

Adrian BARYLSKI\*, Krzysztof ANIOŁEK\*, Marian KUPKA\*, Michał DWORAK\*

## THE EFFECT OF LOAD ON THE TRIBOLOGICAL PROPERTIES OF MAGNESIUM ALLOY WE54 AFTER PRECIPITATION HARDENING

### WPLYW OBCIĄŻENIA NA WŁAŚCIWOŚCI TRIBOLOGICZNE STOPU MAGNEZU WE54 PO UTWARDZANIU WYDZIELENIOWYM

**Key words:** WE54, solution treatment; ageing; hardness; wear.

**Abstract** The paper presents the effect of precipitation hardening on the mechanical and tribological properties of magnesium alloy WE54. Mechanical tests have shown that the hardness and Young's modulus of the alloy increased as the ageing time became longer. Improvement of the mechanical properties had a direct influence on the tribological properties. Tribological tests were performed on a ball-on-disk tribometer, applying variable loads of 2, 5, and 10 N. In the tests, a more than fourfold decrease in the specific wear rate, a threefold reduction in the linear wear, and a ca. 20% reduction of the friction coefficient were observed. The best results were obtained for ageing time of 24 h. The extension of the heat treatment time to 48h caused overageing of the alloy, which resulted in the deterioration of its mechanical and tribological properties.

**Słowa kluczowe:** WE54, przesycanie, starzenie, zużycie.

**Streszczenie** W artykule przedstawiono wpływ utwardzania wydzieleniowego na właściwości mechaniczne i tribologiczne stopu magnezu WE54. Badania mechaniczne wykazały, że wraz ze wzrostem czasu starzenia rosła twardość i moduł Younga stopu. Poprawa właściwości mechanicznych miała bezpośredni wpływ na właściwości tribologiczne. Badania tribologiczne przeprowadzono na stanowisku ball-on-disk, zastosowano zmienne obciążenie (2, 5 i 10 N). Na podstawie przeprowadzonych badań stwierdzono ponad 4-krotne obniżenie specific wear rate, 3-krotne ograniczenie zużycia liniowego i ok. 20% spadek współczynnika tarcia. Najkorzystniejsze wyniki uzyskano dla czasu starzenia 24 h. Wydłużenie czasu obróbki cieplnej do 48 h powodowało przestarczenie stopu, co skutkowało pogorszeniem właściwości mechanicznych i tribologicznych.

### INTRODUCTION AND RESEARCH METHODOLOGY

Magnesium and its alloys belong to a group of the lightest engineering materials. Their low density, high rigidity and high resistance, in particular the resistance to weight ratio, make magnesium alloys suitable for a wide use in different sectors of industry, most often, in the aircraft and automotive industries [L. 1–4]. Magnesium alloys are more and more frequently used in biomedicine as cardiovascular implants, and in orthopaedics due to their biodegradability and high tolerance of living organisms, as well as a density comparable to human bone density [L. 5–8]. A problem that refers to most magnesium alloys in industrial and biomedical applications is their low resistance to corrosion and tribological wear [L. 9–10]. One of the simplest methods for increasing the hardness and strength of magnesium alloys is to strengthen them with second phase particles. In alloys

strengthened by means of precipitation treatment (precipitation hardening, strengthening via ageing), second-phase particles are obtained as a result of a two-stage heat treatment of the alloy that consists in solution treatment and ageing. In the solution treatment process, the primary precipitates are dissolved and the alloy hardness decreases, which is further amplified by a grain growth. In alloy WE54, the rare-earth elements, including yttrium and zirconium, create, together with magnesium, systems with reduced solubility. Therefore, it is possible to perform precipitation hardening. Ageing, in turn, induces the formation of phases  $\beta''$  and  $\beta'$  in the WE54 alloy, and after sufficiently long time of ageing, phase  $\beta$ –Mg<sub>12</sub>NdY [L. 11–14]. The objective of the paper was to examine the effect of precipitation hardening of the Mg-Y-Nd alloy (WE54) on its mechanical and tribological properties examined at different loads.

