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Influence of Heat Treatment on Friction Behaviour of Aluminium 6063 Using Ring Compression Under Lubrication

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ABSTRACT

This research presents an extended study on the influence of heat treatment on the tribological behavior of aluminium alloy 6063 using the ring compression test under lubricated conditions. Ring specimens were heat-treated at four different annealing temperatures (365, 415, 465, and 565°C) for 2.5 hours and cooled in a furnace. Friction coefficient (μ), friction factor (m), and hardness values were systematically evaluated. Results indicate that annealing between 365°C and 415°C significantly reduces hardness and consequently lowers μ and m under applied loads of 20T, 25T, and 30T. This suggests that microstructural recovery and softening at these annealing ranges facilitate lubrication effectiveness. The optimum condition was obtained at 415°C and ≥25T, which resulted in the lowest friction values.

Keywords: heat treatment; friction coefficient; lubrication

1. Introduction

Aluminium alloys, particularly the Al-Mg-Si series such as AA6063, have been extensively used in manufacturing industries due to their excellent combination of light weight, high specific strength, corrosion resistance, and formability [1]. Applications can be found in structural components, automotive and aerospace industries, architectural extrusions, and packaging. However, one of the critical challenges during the forming processes of aluminium alloys is controlling friction at the die–workpiece interface. High friction leads to poor surface finish, accelerated tool wear, increased forming loads, and ultimately reduces component life [2].

To mitigate friction, lubricants are often applied; however, their effectiveness depends not only on the type of lubricant but also on the surface hardness, oxide films, and microstructure of the workpiece material. Heat treatment, particularly annealing, is known to alter the hardness and microstructure of aluminium alloys through recovery and recrystallization [3]. Several researchers have highlighted that reduced hardness often facilitates better lubricant spreading, thereby reducing the real area of contact [4,5]. Nonetheless, excessive softening may compromise strength and lead to dimensional inaccuracies. Thus, a careful balance must be achieved between hardness reduction and tribological performance.

Traditionally, tribological testing of materials is conducted using ball-on-disk tests, pin-on-disk tests, or block-on-ring methods. While these provide important insights into surface tribology, they do not fully represent the bulk friction conditions in forming operations [6]. The ring compression test (RCT) has been recognized as a reliable and standardized method to determine the friction factor (m) and coefficient (μ) in metal forming processes [7]. It has the advantage of simplicity, reproducibility, and direct correlation with bulk deformation mechanics. Recent studies have successfully employed the RCT to investigate the effects of lubrication, temperature, and material condition on frictional behavior [8].

The present study extends this knowledge by systematically evaluating the role of heat treatment in altering the hardness and tribological performance of AA6063 under lubricated ring compression. By integrating hardness measurements with calculated friction coefficients and factors, this research provides insights into the mechanisms by which annealing influences tribology in forming conditions. The outcomes are expected to support both academic understanding and industrial applications in forming and improving tool life.

2. Materials and Methods

Specimens of AA6063-T5 alloy were prepared in the form of rings with an outer diameter of 18 mm, an inner diameter of 9 mm, and a thickness of 6 mm, as shown in Fig. 1. The chemical composition of AA6063 typically includes magnesium and silicon as primary alloying elements, contributing to its precipitation hardening capability [9].

The specimens were subjected to annealing heat treatment at four different temperatures: 365°C, 415°C, 465°C, and 565°C. Each treatment was conducted for 2.5 hours, followed by furnace cooling to simulate industrial practice. Annealing at these ranges was selected based on the known recovery and recrystallization temperatures of Al-Mg-Si alloys. The hardness of the specimens was measured using a Vickers hardness tester with a load of 0.5 kgf, and the average of five indentations was recorded for each condition.

Ring compression tests were conducted using a universal testing machine at three different loads: 20 kN, 25 kN, and 30 kN. A synthetic lubricant (EH-737T) was applied on the contact surfaces to simulate lubricated forming conditions, as shown in Fig. 2. During compression, the reduction in ring height and corresponding change in inner diameter were measured and compared with calibration curves established from standard RCT friction maps. From these correlations, the friction coefficient (μ) and friction factor (m) were derived for each test condition [7,10].

