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Comparative Failure Analysis of A356 and ADC12 Aluminium Alloy Clutch Brackets for Automotive Transmission Applications

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Abstract

The bracket and clutch cable serve as a mechanical link between the clutch pedal inside the cabin and the release fork in the transmission. Failure of this component can disrupt gear-shifting performance and reduce vehicle reliability. Although aluminium alloy brackets are widely used in automotive applications for their lightweight properties, information on the failure behaviour of transmission brackets in city cars remains limited. Therefore, this study aimed to investigate the mechanical properties, microstructural characteristics, and fracture behaviour of aluminium alloy transmission brackets from two different aluminium alloys. The research used metallographic examination, and fractographic analysis with Scanning Electron Microscopy (SEM) and hardness testing. Specimens were sectioned transversely from the bracket component, prepared using standard metallographic procedures, and examined to identify microstructural features and fracture mechanisms. The results showed that both brackets exhibited a relatively homogeneous Al–Si alloy microstructure with rounded grains and spherical porosity, indicating that they were manufactured by high-pressure die casting. The ADC12 aluminium alloys had a higher average hardness of 91.5 HV than A356, which had 78.8 HV. Fractographic observations revealed that the A356 bracket was dominated by ductile fracture characterized by microvoid coalescence, whereas the ADC12 bracket exhibited mixed brittle–ductile fracture features associated with silicon-rich and intermetallic phases. In both samples, casting porosity acted as a stress concentrator and potential crack initiation site. These findings indicate that variations in casting quality and microstructural characteristics significantly influence the hardness and fracture behaviour of aluminium alloy transmission brackets. The study provides useful insights for improving material selection, casting quality control, and the reliability of automotive transmission linkage components.

Keywords: aluminium alloy; clutch system; failure analysis; hardness; clutch bracket

Abstrak

Pengait dan kabel kopling berfungsi sebagai penghubung mekanis antara pedal kopling di kabin dan garpu pelepas pada transmisi. Kegagalan komponen ini dapat mengganggu kinerja perpindahan gigi dan menurunkan keandalan kendaraan. Pengait paduan aluminium banyak digunakan dalam aplikasi otomotif karena ringan. Informasi mengenai perilaku kegagalan pengait transmisi pada mobil perkotaan masih terbatas. Oleh karena itu, penelitian ini bertujuan untuk menyelidiki sifat mekanik, karakteristik mikrostruktur, dan perilaku fraktur pengait transmisi pada paduan aluminium dari dua jenis paduan yang berbeda. Penelitian ini dilakukan melalui pemeriksaan metalografi, analisis fraktografi menggunakan Scanning Electron Microscope (SEM) dan pengujian kekerasan. Spesimen dipotong melintang dari komponen pengait, disiapkan menggunakan prosedur metalografi standar, dan diperiksa untuk mengidentifikasi fitur mikrostruktur serta mekanisme patahan. Hasil menunjukkan bahwa kedua pengait memiliki mikrostruktur paduan Al–Si yang relatif homogen, dengan butiran bulat dan porositas berbentuk bulat, yang menunjukkan bahwa pembuatan dilakukan melalui proses pengecoran dengan cetakan bertekanan tinggi. Pengait asli (merek B) menunjukkan kekerasan rata-rata yang lebih tinggi, yaitu 91,5 HV, dibandingkan dengan pengait A356, yang menunjukkan kekerasan 78,8 HV. Pengamatan fraktografi mengungkapkan bahwa pengait A356 didominasi oleh patahan ulet yang ditandai dengan koalesensi rongga mikro, sedangkan pengait ADC12 didominasi oleh patahan getas-ulet campuran yang terkait dengan fase kaya silikon dan intermetalik. Pada kedua sampel, porositas pengecoran bertindak sebagai konsentrator tegangan dan lokasi potensial untuk inisiasi retak. Temuan ini menunjukkan bahwa variasi kualitas pengecoran dan karakteristik mikrostruktur secara signifikan memengaruhi kekerasan serta perilaku patahan pada pengait transmisi paduan aluminium. Studi ini memberikan wawasan yang berguna untuk meningkatkan pemilihan material, pengendalian kualitas pengecoran, serta keandalan komponen penghubung pada transmisi otomotif.

