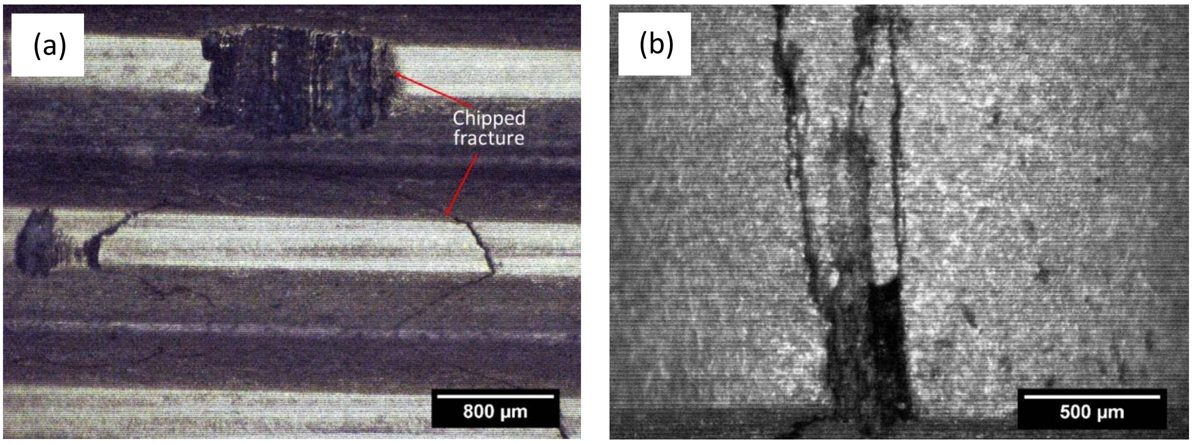


Figure 3: Stereomicroscope images along the defective area on (a) S1, and (b) S2 locations.

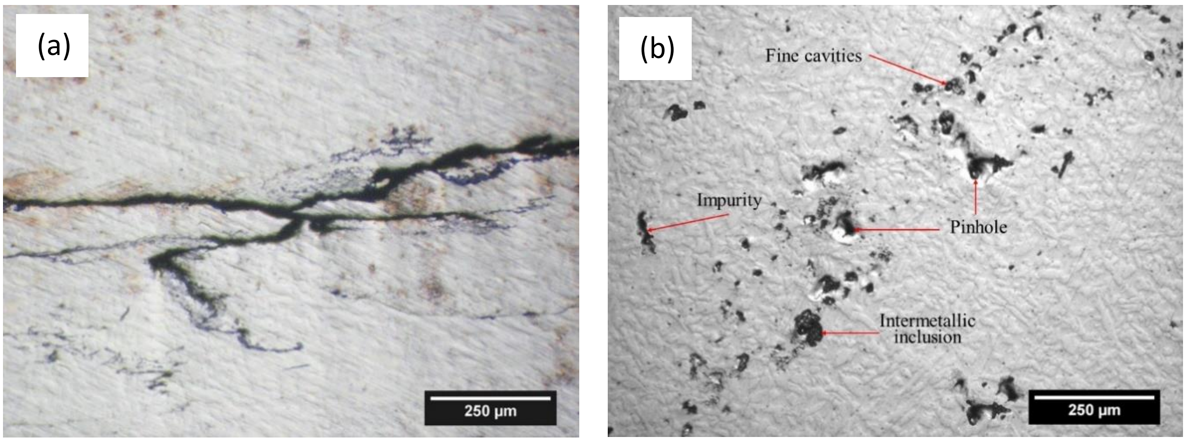


Figure 4: Optical metallographs of the as-polished sample surface at lower magnification; (a) failed valve and (b) brass billet