Fig. 1: The specimens of AA6063-T5 alloy

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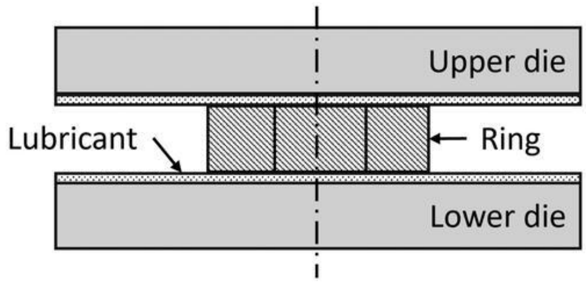

Fig. 2: Ring compression test system

3. Results and Discussion

The experimental results demonstrate a clear relationship between annealing temperature, hardness, and tribological parameters. Hardness decreased significantly after annealing at 365°C and reached its lowest at 415°C (39.84 HV). This drop can be attributed to recovery and recrystallization, which reduce dislocation density and soften the material [11]. At higher temperatures (465°C and 565°C), hardness slightly increased, possibly due to grain coarsening or over-aging phenomena. The geometric parameters of the sample after deformation are in Table 1. The Vickers hardness is shown in Fig. 3.

Table 1: The geometric parameters of the sample after deformation.

Heat Treatment Condition	Load (T)	d_o (mm)	d_i (mm)	t (mm)	d_o final (mm)	d_i final (mm)	t final (mm)
Non heat treatment	20 T	18.00	9.00	6.00	20.85	9.81	4.33
	25 T	18.00	9.00	6.00	22.15	9.98	3.80
	30 T	18.00	9.00	6.00	22.89	10.16	3.41
365°C	20 T	18.00	9.00	6.00	22.42	7.74	3.60
	25 T	18.00	9.00	6.00	24.14	8.22	3.38
	30 T	18.00	9.00	6.00	25.05	9.45	2.98
415°C	20 T	18.00	9.00	6.00	22.27	8.73	3.53
	25 T	18.00	9.00	6.00	24.56	10.37	3.15
	30 T	18.00	9.00	6.00	26.49	12.05	3.00
465°C	20 T	18.00	9.00	6.00	22.85	6.53	3.10
	25 T	18.00	9.00	6.00	25.17	9.73	2.93
	30 T	18.00	9.00	6.00	24.18	11.12	3.10
565°C	20 T	18.00	9.00	6.00	21.48	8.28	3.88
	25 T	18.00	9.00	6.00	23.68	9.53	3.37
	30 T	18.00	9.00	6.00	26.07	11.80	3.00

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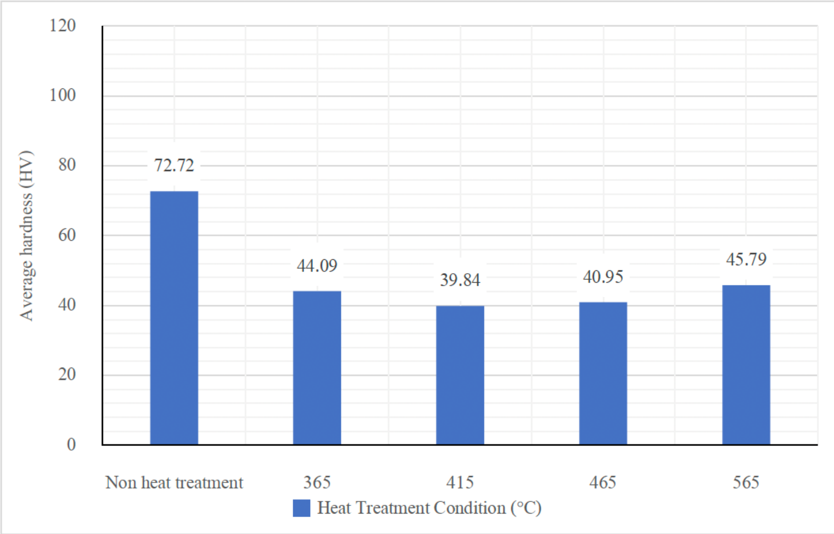