Kata kunci: paduan aluminium; sistem kopling; analisis kegagalan; kekerasan; pengait kopling

1. Introduction

The structural integrity of transmission system components is critical for operational safety, especially when using lightweight aluminum alloys to improve vehicle efficiency. However, these alloys are frequently susceptible to fatigue-induced failures and stress corrosion cracking under complex cyclic loading and environmental stressors [1]. In particular, fracture patterns in aluminum components often stem from inherent material defects, such as porosity or metallic inclusions, which exacerbate crack initiation during prolonged service [2, 3]. Furthermore, internal microstructural inhomogeneities, such as the segregation of alloying elements, can significantly promote premature crack propagation along grain boundaries under repetitive mechanical fatigue [4, 5].

These localized regions of stress concentration frequently facilitate the development of fatigue damage, limiting the component's service life and overall reliability [6]. Specifically, while aluminum alloys offer significant advantages for vehicle light-weighting, their inherent fatigue performance remains a critical limitation in high-stress transportation applications [7].

The increasing demand for lightweight vehicles has driven the extensive use of aluminium alloys in Driven by the need to improve fuel efficiency, reduce greenhouse gas emissions, and optimise vehicle performance, the automotive industry has increasingly adopted lightweight materials. Aluminium alloys possess several attractive properties, including low density, excellent corrosion resistance, and good castability. Owing to their advantageous strength-to-weight ratio, these alloys are widely employed in the automotive industry [9, 10]. Consequently, aluminium castings are widely employed in engine blocks, transmission housings, brackets, suspension components, and transmission linkage systems.

Hypoeutectic Al–Si cast alloys are widely employed in structural applications because they combine low weight with excellent castability, corrosion resistance, and wear performance. Among these alloys, A356 (Al–7 wt.% Si–0.3 wt.% Mg) from the 3xx series has gained considerable attention owing to its excellent combination of strength and ductility. [11]. In addition, ADC12, a widely used Al–Si–Cu alloy, is recognized for its excellent castability, high mechanical strength, and superior fluidity [12].

The clutch cable links the clutch pedal inside the cabin to the release fork in the transmission. This component transmits the pedal input, enabling the clutch system to disengage and transmit engine power during gear changes [13]. Throughout service, the component is subjected to repeated tensile loading. Such operating conditions may lead to progressive material degradation and ultimately result in component failure. Failure of the clutch bracket can significantly impair clutch performance and compromise vehicle reliability and operational safety [14].

Figure 1. Clutch flex cables and b) brackets in the Clutch system [13]

To achieve high production efficiency and dimensional accuracy, transmission linkage components are commonly manufactured from Al–Si casting alloys using the High Pressure Die Casting (HPDC) process. HPDC is widely used in the automotive sector because it enables production of geometrically complex components with excellent dimensional precision and high productivity [9]. Furthermore, the rapid solidification associated with HPDC generally produces a refined microstructure, thereby improving mechanical properties. Nevertheless, HPDC components are often susceptible to casting-related defects, including gas porosity, shrinkage porosity, oxide films, and non-metallic inclusions, all of which may adversely affect the material's structural integrity [15].

Among these defects, porosity is considered one of the most detrimental factors affecting the mechanical performance of cast aluminium alloys. Porosity acts as a local stress concentrator, reducing tensile strength, ductility, fracture toughness, and fatigue resistance [16]. Nourian-Avval and Fatemi [15] reported that fatigue cracks in high-pressure die-cast aluminium alloys frequently initiate at pores located either on or beneath the component surface. Similarly, Osmond, et al. [17] demonstrated that increasing porosity content significantly reduces the fatigue life of cast Al–Si alloys due to accelerated crack initiation and propagation mechanisms.

In addition to porosity, the microstructural characteristics of aluminium alloys play a crucial role in determining their resistance to fatigue failure. Typical HPDC Al–Si–Cu alloys consist of a primary α-Al matrix, eutectic silicon particles, and various intermetallic compounds containing iron and copper. The morphology, distribution, and volume fraction of these phases significantly influence crack initiation and propagation behaviour. Lattanzi, et al. [18] reported that casting defects and microstructural heterogeneities in high-pressure die-cast AlSi9Cu3(Fe) alloys substantially reduce fatigue strength by promoting early crack nucleation. Likewise, Bogdanoff [19] highlighted that microstructural discontinuities, particularly porosity and brittle intermetallic phases, strongly influence the fatigue behaviour of cast aluminium alloys.

