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Effect of Remelting and Recasting on Microhardness Distribution and Microstructural Evaluation of Aluminum Alloy 6061-T6

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Abstract: Aluminum Alloy 6061-T6 is widely used in engineering applications because of its favorable mechanical properties, corrosion resistance, and formability. This study investigated the effect of a single remelting and recasting cycle on the microstructure and spatial distribution of microhardness of Aluminum 6061-T6. The alloy was remelted at approximately 800 °C and gravity cast into a metal mold. Microstructural characterization was performed using optical metallurgical microscopy, while Vickers microhardness was measured at multiple locations across the casting. The wrought material exhibited a relatively homogeneous microstructure with fine and uniformly distributed microstructural features and an average hardness of 134 HV0.5. After remelting and recasting, the average hardness decreased to approximately 89 HV0.5, with values ranging from 80 HV0.5 to 103 HV0.5. Optical microscopy showed a coarser and more heterogeneous microstructure after recasting, together with features consistent with casting-related imperfections. The observed reduction and spatial variation in microhardness were associated with the transition from the original precipitation-hardened T6 condition to a more heterogeneous as-cast microstructure.

Keywords: aluminum alloy 6061-T6; remelting; recasting; microstructure evolution; hardness distribution; precipitation hardening

1. Introduction

Aluminum (Al) is a lightweight metal universally characterized by a low density of 2.70 g/cm³. The relatively low inherent strength, which is increased through alloying and heat treatment, promotes extensive use in applications requiring a high strength-to-weight ratio, such as transport and the automotive industry [1], [2]. Aluminum is also a relatively good electrical and thermal conductor, highly resistant to corrosion due to its thin but strong oxide layer that forms on the surface. The melting point is approximately 660 °C, with face-centered cubic (FCC) crystal structure giving it an outstanding ductility during the forming processes.

Aluminum alloys are further strengthened by Mg, Si, Cu, and Zn solid solution and precipitation hardening mechanisms [3], [4]. Additionally, the precipitation of Mg_2Si particles in Al-Mg-Si alloys (6xxx series) hinders dislocation motion, which increases strength and hardness [5].

Wrought alloys of the 6xxx series, particularly Aluminum 6061-T6, are used in industries due to the mechanical properties, corrosion resistance, and good formability [6]. Furthermore, it is widely applied in construction, automotive, and aerospace industries because of the stable performance over different working conditions [7]. A significant benefit is that T4 and T6 heat treatments promote the formation of a homogeneous distribution of Mg_2Si precipitates in the Aluminum matrix [8]. This heat treatment significantly increases the material hardness and strength, obtained by the precipitate hardening mechanism [5], [9]. Aluminum recycling achieved through remelting and recasting is gradually attaining importance, considering the increasing focus on material efficiency and industrial sustainability. Based on the great energy savings in comparison to primary production, Aluminum is among the most recyclable materials available [10]. As a result, industries need to understand how remelting and recasting change material properties [11]. Aluminum 6061-T6 is not primarily designed for casting applications because of its relatively low fluidity and the possibility of defects such as porosity or hot cracking during solidification [12]. Remelting may alter the chemical composition, particularly through possible magnesium loss or oxidation, and may also eliminate the heat-treatment condition responsible for material strengthening [13], [14]. This contributing factor was not experimentally confirmed because the chemical composition of the recast alloy was not analyzed.

Earlier studies have shown that Aluminum 6061-T6 manufactured through casting generated a coarse and heterogeneous microstructure because of its solidification features [15]. However, the mechanical properties decreased due to dendrite structures formed during solidification with casting defects [16]. The hardness property is directly related to microstructural changes caused by thermal cycling [17]. Several studies have shown the importance of changes in precipitate distribution and grain size on hardness. Higher values of hardness were matched with finer and more homogeneous structures [6], [8], [18], while a coarser microstructure led to lower hardness values. The hardness of Aluminum 6061-T6 alloy was improved through proper aging mechanisms, including artificial and natural precipitate hardening heat treatment [8], [9]. This improvement is attributable to the precipitation of small-sized Mg_2Si dispersoids in the solid solution of Aluminum matrix. Remelting and recasting processes altered the established reinforcement structure. The recasting process is considered an integral part of industrial material recycling. Therefore, it is crucial to comprehend microstructural changes and mechanical characteristics induced by new casting [13].