Fig. 3: Vickers hardness of Al6063 after heat treatment at different temperatures

The calibration curves of the friction coefficient (μ) and the friction factor (m) are shown in Fig. 4. The friction coefficient (μ) decreased with increasing load across all heat treatment conditions. At 20T, μ values ranged between 0.06 and 0.15, depending on the annealing condition, whereas at 30T, values dropped to 0.02–0.03, as shown in Fig. 5. This trend is explained by enhanced lubricant entrainment at higher contact pressures, which minimizes asperity interaction.

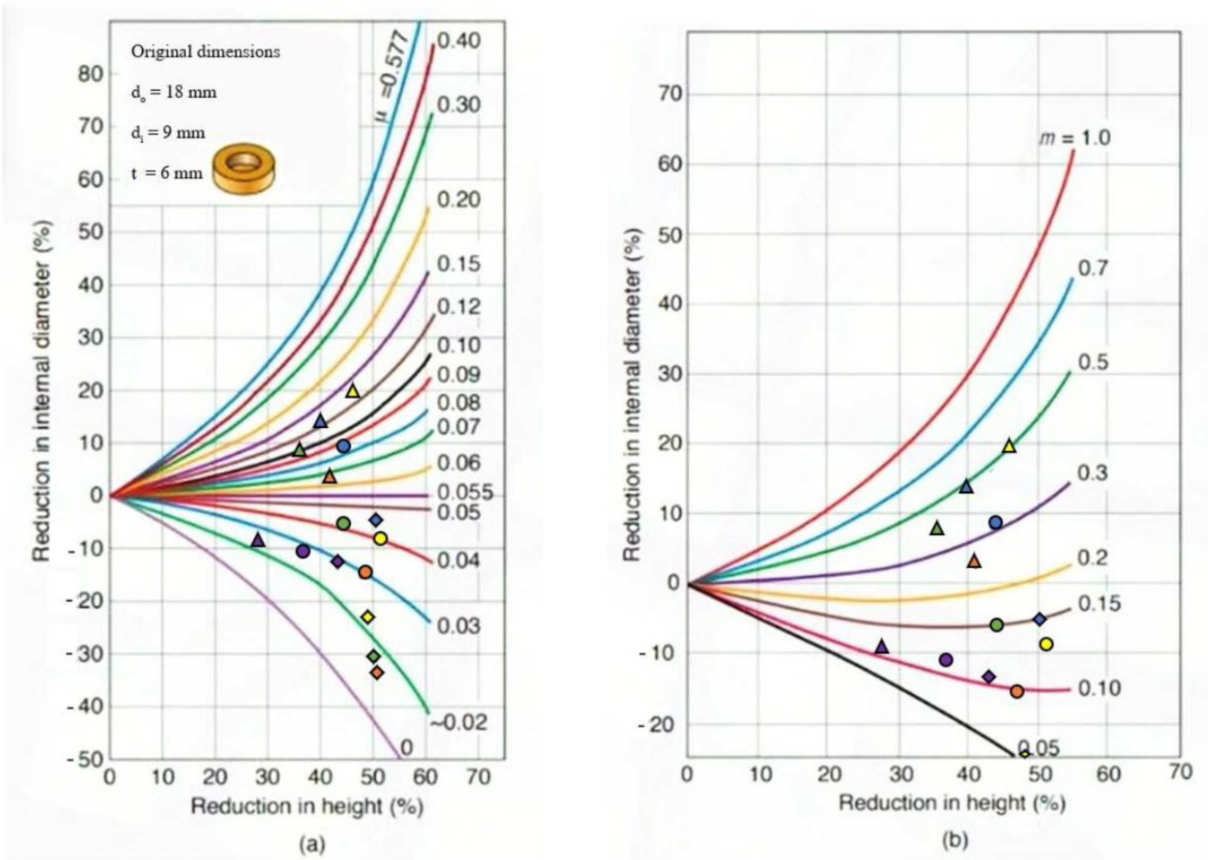

Fig. 4: Calibration curves of a) friction coefficient (μ) and b) friction factor (m)