The fracture behavior of cast aluminum components is generally governed by a combination of casting defects and cyclic loading conditions. During service, local stress concentrations around pores, inclusions, or brittle intermetallic particles may trigger microcrack formation. Under repeated loading, these microcracks gradually propagate through the aluminium matrix until catastrophic failure occurs. Szalva and Orbulov [20] demonstrated that reducing porosity through vacuum-assisted die casting significantly improved the fatigue life of AlSi9Cu3 alloys, emphasizing the critical role of casting quality in component durability.

Failure analysis has become an essential approach for identifying the root causes of mechanical failures in engineering components. Comprehensive failure investigations commonly involve visual inspection, hardness testing, metallographic examination, and fracture surface analysis using Scanning Electron Microscopy (SEM). Metallographic analysis provides valuable information regarding microstructural features and casting defects, while SEM fractography enables detailed examination of crack initiation sites and fracture mechanisms Metals [10]. Integrating these techniques enables the systematic establishment of the relationship among manufacturing defects, microstructural characteristics, and mechanical performance.

Although numerous studies have investigated fatigue and fracture behaviour in cast aluminium alloys, limited information is available concerning the failure mechanisms of transmission bracket components used in city cars. Given the critical function of these components in the transmission system, a thorough understanding of their failure behaviour is necessary to improve reliability and prevent similar failures in future applications.

Therefore, the present study aims to investigate the failure of an aluminium alloy transmission bracket used in a passenger City Car through hardness testing, metallographic characterisation, and SEM fractographic analysis. Particular attention is given to how casting defects, microstructural characteristics, and mechanical properties influence the observed failure mechanism. The findings are expected to provide important insights into the causes of failure, supporting the development of more durable and reliable Clutch linkage components for automotive use.

2. Materials and Methods

In this study, the material used in the bracket component of city car transmissions from different manufacturers was characterised. The chemical composition testing of the aluminium alloy bracket material was carried out using a spectrometric analyser, an OES spectrometer (Oxford Instruments) (Table 1). The research commenced with transverse sectioning of the bracket samples using a saw. Hardness testing was performed on both samples using the Vickers method (Future-Tech FM-800 Series) with a 100 gf load applied at five measurement points on each sample, in accordance with ASTM E384. Sample preparation for microstructural examination followed ASTM E3. Both samples were polished using abrasive papers with progressively finer grades until a smooth surface was obtained. Following polishing, the specimens were etched in a solution consisting of 1.5 mL HCl, 1 mL HF, 2.5 mL HNO_3, and 100 mL H_2O, in accordance with ASTM E407. Microstructural examination was performed using a metallurgical optical microscope (Raxvision Material Plus MM10A). Fracture surface analysis of the bracket was performed using a scanning electron microscope (Hitachi TM3000 Tabletop Microscope). The experimental procedure is schematically presented in Figure 2.