Several previous studies focused mainly on global mechanical performances such as tensile or mean hardness, neglecting local fluctuations within the material. However, the local fluctuations aid in predicting the behavior of the metal in actual service. Studies investigating the spatial variation of microstructure and hardness in localized regions, particularly in remelted and recast Aluminum 6061-T6, remain limited. Spatially resolved microhardness measurements show local variations in mechanical response across the recast section compared to the average hardness. This prompted the 81 measurement locations to be distributed across the casting. The aim was to characterize hardness variations with respect to position, thereby providing extra information concerning spatial heterogeneity concealed by an overall average value.

The influence of remelting and recasting on local mechanical properties and their relationship with microstructural heterogeneity is not fully understood. Therefore, this present study aimed to fill the gap by analyzing the distribution of localized hardness in correlation with experimentally observed microstructures. The novelty of this study lies in the spatially resolved hardness characterization and its qualitative relationship with microstructural heterogeneity in remelted Aluminum 6061-T6. The objective is to investigate the influence of a single remelting and recasting cycle on microhardness and microstructure of the alloy. The relationship between microstructural changes and variations in local microhardness after a single remelting and recasting process was also examined.

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2. Materials and Methods

This study was conducted using a single independently produced casting, with multiple Vickers microhardness measurements performed across the specimen surface. The purpose was to characterize the local hardness distributions rather than the comparison between independently cast samples. The raw material was wrought Aluminum Alloy 6061-T6 in the form of a round bar with a diameter of 50.8 mm (2 inch), acquired from a commercial distributor. The initial step focused on performing chemical composition analysis using Laser-Induced Breakdown Spectroscopy (LIBS) at six distinct points across the surface cross-section, with the averaged test results shown in Table 1. Subsequently, the surface cross-section was polished using abrasive paper in preparation for preliminary hardness testing carried out through micro-Vickers method using Micro Vickers Hardness Tester FM-800 Future Tech. The hardness measurements were performed at six indentation sites, correlating with the previously analyzed composition locations. The final stage comprised microscopic examination of the raw material's microstructure using Metallurgical Microscope MT7100L Meiji Techno. Meanwhile, this microstructural observation procedure conformed to the metallographic processing protocols outlined in ASTM E3-11 [19].

Table 1. Chemical composition of Aluminum 6061-T6

Elements	Al	Mg	Si	Fe	Cu	Mn	Cr	Ni	Zn
Amount / wt %	97.88	0.98	0.52	0.28	0.13	0.04	0.03	0.07	0.03

The alloy was melted in a graphite crucible using a portable electric furnace. The pouring temperature of approximately 800 °C was selected based on preliminary casting trials, as lower temperatures resulted in incomplete mold filling. After the melt reached approximately 800 °C, it was held at this temperature for approximately 10 min before being poured into the prepared metal mold. No degassing treatment was applied prior to pouring. The melt temperature was monitored using a K-type thermocouple. After pouring, the casting was allowed to cool naturally in the metal mold for approximately 90 min before the mold was opened. The shape and dimensions of the metal mold are shown in Figure 1.

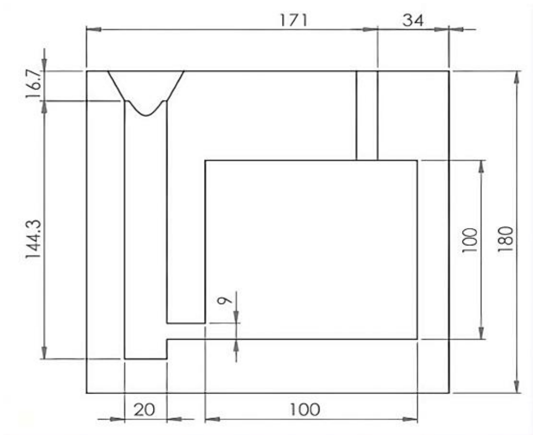

Figure 1. Shape and dimensions of the metal mold

The recast product was milled and ground on both surfaces in preparation for Vickers microhardness testing in accordance with ASTM E384-17 [20]. The measurements were performed using a test force of 4.903 N (0.5 kgf) and a dwell time of 15 s. Microhardness was measured across the entire cross-section of the casting with respect to the ingate/runner position. Nine measurement locations were arranged horizontally from the ingate and nine vertically from the bottom to the top of the casting, resulting in a total of 81 measurement locations. The spacing between adjacent locations was approximately 10 mm, with the outermost locations positioned approximately 5 mm from the mold edges. Two indentations were performed at each location, and

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the average hardness value was reported. The distribution of the microhardness measurement locations is shown in Figure 2.