△ 20T, ○ 25T, ◇ 30T, ■ Non heat, ■ 365°C, ■ 415°C, ■ 465°C, ■ 565°C

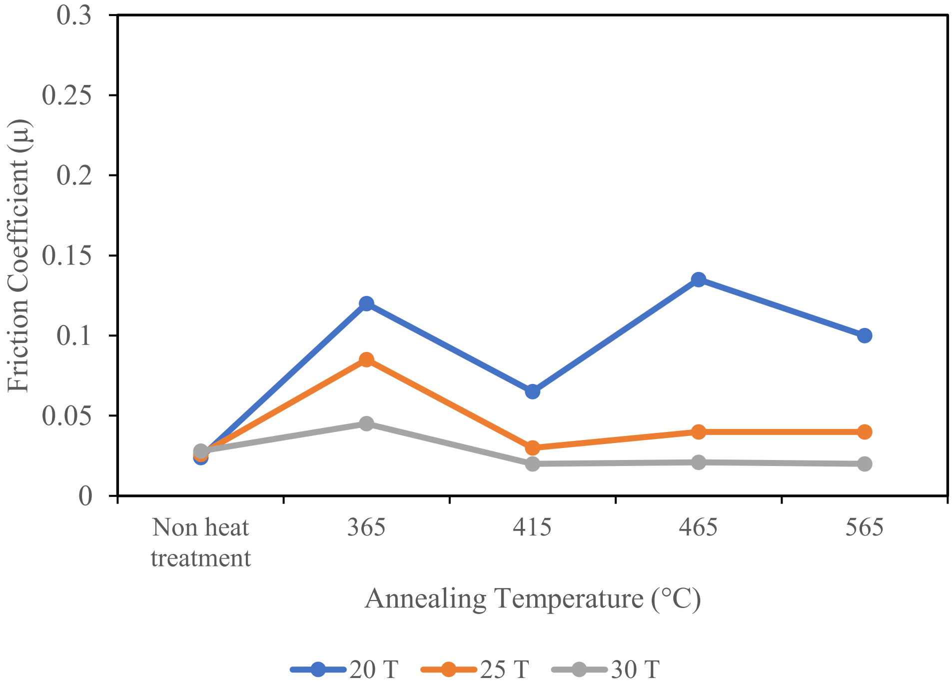

Fig. 5: Friction coefficient (µ) of experiments

The friction factor (m) also followed a similar trend. The most significant reduction in m occurred between 365°C and 415°C, consistent with the observed reduction in hardness. At 415°C and 30T, the lowest m values (<0.05) were recorded as shown in Fig. 6. This confirms that a softer matrix supports lubrication effectiveness, thereby lowering friction during bulk forming