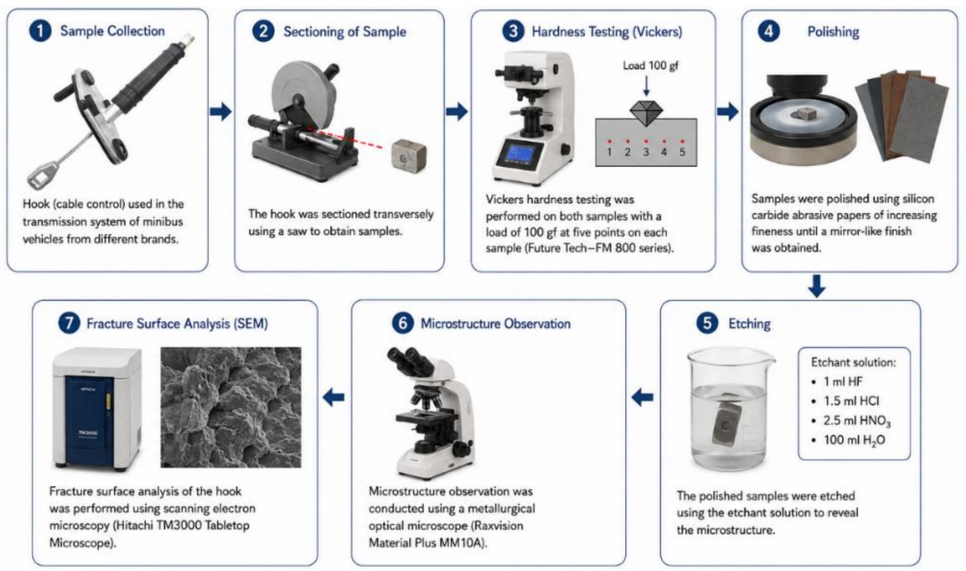

Figure 2. Schematic process of research

3. Results and Discussion

3.1. Chemical composition of Aluminium Alloys

Table 1 presents the chemical composition analysis of transmission brackets from two manufacturers (A356 and ADC12). The results indicate notable differences in alloying elements, suggesting that the brackets were produced from different aluminium casting alloys. The A356 bracket contains approximately 6.5 wt.% Si,% Si, 0.25 wt.% Mg, 0.20 wt.% Cu, and 0.20 wt.% Fe, with aluminium as the balance element. This composition closely resembles that of Al–Si–Mg aluminum alloys, which have gained widespread acceptance in automotive cast components for their excellent castability, satisfactory corrosion resistance, and favorable mechanical properties. Magnesium promotes the formation of Mg_2Si precipitates, which strengthen the alloy through precipitation hardening. Furthermore, the relatively low iron content helps minimize brittle Fe-rich intermetallic phases that may reduce ductility and fracture resistance.

In contrast, the bracket from ADC12 exhibits higher silicon (9.6 wt.%) and copper (1.5 wt.%) contents, together with 0.8 wt.% Fe, 0.3 wt.% Mg, and minor amounts of nickel and tin. This composition is consistent with ADC12 aluminium alloy (Al–Si–Cu), which is commonly employed in high-pressure die-casting applications [21]. The elevated silicon concentration enhances fluidity during casting and improves wear resistance, while copper increases hardness and tensile strength. However, higher copper and iron contents may reduce corrosion resistance and ductility compared with A356 alloy.

The compositional differences indicate that the two brackets were manufactured using distinct alloy systems designed to achieve different performance requirements. A356 aluminium alloys are generally associated with improved toughness and fatigue resistance, whereas ADC12 provides superior castability and hardness. Consequently, microstructure, hardness, and fracture behavior are expected to differ between the two brackets, as discussed in the following sections.

Table 1. Composition of bracket

Type	Si	Cu	Mg	Mn	Fe	Zn	Ti	Ni	Sn	Al
A356	6.5	0.2	0.35	0.10	0.14	0.1	0.01	-	-	bal
ADC12	9.6	1.7	0.3	0.3	0.83	0.2	-	0.1	0.2	bal

Overall, the chemical composition results suggest that A356 was likely produced from an Al–Si–Mg casting alloy, while Brand B was manufactured from an Al–Si–Cu die-casting alloy (ADC12). These differences are anticipated to significantly influence the mechanical performance and failure characteristics of the transmission brackets.

3.2. Microstructure of Bracket

The observed microstructure shows a fine, homogeneous distribution of primary α-Al phase embedded in an Al-Si eutectic matrix, accompanied by several spherical pores. Besides the spherical and rosette-like grains, the microstructure additionally contains fine dendritic and equiaxed grains, as illustrated in Fig. 3 [22]. These fine secondary α-Al grains precipitated from the residual liquid phase during the final stages of solidification [23]. The refined microstructure indicates a high cooling rate during solidification, while rounded gas porosity is characteristic of pressure-assisted casting processes. These features strongly suggest that the transmission bracket was manufactured using the high-pressure die casting (HPDC) process, which is commonly employed for producing automotive aluminium alloy components such as brackets, housings, and transmission linkage parts. The microstructural characteristics are consistent with Al-Si-Mg die-casting alloys, particularly A356 or equivalent grades [23].