The metallurgical microscope images presented in Figure 5 provide a comprehensive and detailed view of the as-polished valve sample. The findings reveal the presence of fine dark scars and foamy dark surfaces with irregular shapes that are distributed throughout the brass valve matrix. These imperfections appear to result from multidirectional microcracks arising from residual stresses after forging, which could have been further exacerbated by subsequent machining. The propagation of the cracking through both fine-rounded cavities and intermetallic inclusions with irregularly shaped cavities is indicative of the presence of solid or porous oxide, as well as air inclusions or dross that likely originated from the brass billet. The argument regarding the presence of dross in the brass billet is further substantiated by the metallograph image depicted in Figure 5(b), which displays a similar topography as observed in Figure 5(a). The absence of cracks in the billet matrix provides further confirmation that the cracks on the failed valve were most likely caused by the secondary and tertiary processes such as hot forging and pneumatic testing.

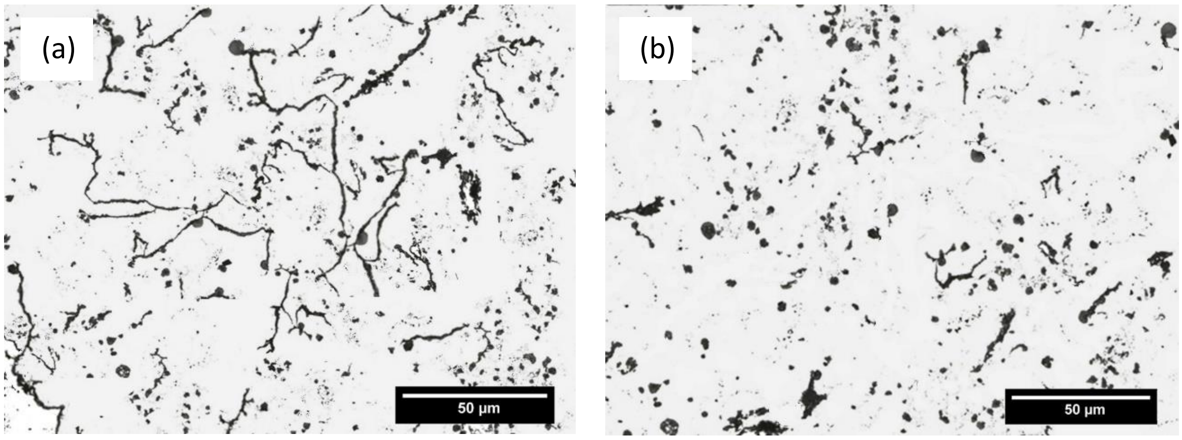


Figure 5: Optical metallographs of the as-polished sample surface at higher magnification; (a) failed valve and (b) brass billet

Dross is a common issue in casting, arises from improper casting processes or material erosion from the furnace, causing impurities such as dirt, slag, and solid foreign impurities in the billet. It is characterized by a solid or porous mass, irregular oxide inclusions, and air-entrapped rounded cavities. Although the presence of dross in the billet matrix cannot be completely eliminated, it renders brass valves prone to cracking and fracture under stress, leading to valve failure and system damage [11]. In the current case, residual stress due to forging and subsequent machining results from the presence of dross in the valve metal matrix when not properly skimmed off before pouring during the casting process. This further promotes the propagation of internal cracks, ultimately leading to component fracture.

Microanalysis results from SEM and EDS are displayed in Figure 6. The analysis was conducted to study the possibility of fatigue failure on the failed valve. There are three stages of fatigue failure, i.e., initiation, propagation, and final fracture. The analysis of SEM-EDS focuses on the results from the first and second stages only. The first stage, which is the initiation stage, allows to investigate the area where the progressive crack starts. The point where a crack starts can be very small and hard to figure out from the subsequent stages of crack propagation. Most of the time, grinding and machining marks, corrosion pits, non-metallic inclusions intersecting the metal surface, scratches, or notches are what cause fatigue to start. Conversely, because the initiation point is always parallel to the direction of stress, the curvy design of the valve is supposed to be the root cause of the excessive mechanical stress given to that zone during forging. As for this present study, the crack was observed to start near the curved area (Figure 2(d)). However, no obvious indicators of a crack initiation point were observed in the E1 point (Figure 6(a)).