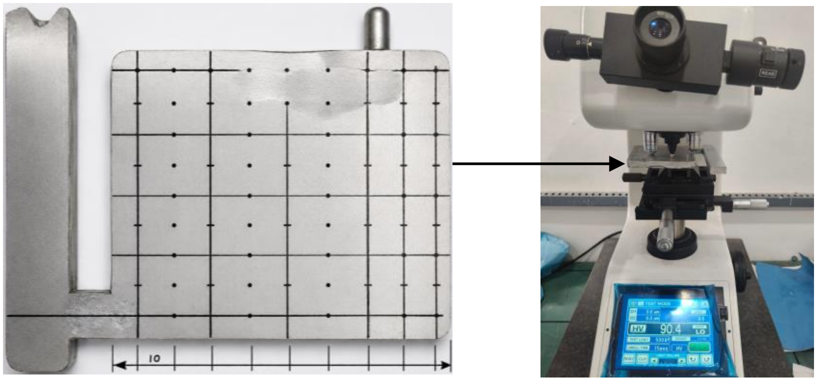

Figure 2. Distribution of hardness testing indentation locations

The final step involved microstructural observation at locations adjacent to the microhardness measurement points. The specimens were cut, progressively ground using graded abrasive papers, and polished to a mirror-like finish in accordance with ASTM E3-11(2017) [19]. Etching was performed using Keller's reagent in accordance with ASTM E407-07(2015)e1 [21]. The microstructure was observed using a metallurgical microscope at various magnifications.

3. Results and Discussion

3.1. Microhardness Test of Wrought Aluminum 6061-T6

Six test points were selected across the surface to determine the average Vickers microhardness of the raw Aluminum 6061-T6 material. As shown in Table 2, hardness values between 130 HV0.5 and 137 HV0.5, with an average of 134 HV0.5, had an even distribution on the tested surface.

Table 2. Hardness values of Aluminum 6061-T6

Test location	1	2	3	4	5	6	Average
Hardness / HV0.5	135	132	135	137	130	135	134

The measured hardness values of the wrought Aluminum 6061-T6 ranged from 130 to 137 HV0.5, with an average value of 134 HV0.5, indicating relatively low variation across the tested locations. The relatively high and uniform hardness is consistent with the precipitation-hardened T6 condition of the alloy. In Al-Mg-Si alloys, this strengthening condition is generally associated with fine strengthening precipitates that hinder dislocation motion and contribute to increased hardness.

3.2 Micro Vickers Hardness Distribution of Remelting Aluminum 6061-T6

Micro-Vickers hardness measurements of the remelted and recast Aluminum 6061-T6 were obtained at 81 measurement locations distributed across the casting, as shown in Table 3. The measured hardness values ranged from 80 to 103 HV0.5, with an overall average of approximately 89 HV0.5. This average value was approximately 33 % lower than that of the wrought material, which had an average hardness of 134 HV0.5. In addition to the overall reduction in hardness, the recast material exhibited greater spatial variability across the investigated casting.

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Pouring Temperature : 800 °C

location of Indentation away from in gate →; location of Indentation from battom to top ↑; Runner/Ingate; Vickers microhardness (HV 0.5/15)

Row	1	2	3	4	5	6	7	8	9	Avrg (HV0.5)	StDev
9	103	90	93	83	89	83	94	96	103	93	7.4
8	102	91	90	80	83	81	90	97	101	91	8.2
7	100	87	88	83	83	82	87	90	101	89	7.0
6	98	82	86	84	87	83	88	88	96	88	5.5
5	97	90	89	84	82	81	100	99	101	91	8.0
4	89	86	85	80	85	90	100	96	93	89	6.2
3	92	86	85	85	86	81	90	88	88	87	3.2
2	86	82	81	90	86	85	93	86	82	86	3.9
1	83	92	93	95	94	86	89	86	87	89	4.2
Avrg (HV0.5)	94	87	88	85	86	84	92	92	95		
StDev	7.2	3.7	4.0	4.8	3.7	3.0	4.9	5.2	7.6		

Table 3. Spatial distribution of Vickers microhardness (HV0.5) across the surface of remelting Aluminum 6061-T6

The recast material showed greater spatial variation in hardness compared with the wrought Aluminum 6061-T6. The spatial distribution of hardness values across the casting is shown in Figure 3.