Magnesium alloy WE54 was used in the tests in the form of rods, 1 inch in diameter (25.4 mm), manufactured

\* University of Silesia, Institute of Materials Science, ul. 75 Pułku Piechoty 1A, 41-500 Chorzów, Poland, e-mail: adrian.barylski@us.edu.pl, tel. 323497701.

by Magnesium Elektron (UK). Specimens cut out from the rod had a form of discs 5 mm in thickness. Heat treatment (solution treatment and ageing) of alloy WE54 was conducted in an electric resistance furnace, in an atmosphere of air. Solution treatment was conducted at a temperature of 545°C for 8 h. In the next stage, the specimens were quenched in ice water with a temperature of 0°C (designation – CIW). Ageing was conducted at 250°C for 8 to 48 h, after which the specimens were quenched in the air.

Hardness  $H$  and elastic modulus  $E$  were determined using an Anton Paar NHT<sup>2</sup> nano-hardness testing machine in accordance with standard ISO14577. A Berkovich indenter load adopted for the tests was 100 mN. The indenter was loaded and unloaded for 30 s. The load was maintained for 10 s. Parameters such as hardness and elastic modulus were calculated by means of the Oliver-Pharr method [L. 15]. Ten indents were made for each specimen, and the achieved results were averaged.

Tribological tests of the magnesium alloy in its as-received condition and after heat treatment were performed with an Anton-Paar tribometer (TRN). A ball-on-disc friction system was used in the tests (Fig. 1).

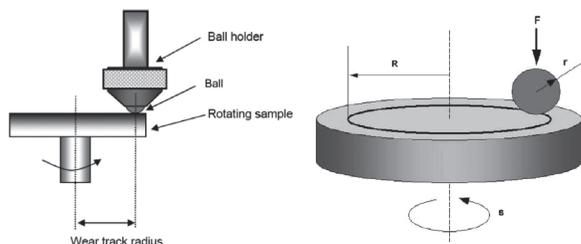


Fig. 1. The examined friction pair

Rys. 1. Badany węzeł tarcia

ZrO<sub>2</sub> balls with a diameter of 6 mm were used in the tests. Specimens for tribological tests were ground on abrasive papers, so as to obtain roughness  $R_a = 0.1$  mm. For each tested case, 4 repetitions were done. Tribological tests were performed in rotary motion, in conditions of technically dry friction. Test parameters were as follows:

- Sliding speed: 0.1 m/s,
- Friction distance: 100 m,
- Friction distance diameter: 14 mm,
- Load: 2, 5 and 10 N.

Ambient parameters were consistent with standard ASTM G-99 (2017) [L. 16]. The average area of the wear trace  $P$  was determined using a Mitutoyo SurfTest SJ-500 profilographometer. Specific wear rate  $V_w$  was determined from formula (1):

$$V_w = \frac{V}{F_n \cdot s} \left[ \frac{mm^3}{N \cdot m} \right] \quad (1)$$

where  $F_n$  – the load applied [N],  $s$  – friction distance [m],  $V$  – volume of the wear trace of the disc determined from the formula:  $V = P \cdot 2\pi r$  [mm<sup>3</sup>],  $P$  – average area of the wear trace [mm<sup>2</sup>],  $r$  – radius of the friction distance [mm].

The linear wear  $L_w$  was determined as a difference between the indications of the micrometric sensor before and after the tests. The friction coefficient was determined as a quotient of the recorded friction force,  $F_f$ , and the normal force applied,  $F_n$ .

## RESEARCH RESULTS AND THEIR ANALYSIS

The effect of heat treatment on the mechanical properties (hardness  $H$ , Young's modulus  $E$ ) of magnesium alloy WE54 was assessed using a nano-hardness testing machine. The tests showed that, in the as-received condition, the hardness was 1.075 GPa. The dissolution of precipitates and grain growth during solution treatment conducted at a temperature of 545°C for 8 h (quenching in ice water) caused a decrease in hardness to 0.913 GPa (Fig. 2). The subsequent stage of heat treatment was ageing. Measurements showed that as the ageing time increased, especially in the range of 8-24 h, hardness increased as well. The ageing process conducted for 48 h caused overageing of the alloy and another decrease of mechanical properties (Fig. 2). Similar results can be observed in the case of measurements of the Young's modulus (Fig. 3), which also decreased during solution treatment and increases as the ageing time increases. The most advantageous mechanical properties were obtained for the WE54 alloy subjected to solution treatment and then aged for 24 h (hardness: 1.18 GPa, Young's modulus: 50 GPa).