In addition, the SEM image of E2, which was presumed to be the result of fatigue failure, indeed resembled a striation structure (Figure 6(b)). However, this assumption can be denied since the failed valve sample had not yet been used in operation by the user. Consequently, this fractography surface can be suggested to originate from a crack propagation due to the high air pressure present during pneumatic testing. It was believed that the blackish-dark color of the fractured surface (Figure 2(d)) was due to the oxidation interaction with the chrome plating chemicals and continued during the storage period. This changed the surface from its original, which was probably in a quite shiny condition.

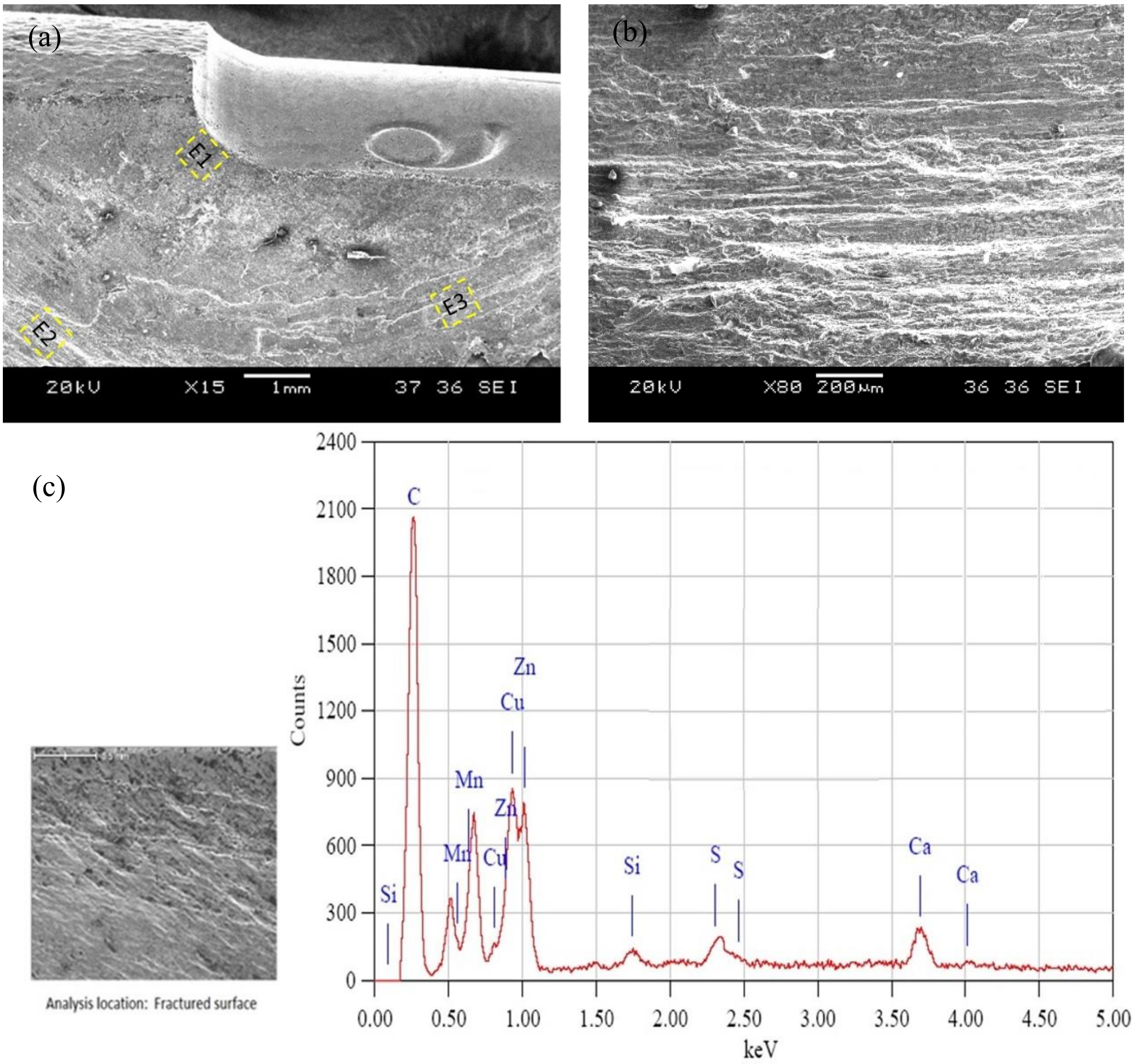


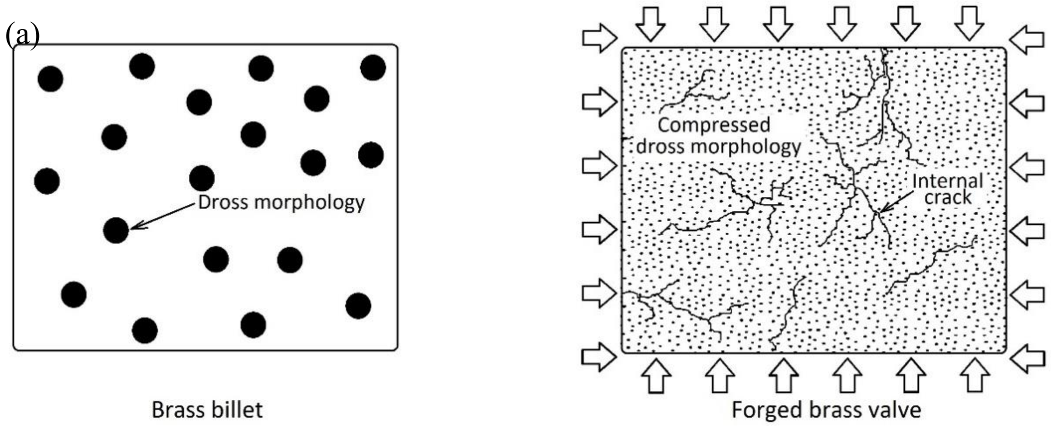
Figure 6: SEM micrographs of the failed valve sample analysed using SEM-EDS to investigate the possibility of fatigue failure. (a) The analysis points to the fracture surface at the curvature area, showing E1, E2, and E3. (b) Enlarged image of the striation-like structure at E2 and (c) EDS micro-elemental analysis result at E3

The EDS pattern at point E3 on the fractured surface is depicted in Figure 6(c). The brass matrix was composed predominantly of Cu, Zn, and a small portion of Mn as an alloying element. Mn is known to readily form intermetallic solids with other metals. Referring to the Table 1, this brass valve also contained Pb. However, Pb could not be identified by EDS because its energy levels exceeded the EDS detection threshold. In addition, the surface of the fracture was composed of C, S, and Ca elements. The presence of C was most likely the contamination detected in the EDS analysis of surface composition. It may also be present because of carbon-related gas reactions in the storage environment. Ca was considered to have been added to the molten brass as a casting additive or flux, while S was believed to have originated from the furnace environment.

Cracks that develop after the forging process are commonly known as "forging cracks." However, it is essential to note that the hot forging process, when carried out with accurate parameters and proper procedures, does not usually cause product failure. Brass alloys, known for their ductility and excellent malleability, are not affected by forging temperatures of about 700 °C as this fall within the acceptable forging range of 650 to 815 °C. Therefore, the occurrence of failure in the forged product must have a different cause. In the present study, visual inspection revealed the presence of cracks on the inner wall surface of the valve. From the investigation, the nature of the cracks was attributable to inward mechanical stress resulting from the forging process. The excessive mechanical stress was due to the valve's curvy design, which amplified the stress on the curved area during the forging process. Two possible root causes of the failure of this forged product were identified, namely, (a) defects in the starting material and (b) improper forging processes[12].