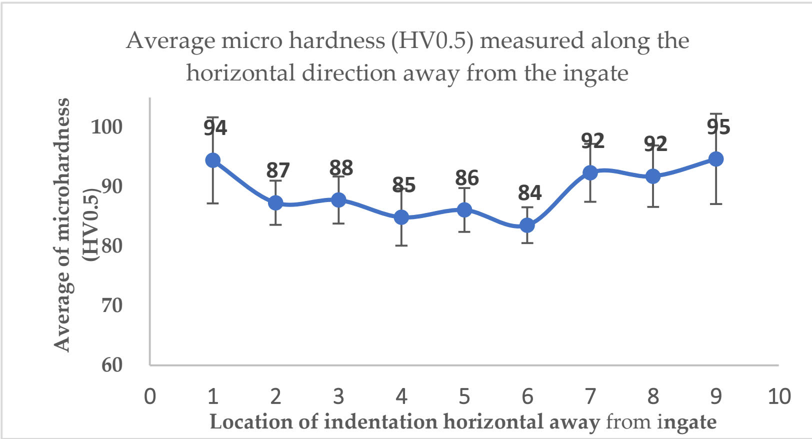

Figure 3. Microhardness distribution based on location of indentation away from ingate/runner

The hardness values measured along the horizontal direction from the ingate ranged from approximately 84 to 95 HV0.5, showing a non-uniform spatial distribution across the casting. A decrease followed by an increase in average hardness was observed with increasing distance from the ingate. This pattern may reflect differences in local solidification conditions within the casting, although the cooling rate and thermal gradients were not directly measured in the present study. The corresponding standard deviations ranged from 3.0 HV0.5 to 7.6 HV0.5, indicating different levels of hardness variability among the measurement positions.

Microhardness distribution evaluated from the bottom toward the top of the mold showed a gradual increase in hardness values from 86 HV0.5 to 93 HV0.5 at the upper region of the mold, as in Figure 4. This result suggests that the observed vertical variation in hardness may reflect differences in local solidification conditions within the casting.

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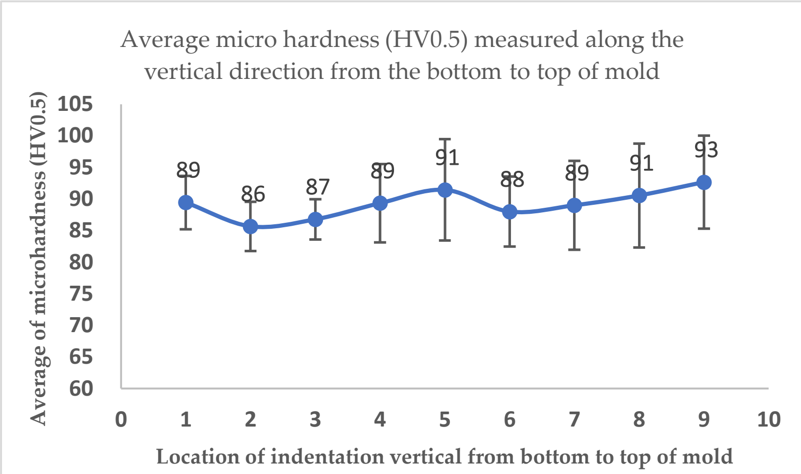

Figure 4. Average of microhardness (HV0.5) distribution based on location of indentation from the bottom to top of the mold

The corresponding standard deviations ranged from 3.2 HV0.5 to 8.2 HV0.5, indicating differences in hardness variability along the vertical direction of the casting. Greater variability was observed at some locations in the lower region than in the upper region. These variations may be associated with differences in local solidification conditions; however, cooling rates and thermal gradients were not directly measured in this study.