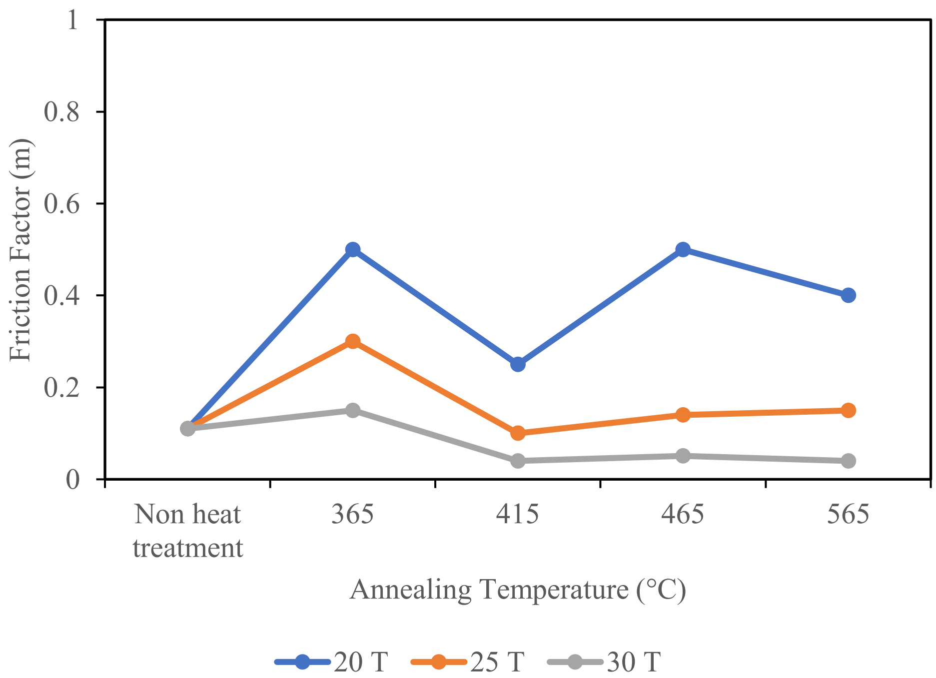

Fig. 6: Friction factor (m) of experiments

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Comparisons with previous studies reveal consistent findings. For example, Rajesh et al. [3] reported that annealed aluminium alloys exhibited lower friction in RCT under lubricated conditions. Similarly, Martín et al. [7] validated that RCT is highly sensitive to changes in lubrication and material properties. Our results strengthen these findings by explicitly linking annealing-induced hardness changes with tribological behaviour in AA6063.

The significant drop in hardness between 365°C and 415°C, as shown in Fig. 3, can be attributed to recovery and recrystallization processes, which effectively reduce dislocation density and soften the material. This softening leads to improved lubricant entrainment at the tool–workpiece interface. As a result, both the friction coefficient (μ) and friction factor (m) decreased, particularly under higher loads (25T–30T). The lowest μ (~0.02–0.03) and m (<0.05) were achieved at 415°C and 30T, confirming this condition as the optimum for minimizing friction in AA6063 forming.

The present findings align well with previous tribological studies using the ring compression test. Rajesh and SivaPrakash [12] demonstrated that the use of lubricants such as MoS_2 and graphite effectively lowered μ and m in aluminium alloys, consistent with the reduced friction observed here after annealing at 415°C. Similarly, Demisie et al. [13] reported that lubricated wheel steels showed lower μ values (~0.09 in oil) compared to dry conditions (~0.15), supporting the idea that optimized surface conditions and lubrication reduce contact friction. Yilmaz [14] also confirmed that lubrication and die expansion critically influenced m values and dimensional accuracy in aluminium forging, paralleling the improvements recorded in our study.

Interestingly, Barati et al. [15] found in AZ61 magnesium alloys that increasing temperature and DRX promoted higher m values under certain strain rates, contrasting with the decreased m observed in our AA6063 tests. This difference may be attributed to the role of recovery and recrystallization in AA6063 versus dynamic recrystallization in AZ61, highlighting the material-dependent mechanisms in frictional behaviour.

Overall, our work strengthens the consensus that both microstructural modification and lubrication play vital roles in controlling friction. The ability to pinpoint an optimum annealing condition (415°C at ≥25T) under lubricated forming provides new insight for industrial practice and complements the broader tribological literature."

4. Conclusion

This study confirms that heat treatment has a significant impact on the tribological behavior of AA6063 alloy under lubricated conditions. Hardness decreased significantly between 365°C and 415°C, reaching a minimum at 415°C. The friction coefficient (μ) and friction factor (m) decreased with increasing load, with the lowest values observed at loads of 25 T or greater. Annealing at 415°C provided the optimum balance between reduced hardness and lubrication efficiency. Beyond 415°C, no substantial improvement was observed, suggesting a threshold condition.

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