Large castings and forgings are frequently produced from brass billets, which are known to contain existing smelting casting defects. However, with an acceptable forging procedure, these defects can be forged together while minimizing the degradation of the final product's mechanical properties. To ensure an effective forging process, it is crucial to control the level of raw material defects prior to forging. In this study, metallographic analysis revealed that the failure of the brass oxygen valve was caused by internal dross that was not appropriately eliminated during the casting procedure at the billet manufacturing stage. Despite the forging process being able to compress the dross morphology, it was still unable to enhance the mechanical strength of the forged product [13,14]. Figure 7 illustrates a schematic representation of the forged product's failure mechanism. Figure 7(a) shows the matrix of a brass billet, and Figure 7(b) illustrates the microstructure transformation that occurred after forging. Dross morphologies serve as notches in the brass matrix, causing stress concentration points and are regarded as weak spots where cracks can easily form. During the forging process, these dross morphologies are treated as plastic zones, which undergo an increase in applied stress and generate plastic strain in the weak region. A crack is formed when the plastic strain in the weak region exceeds a certain value. When the amount of raw material defects exceeds the required level and is forged using the standard forging method, the cracking phenomenon is known as forging cracks induced by raw material defects. Therefore, it is essential to control the level of raw material defects in brass billets during casting to avoid the formation of weak spots and subsequent failure during the forging process.

Forging cracks are a common phenomenon that can occur during hot forging when the deformation process takes place at high temperatures. At such temperatures, cracks tend to grow and come into contact with air, leading to the formation of forging cracks. Hot forging of brass valve products can be particularly challenging due to the expansion and contraction of the metal, which can result in cracking. In the present investigation, the forging process was carried out within the appropriate temperature range. However, assessing the actual operation at the site posed a challenge. It is important to note that accurate control of the forging process parameters is crucial to minimize the formation of forging cracks. The parameters include the forging temperature, the deformation rate, and the degree of deformation. Proper forging techniques can prevent the occurrence of forging cracks by ensuring that the metal remains within its ductile temperature range during the deformation process. The design of the product is also a critical factor in preventing forging cracks. The shape of the product should be designed to minimize stress concentrations, as stress concentration points are more likely to lead to the formation of cracks. Additionally, the starting material should be of high quality and free from defects that could lead to cracks during the forging process.



(b)

Figure 7: Schematic diagram illustrating the effect of microstructure on failed brass valves (a) before and (b) after hot forging

As a preventive measure, several techniques can be employed to reduce the amount of dross present in the initial brass billet. One approach involves carrying out the melting process with an additive or flux, either in a vacuum or in an inert environment, which can lower the amount of dross formation. Another method is to add one or more supplementary components to the mixture before pouring the molten metal into the billet mold, causing the dross to rise and float to the surface, where it can be easily removed by skimming. If these techniques are ineffective, specialized ladles that allow the metal to be poured from the base can be utilized. Additionally, ceramic filters can be implemented into the gating system to trap impurities before the metal enters the mold. Alternatively, swirl gates can be constructed, which swirl the liquid metal as it is poured, forcing lighter inclusions to the center of the casting, and preventing them from being cast [3,15].

Reducing dross formation in the initial billet is crucial since it can significantly impact the quality of the final product. Dross is an undesirable byproduct of the melting process that can contain impurities, such as oxides, that weaken the strength and durability of the brass. Furthermore, dross can cause defects in the casting, such as porosity, which can compromise its structural integrity. Therefore, it is vital to implement effective strategies to minimize dross formation in the initial billet. By using additives or fluxes during the melting process, or by employing specialized equipment such as ladles, ceramic filters, or swirl gates, it is possible to remove impurities and ensure that the final brass casting meets the desired quality standards.

Conclusions

The failure analysis showed that the brass valve failed due to cracking caused by dross in the starting billet. Dross weakens the mechanical qualities of brass, making it prone to cracks. Preventive measures such as additives, fluxes, specialized ladles, ceramic filters, or swirl gates should be used to minimize dross formation and ensure high-quality products with superior mechanical properties.