The hardness values represent internal spatial variability within the examined casting rather than the reproducibility or generalizability of all remelted Aluminum 6061-T6 castings, since only one casting was studied. As a result, several castings should be assessed in future studies to examine casting-to-casting variability and reproducibility.

3.3 Effect of the Recasting Process on Microstructure of Aluminum 6061-T6

Microstructure of remelting Aluminum 6061-T6 samples produced through melting and casting was compared to wrought raw material to analyze its structure after recasting. A metallurgical microscope was used to observe microstructural features. This was because the present study focused on the qualitative rather than quantitative assessment of grain size, phase fractions, and particle distribution. Therefore, the analysis centered mostly on visual observation of microstructural morphology, particle-like microstructural features, and dendritic-type features. Microstructure images of wrought raw Aluminum 6061-T6 product (metallographic) are shown in Figure 5. Wrought microstructure in Figure 5a shows a light-colored Aluminum alloy (α) matrix embedding relatively fine, dark particles that are properly distributed. These dark microstructural features may be associated with precipitate-containing regions typically observed in Al-Mg-Si alloys. The interpretation of the observed dark microstructural features was based on their morphological appearance and contrast, together with the established literature on precipitation behavior in Al 6061-T6. However, their chemical identity cannot be conclusively determined because no complementary phase or compositional characterization was performed. In Al-Mg-Si alloys, Mg_2Si-containing precipitates formed during artificial aging contribute to precipitation strengthening and improved mechanical properties.

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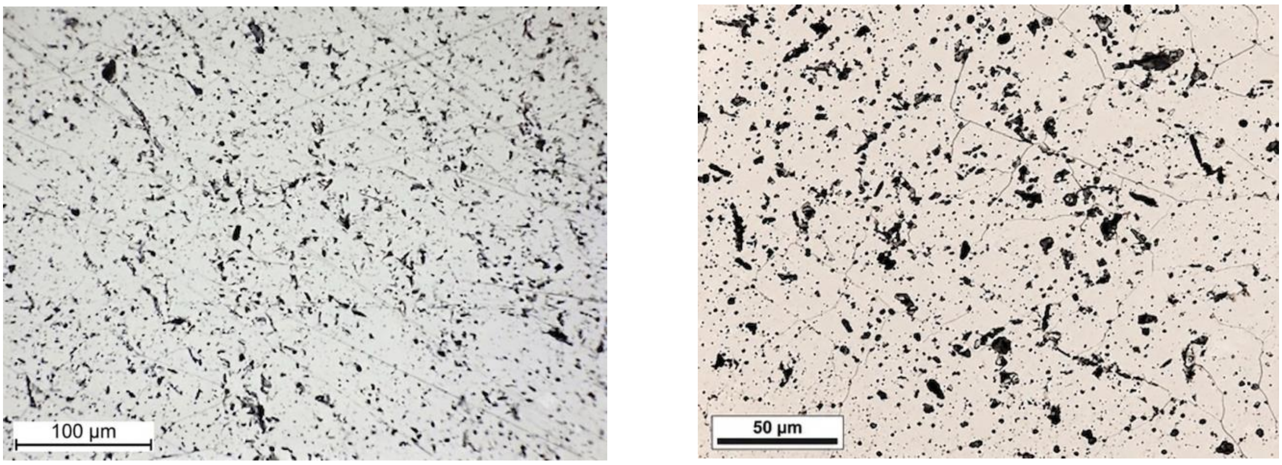
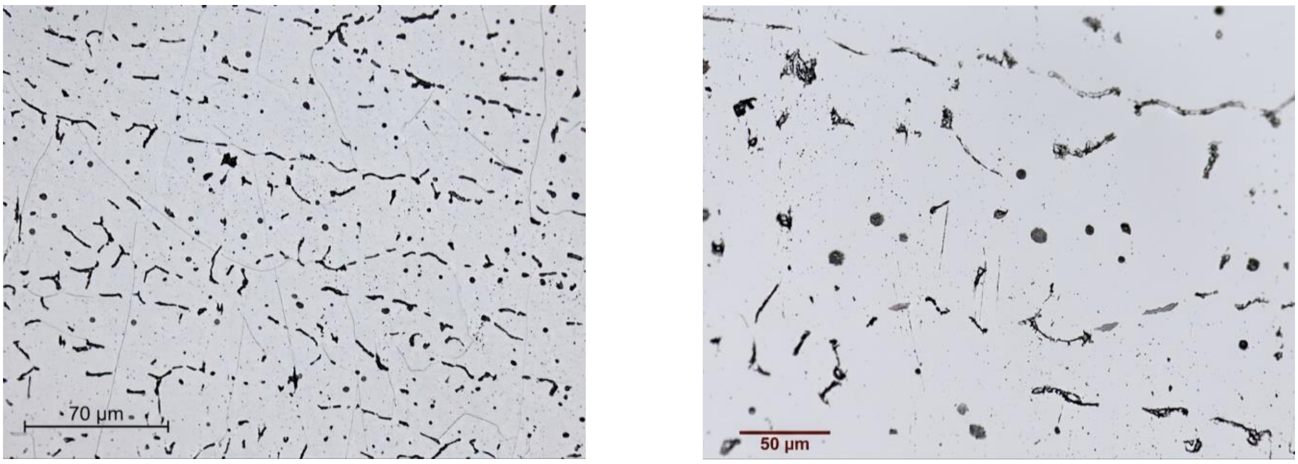


