

## ABSTRAK

# MODIFIKASI MIKROSTRUKTUR PADUAN Al-6061 MELALUI PENAMBAHAN 0,5 WT% Zr DAN PERLAKUAN *DEEP CRYOGENIC* PADA PROSES *SOLUTION TREATMENT*

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Paduan Al-6061 dapat diperkuat melalui mekanisme *precipitation hardening* yang mempengaruhi mikrostruktur dan sifat mekaniknya. Penambahan unsur zirkonium (Zr) membentuk dispersoid  $\text{Al}_3\text{Zr}$  yang menghambat migrasi batas butir, dan *deep cryogenic treatment* (DCT) yang mempercepat pendinginan untuk membentuk larutan padat lewat jenuh. Penelitian ini mengkaji pengaruh penambahan 0,5 wt.% Zr dan variasi temperatur *solution heat treatment* (SHT) dengan DCT terhadap strukturmikro, pembentukan  $\text{Al}_3\text{Zr}$  dan  $\text{Mg}_2\text{Si}$ , serta kekerasan paduan Al-6061-Zr. Paduan Al 6061–0,5 Zr wt.% difabrikasi melalui *sand casting* dan dihomogenisasi pada 450°C dengan pendinginan udara, lalu dikarakterisasi menggunakan *optical emission spectroscopy* (OES) pada 3 titik. Sampel *as-homogenization* diberi perlakuan SHT (490°C, 520°C, dan 550°C) selama 1,5 jam, *water quenching*, dan DCT dengan nitrogen cair (-196°C). Hasil OM dan SEM-EDS menunjukkan pertumbuhan butir pada SHT 490°C, 520°C, dan 550°C yaitu 118,815  $\mu\text{m}$ ; 147,455  $\mu\text{m}$  dan 160,69  $\mu\text{m}$ . Fasa kedua yang diidentifikasi sebagai *retained*  $\text{Mg}_2\text{Si}$  berdasarkan analisa XRD, terkonfirmasi masih terdeteksi pada seluruh variasi SHT. Meskipun peningkatan temperatur SHT meningkatkan kelarutan  $\text{Mg}_2\text{Si}$  dalam  $\alpha$ -Al, tetapi juga meningkatkan difusivitas Mg yang mendorong redistribusi dan segregasi lokal Mg pada daerah kaya Zr yang terindikasi dari kemiripan distribusi Mg dan Zr hasil elemental *mapping*. Kondisi ini diduga memicu pembentukan kembali fasa kaya Mg selama pendinginan, sehingga sampel SHT 490°C menghasilkan mikrostruktur lebih homogen dengan pelarutan fasa kedua lebih tinggi dibandingkan temperatur SHT yang lebih tinggi. Setelah *artificial aging*, kekerasan meningkat dari 95,5 HV menjadi 137,67 HV (44,2%). Dispersoid  $\text{Al}_3\text{Zr}$  efektif mempertahankan stabilitas mikrostruktur, sementara kombinasi SHT, DCT, dan *artificial aging* mengoptimalkan penguatan presipitasi pada paduan Al-6061.

Kata kunci: Al-6061, *deep cryogenic treatment*, dispersoid  $\text{Al}_3\text{Zr}$ , presipitat  $\text{Mg}_2\text{Si}$ , *solution heat treatment*

## **ABSTRACT**

### **MODIFICATION OF THE MICROSTRUCTURE OF Al-6061 ALLOY BY THE ADDITION OF 0.5 WT% Zr AND DEEP CRYOGENIC TREATMENT DURING THE SOLUTION TREATMENT PROCESS**

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*Al-6061 alloy can be strengthened through a precipitation hardening mechanism that influences its microstructure and mechanical properties. The addition of zirconium (Zr) promotes  $Al_3Zr$  dispersoids formation that inhibits grain boundary migration, while deep cryogenic treatment (DCT) accelerates cooling to produce a supersaturated solid solution. This study investigates the effect of adding 0.5 wt% Zr and varying the solution heat treatment (SHT) temperatures combined with DCT on the microstructure, formation of  $Al_3Zr$  and  $Mg_2Si$  phases, and hardness of Al-6061-Zr alloys. The Al-6061-0.5 wt% Zr alloy was fabricated by sand casting and homogenized at 450°C followed by air cooling. The alloy composition was characterized using optical emission spectroscopy (OES) at three locations. The homogenized samples were subjected to SHT at 490°C, 520°C, and 550°C for 1.5 h, followed by water quenching and DCT using liquid nitrogen at -196°C. OM and SEM-EDS analyses revealed grain sizes of 118.815  $\mu m$ ; 147.455  $\mu m$  and 160.69  $\mu m$  at 490°C, 520°C, and 550°C, respectively. XRD analysis confirmed retained  $Mg_2Si$  under all SHT conditions. Although increasing the SHT temperature enhanced  $Mg_2Si$  solubility in the  $\alpha$ -Al matrix, the higher diffusivity of Mg also promoted its redistribution and local segregation in Zr-rich regions, as indicated by the similar Mg and Zr in elemental mapping. This condition likely triggers Mg-rich phases during cooling, resulting in a more homogeneous microstructure and greater second-phase dissolution in the sample treated at 490°C compared with those treated at SHT temperatures. After artificial aging, hardness increased from 95.5 HV to 137.67 HV (44.2%).  $Al_3Zr$  dispersoids effectively maintained microstructural stability, while the combination of SHT, DCT, and artificial aging optimized precipitation strengthening in the Al-6061 alloy.*

*Keywords: Al-6061, deep cryogenic treatment,  $Al_3Zr$  dispersoids,  $Mg_2Si$  precipitates, solution heat treatment*