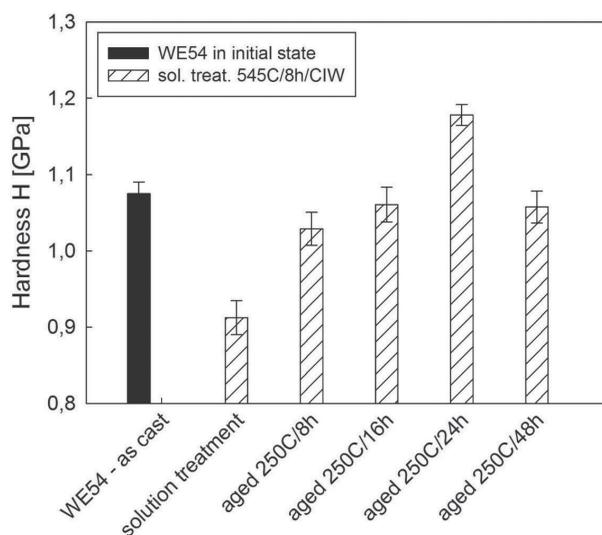


Fig. 2. Changes in hardness  $H$  of magnesium alloy WE54 in the initial state and after heat treatment

Rys. 2. Zmiany twardości  $H$  stopu magnezu WE54 w stanie dostawy i po obróbce cieplnej

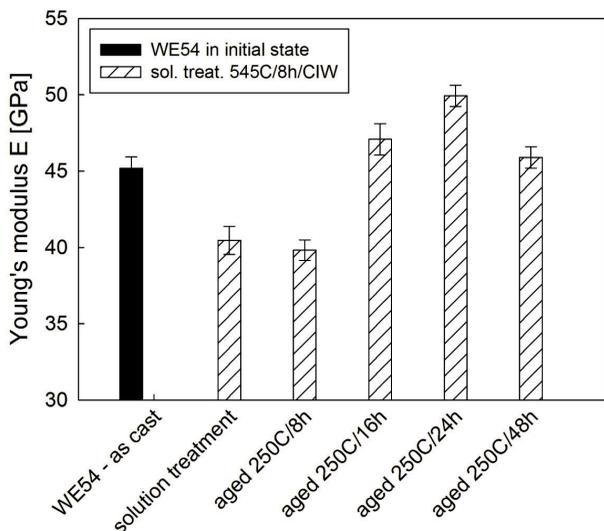


Fig. 3. Changes in Young's modulus  $E$  of magnesium alloy WE54 in the initial state and after heat treatment

Fig. 3. Zmiany modułu Young'a  $E$  stopu magnezu WE54 w stanie dostawy i po obróbce cieplnej

Heat treatment, including in particular precipitation hardening, also has a direct influence on the tribological properties of the investigated magnesium alloy. For each of the loads applied (2, 5, and 10 N), the highest specific wear rate (Fig. 4) was characteristic of alloy WE54 in its initial state ( $V_w = 4.23 \cdot 10^{-3}$  (2 N),  $4.01 \cdot 10^{-3}$  (5 N), and  $3.33 \cdot 10^{-3}$  (10 N)  $\text{mm}^3/\text{Nm}$ ). After solution treatment and quenching in ice water, the tribological tests showed a more than twofold reduction in the specific wear rate compared to the initial material. The improvement of mechanical properties observed during the ageing of the alloy also translates into an increase in the wear resistance. The alloy with the highest hardness and Young's modulus, obtained through ageing at 250°C for 24 h, was also characterised by the lowest specific wear rate, irrespective of the load applied. This was a reduction in wear by 3 to 4 times compared to the initial material ( $V_w = 1.77 \cdot 10^{-3}$  (2 N),  $1.29 \cdot 10^{-3}$  (5 N), and  $0.76 \cdot 10^{-3}$  (10 N)  $\text{mm}^3/\text{Nm}$ ).

Similar dependencies were also visible in the case of linear wear  $L_w$ , where a reduction in wear by 1.7–3.2 times was observed for alloy WE54 subjected to solution treatment and ageing (Fig. 5), compared to the as-received material ( $L_w = 67.5$  (2 N);  $72.3$  (5 N);  $127.3$  (10 N)  $\mu\text{m}$ ). The lowest value was obtained for an alloy subjected to solution treatment at 545°C for 8 h, quenched in water with a temperature of 0°C and aged at 250°C for 24 h, as in the case of the specific wear rate. Extension of the ageing time to 48 h due to overageing of the alloy and the deterioration of its mechanical properties also caused another increase in the specific wear rate and linear wear.