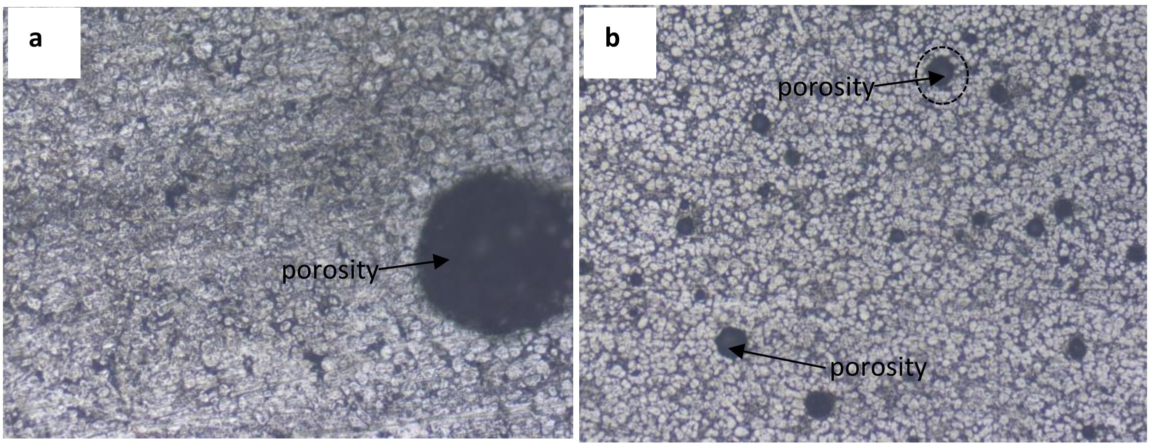

Figure 3. Microstructure of bracket (a) A356 and (b) ADC12 (200X)

Furthermore, Figure 3 shows that both materials were manufactured using a semi-solid processing technique under high-pressure conditions, resulting in a fine and globular primary α-Al morphology. This occurred because external pressure applied during solidification of the semi-solid slurry within the mould cavity promoted the formation of finer particles. The morphological characteristics of the primary α-Al phase are consistent with findings reported by Guo, et al. [24], who observed a similar globular primary α-Al structure in A356 aluminium alloy produced by a semi-solid technique at pressures up to 90 MPa.

3.3. Fracture Surface Analysis using SEM

SEM examination of the fracture surface revealed a rough and highly irregular morphology characterized by numerous cavities, particle pull-out features, and microvoids (Figure 4-a,c). The fracture surface exhibited evidence of microvoid nucleation, growth, and coalescence, indicating a predominantly ductile fracture mechanism. Several large voids were observed, likely originating from casting porosity inherent in the manufacturing process. These defects likely acted as stress concentration sites and facilitated crack initiation under cyclic service loading. The fracture morphology is consistent with the behavior of high-pressure die-cast Al–Si–Si alloys such as A356 commonly employed in automotive transmission linkage components. Combined metallographic and fractographic observations suggest that failure initiated at casting defects and then propagated under repeated loading before final ductile overload fracture.