Acknowledgements

The author would like to acknowledge the Fundamental Research Grant Scheme (FRGS) support under the grant number FRGS/1/2020/TK0/UNIMAP/02/85 from the Ministry of Higher Learning Malaysia.

Author Contributions

All authors contributed toward data analysis, drafting, and critically revising the paper and agreed to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare.

Compliance with Ethical Standards

The work is compliant with ethical standards.

References

[1] Kunčická, L., Jambor, M., Weiser, A. & Dvořák, J. (2021). Structural factors inducing cracking of brass fittings. *Materials (Basel)*, 14(12), 3255.

[2] Khan, N. Z. & Azam, K. (2015). Manufacturing Defects of Brass Products and suggested Remedies. *International Journal Innovation Science Engineering Technology*, 2(9), 497–514.

[3] Fadhil, A. A., Ghattas, M. S., Iskander, B. A., Ajeel, S. A. & Enab, T. A. (2018). Structural characterization and detecting processes of defects in leaded brass alloy used for gas valves production. *Alexandria Engineering Journal*, 57(3), 1301–1311.

[4] Muikku, A., Hartikainen, J., Vapalahti, S. & Tiainen, T. (2006). Experimental Work on Possibilities to Predict Casting Defects in LPDC Brass Castings. In Materials Science Forum, Switzerland, 2006.

[5] El-bahloul, A. M. M., Samuel, M. & Fadhil, A. A. (2015). Copper-Zinc-Lead Alloys, Common Defects through Production Stages and Remedy Methods. *Online Journal Science Technology*, 5(2), 17–22.

[6] Kunčická, L., Benč, M. & Andreyachshenko, V. (2021). Effect of Residual Stress on Cracking of Hot Die-Forged Brass Fittings," *IOP Conference Series Materials Science and Engineering*, 1190(1), 012031.

[7] Hameed, A. H. & Abed, A. T. (2014). Effect of secondary cooling configuration on microstructure of cast in semi-continuous casting of copper and brass. *Applied Mechanics and Materials*, 575, 8-12.

[8] Liu, W., Xing, P., Zhao, H., Wang, C., Chen, Y., Guo, S., Liu, F. & Huang, T. (2020). Component Analysis of Defects in Secondary Special Brass Alloy. In *Annual Meeting & Exhibition Supplemental Proceedings, The Minerals, Metals & Materials Series*, (Springer International Publishing), pp 1201–1213.

[9] Rathi, M. G. & Jakhade, N. A. (2014). An Overview of Forging process with their Defects. *International Journal of Scientific and Research Publications*, 4(6), 1-7.

[10] Chunlei, G., Nan, Z., Yuehua, K., Shuncheng, W. & Kaihong, Z. (2019). Failure analysis of lead-free brass valve bodies. *Engineering Failure Analysis*, 100(June 2019), 536–543.

[11] Mahinroosta, M. & Allahverdi, A. (2018). Hazardous aluminum dross characterization and recycling strategies: A critical review. *Journal of environmental management*, 223, 452-468.

[12] Chander, S. & Chawla, V. (2017). Failure of Hot Forging Dies-An Updated Perspective. *Materials Today Proceeding,* 4(2), 1147–1157.

[13] Deep, G., Rajora, V., & Singh, I. (2016). Study on process parameters for brass casting. In Proceedings of the 3rd National Conference on Advancements in Simulation & Experimental Techniques in Mechanical Engineering (NCASEme-2016), India, 26-27 Feb 2016.

[14] Zagretdinov, Z. T., Safronov, N. N. & Kharisov, L. R. (2019). Getting Aluminum Bronze Castings with SHS-Cast. *Helix*, 9(4), 5191–5196.

[15] Shimov, G., Bogatov, A. & Kovin, D. (2018). Fem simulation of copper busbar pressing on the continuous extrusion line"conform". *Solid State Phenomenon,* 284, 547–551.