a b

Figure 5. a) Microstructure image of Wrought Aluminum 6061 at 200x magnification. b) Metallographic microstructure of wrought Al 6061-T6 showing the α-Al matrix alongside the distributed dark microstructural features at 500x magnification.

The dark microstructural features appeared relatively fine and homogeneously distributed within the matrix, as shown in Figure 5b. Such a microstructural appearance is consistent with the precipitation-hardened T6 condition of the wrought alloy. The production of Aluminum 6061-T6 using deformation processing led to a fine, homogeneous microstructure, which accounted for the hardness of the resulting product. In addition, the product lacked any dendritic-type structure typical of a cast material, validating the use of wrought deformation processing.

As can be seen in Figure 6, the remelting and recasting process strongly affected the morphology and spatial distribution of the microstructural features compared to those observed for wrought Al 6061-T6, which has relatively fine and uniformly distributed microstructural features.



a **b**

Figure 6. a) Microstructure image of remelting and recasting product of Aluminum 6061 at 200x magnification. b) Metallographic microstructure of remelting and recasting product of Aluminum 6061 showing the α-Al matrix including the distributed dark microstructural features at 500x magnification.

Figure 6a shows the recast product microstructure of wrought Aluminum 6061-T6 after molding with a metal mold, with clear differences in comparison to the original material. The bright matrix dominated the microstructure, while larger and darker microstructural features were heterogeneously distributed [23]. Figure 6b shows that these features appeared coarser after the remelting and recasting process. The remelted specimen

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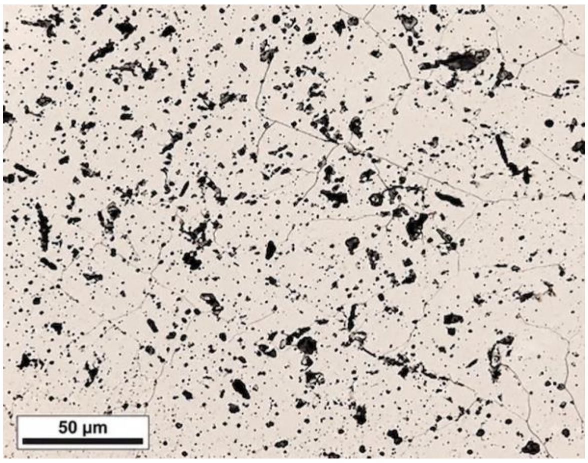
exhibited larger and more heterogeneously distributed microstructural features compared with the fine and more uniformly distributed features observed in the wrought material, as shown in Figure 5b. The observations suggested substantial microstructural changes following the solidification process. Random dark areas were also observed, which may be associated with casting-related imperfections such as porosity.

Microstructure of recast material has certain features typical of solidification. However, it differed from the more homogeneous structure of the original material, as shown in Figure 7.