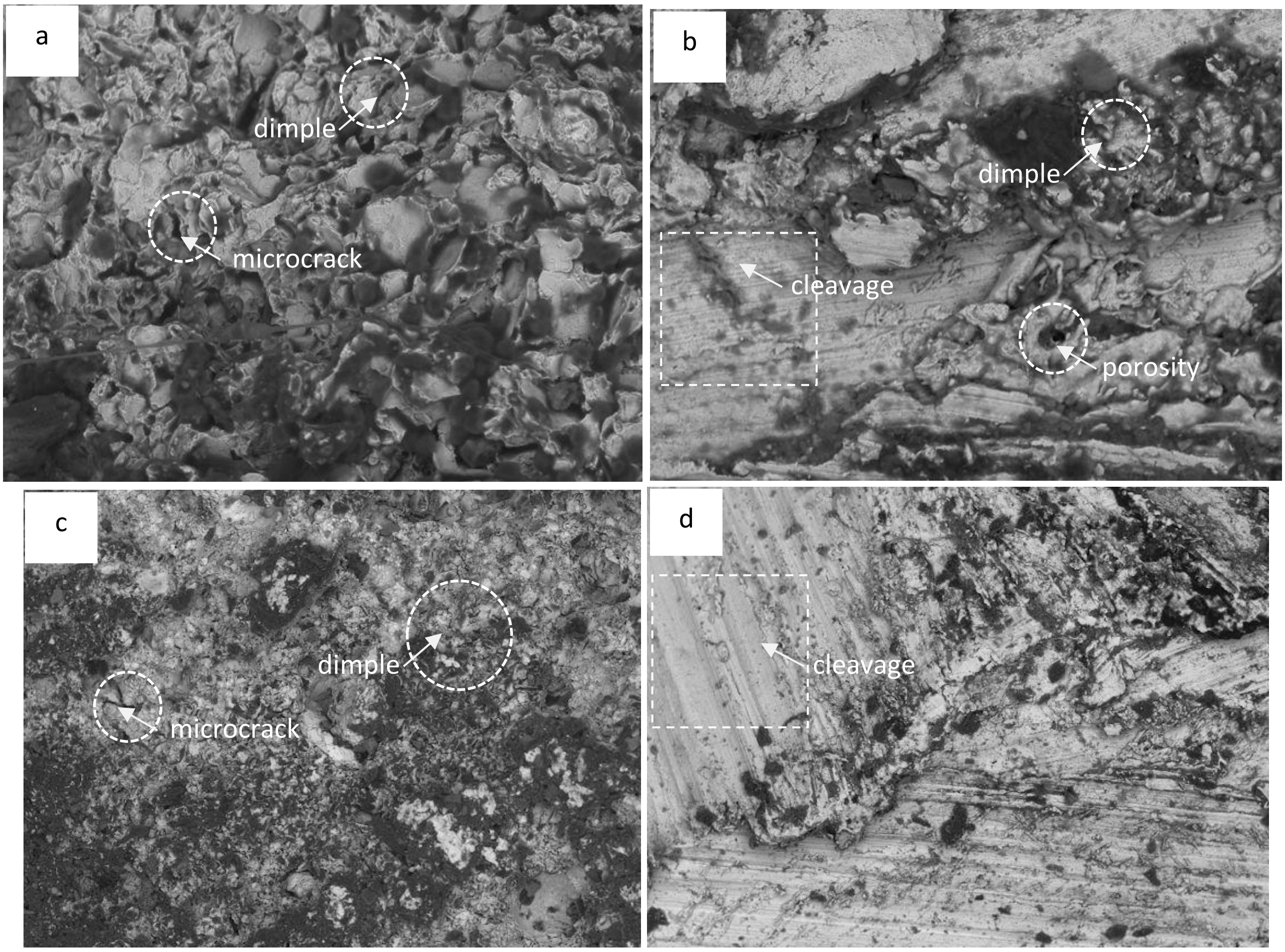

Figure 4. Fracture surface morphology of the Clutch Bracket: a) A356, b) ADC12, c) A356, d) ADC12.

SEM fractographic analysis revealed a mixed-mode fracture characterized by localized flat facets, secondary microcracks, microvoids, and particle pull-out features (Figure 4-b,d). The presence of cleavage-like regions suggests brittle fracture of silicon-rich and Fe-containing intermetallic phases, whereas the occurrence of microvoids indicates localised ductile deformation within the aluminium matrix. Several pores and cavities were observed on the fracture surface, implying that casting defects acted as preferential crack initiation sites. The fracture morphology indicates that failure most likely initiated under cyclic loading and subsequently propagated through both the aluminium matrix and the brittle intermetallic constituents before the final overload fracture. These observations are consistent with the behaviour of high-pressure die-cast Al–Si–Cu alloys (ADC12) commonly used in automotive transmission linkage components.

3.4. Hardness Vickers of Clutch Bracket

The hardness test results showed that the ADC12 Clutch Bracket had an average hardness of 91.5 HV, whereas Bracket A356 had a lower hardness of 78.8 HV. According to Gu, et al. [23], the hardness of ADC12 aluminium alloy typically ranges from 60 to 90 HV, depending on the casting method employed [22]. These results are consistent with those reported by Gu, et al. [23], who observed a hardness value of 90 HV. This represents a reduction of approximately 13.9% in hardness. The higher hardness of ADC12 indicates superior resistance to localized plastic deformation and wear. The difference may be attributed to variations in alloy composition, casting quality, cooling rate, and microstructural refinement. The lower hardness observed in the aftermarket bracket suggests inferior mechanical performance and may reduce fatigue resistance and service life under the cyclic loading encountered during gear-shifting operations.