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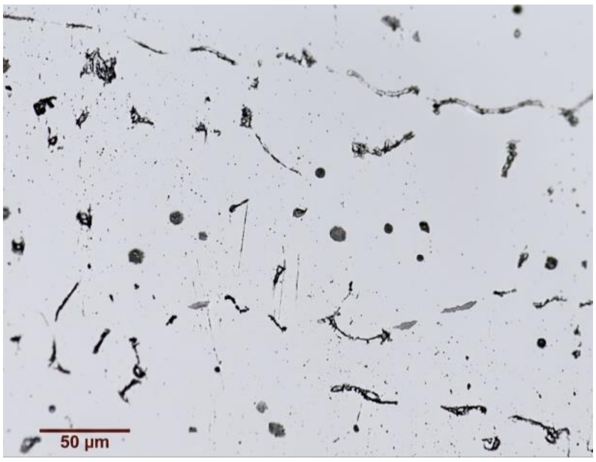

b

Figure 7. Comparison of Microstructure images of Wrought and Recast Aluminum 6061-T6 a) Microstructure image of Wrought Aluminum 6061-T6 at 500x magnification. b) Microstructure image of remelting and recasting product of Aluminum 6061-T6 at 500x magnification.

Microstructure of wrought Aluminum 6061-T6 offers a more homogenized and refined structure with finer and more uniformly distributed constituent particles that reflect the previous thermomechanical processing. Furthermore, the recast Aluminum 6061-T6 showed a coarser and more heterogeneous structure, with randomly dispersed features that may be associated with casting-related imperfections such as porosity. These microstructural differences were consistent with the spatial variation in hardness observed in the recast material [22].

3.4 Relationship between Microstructure and Hardness of Wrought and Remelting Aluminum 6061-T6

Aluminum 6061-T6 is a precipitation-hardened alloy, and the wrought material examined in this study exhibited a relatively homogeneous microstructure together with an average hardness of 134 HV0.5. In contrast, the recast product showed a more irregular and heterogeneous microstructure and a lower average hardness of 89 HV0.5. The observed microstructural features and hardness reduction are consistent with the loss of the original precipitation-hardened T6 condition during remelting and subsequent solidification, as illustrated by the microstructural comparison in Figure 7. Casting-related imperfections, including possible porosity, may also have contributed to the observed reduction in hardness [23].

The substantial reduction in hardness observed after remelting and recasting was associated with the loss of the precipitation-hardened T6 condition. The original Aluminum 6061-T6 derives its high hardness from precipitation strengthening developed during solution heat treatment and artificial aging. During remelting, the original precipitation-hardened condition was lost, and after solidification the material remained in the as-cast condition because no subsequent solution treatment or artificial aging was applied. The loss of the T6 precipitation-hardened condition is consistent with the significant reduction in hardness observed after recasting. Casting-related microstructural heterogeneity and possible casting imperfections may also have contributed to the observed reduction and spatial variation of local hardness within the examined casting.

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The observed heterogeneity of microstructure was associated with the variation in local hardness measured within the examined casting. The observed spatial variation in hardness was qualitatively consistent with the overall microstructural heterogeneity observed in the recast material. This relationship should be interpreted qualitatively because the microstructural observations were not quantitatively correlated with individual hardness measurement locations. The reduction and spatial variation of hardness in the recast Aluminum 6061-T6 was interpreted in terms of the transition from a relatively homogeneous, precipitation-strengthened wrought condition to a more heterogeneous cast microstructure.

This present study was conducted using a single independently produced remelted and recast Aluminum 6061-T6 casting. Therefore, the reported microhardness values represent the spatial distribution of local hardness within the examined casting rather than casting-to-casting reproducibility. The observed trends should be interpreted within the scope of the investigated specimen. Future studies on multiple independently produced castings are recommended to evaluate the reproducibility of the observed hardness distribution and microstructural characteristics.

4. Conclusions

In conclusion, microstructure and mechanical properties of Aluminum 6061-T6 depended on remelting and recasting process. The wrought alloy showed a relatively homogeneous microstructure with fine and uniformly distributed microstructural features, together with an average hardness of approximately 134 HV0.5. In comparison, the hardness of the recast material decreased to approximately 89 HV0.5 with increased variability. Microstructural analysis indicated a coarser and more heterogeneous microstructure after recasting, together with features that may be associated with casting-related imperfections. The spatial variation in hardness was qualitatively consistent with the overall microstructural heterogeneity observed in the recast material. Based on the examined casting, the results suggest that the reduction in hardness is consistent with the transition from the original precipitation-hardened T6 condition to a more heterogeneous as-cast microstructure.

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