Grain size plays a crucial role in determining the hardness of Al–Si alloys. Reducing grain size increases the density of grain boundaries, which act as barriers to dislocation motion. Consequently, the resistance to plastic deformation increases, leading to higher hardness values in accordance with the Hall–Petch relationship. In cast Al–Si alloys, finer α-Al dendrites and smaller secondary dendrite arm spacing (SDAS) are generally associated with improved hardness and strength. Therefore, the higher hardness observed in the original transmission bracket may be attributed to a finer microstructure and fewer casting defects compared with the aftermarket component [9].

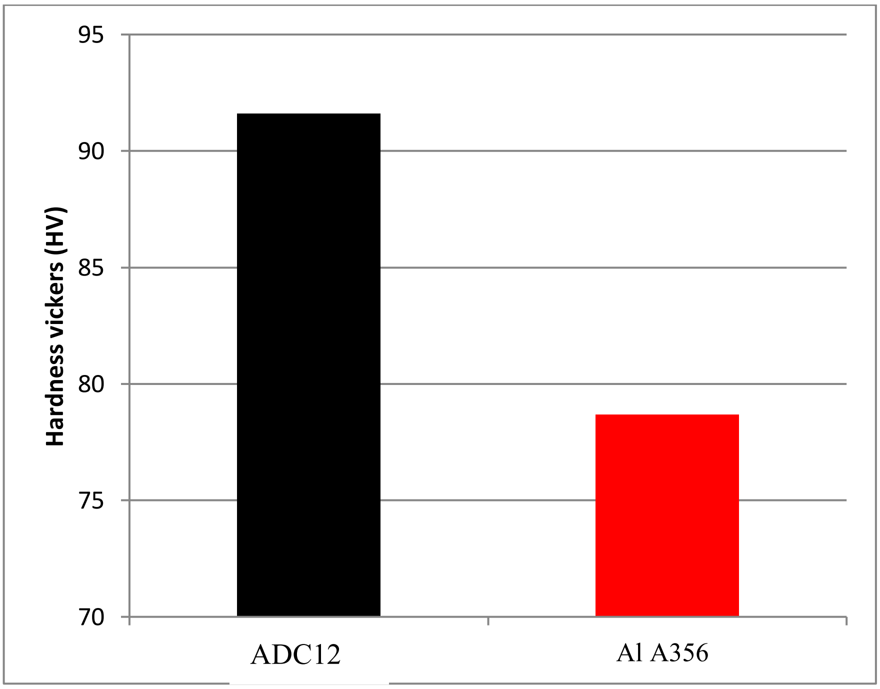

Figure 5. Vickers hardness of the Clutch bracket

4. Conclusion

The present study investigated the failure characteristics of aluminium alloy Clutch brackets used in city cars through hardness testing, metallographic examination, and SEM fractographic analysis. The microstructural observations revealed that both bracket samples exhibited a relatively homogeneous Al–Si alloy microstructure with spherical porosity, indicating that the components were manufactured by high-pressure die casting (HPDC). Although the overall microstructures were similar, the study observed differences in casting quality and defect distribution. Hardness testing showed that Aluminium ADC12 had a higher average hardness (91.5 HV) than the bracket A356 (78.8 HV), indicating better resistance to localized plastic deformation. The chemical composition and hardness analyses indicate that A356, not ADC12 aluminium alloy, was the primary material for the Clutch bracket. Furthermore, Fractographic analysis showed that bracket A356 predominantly failed by ductile fracture, characterized by microvoid nucleation, growth, and coalescence. In contrast, bracket ADC12 exhibited a mixed brittle–ductile fracture mode associated with silicon-rich and Fe-containing intermetallic phases. In both samples, casting porosity acted as a stress concentrator and potential crack initiation site. Overall, the results indicate that casting defects, particularly porosity, together with microstructural characteristics and mechanical properties, play a significant role in determining the failure behaviour of aluminium alloy Clutch brackets. Improving casting quality and minimizing porosity are therefore essential to enhance the reliability and service life of transmission linkage components in automotive applications. Further investigations should include quantitative compositional analysis employing OES or EDS techniques to identify the alloy grade and evaluate the effects of alloying elements on mechanical performance. Fatigue testing under cyclic loading conditions representative of actual gear-shifting operations is also recommended to better understand crack initiation and propagation mechanisms during service. Additionally, adopting advanced non-destructive characterization methods, such as X-ray Computed Tomography (XCT), could improve understanding of internal microstructural features and defects.

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