The friction coefficient recorded during the tribological tests (Fig. 6) was also undergoing beneficial changes induced by heat treatment. In the initial state in

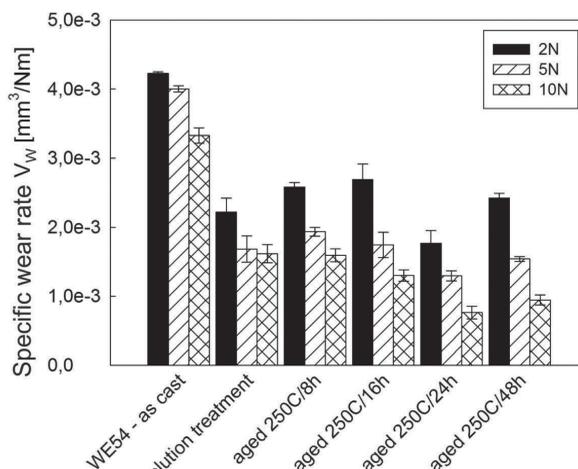


Fig. 4. Changes in specific wear rate  $V_w$  of magnesium alloy WE54 in the initial state and after heat treatment

Fig. 4. Zmiany specific wear rate  $V_w$  stopu magnezu WE54 w stanie dostawy i po obróbce cieplnej

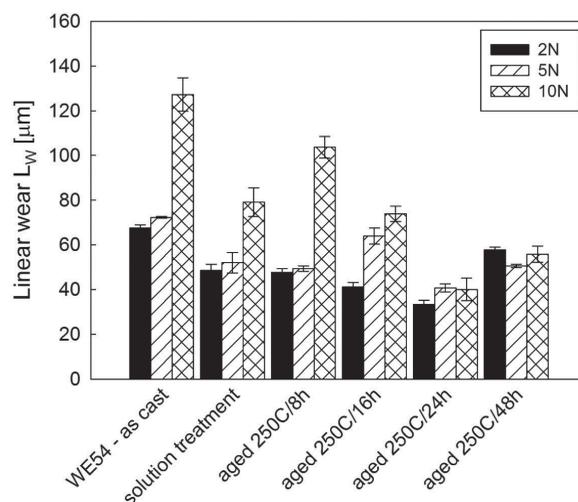
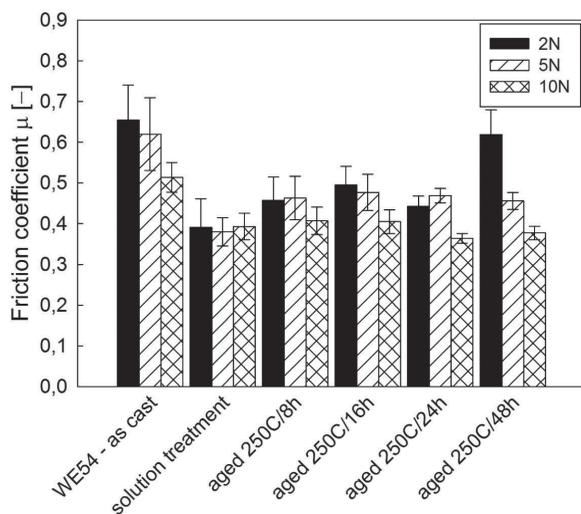


Fig. 5. Changes in linear wear  $L_w$  of magnesium alloy WE54 in the initial state and after heat treatment

Fig. 5. Zmiany zużycia liniowego  $L_w$  stopu magnezu WE54 w stanie dostawy i po obróbce cieplnej

the WE54-ZrO<sub>2</sub> friction pair, depending on the applied load of 2-10 N, the stabilised friction coefficient was from 0.51 to 0.65. At the same time, the tribological tests of the magnesium alloy subjected to heat treatment showed a considerable decrease, by 20%, in the friction coefficient (Fig. 6) compared to the magnesium alloy in the as-received condition. As the results from the tests indicate, alloy overageing also has an adverse effect on the friction coefficient. This effect was observed, in particular, at low loads (2 N). No wear of the ceramic balls (ZrO<sub>2</sub>) was observed during the tribological tests. The obtained research results prognosticate a longer operating life of the WE54 magnesium alloy subjected to precipitation hardening.



**Fig. 6. Changes in friction coefficient  $\mu$  of magnesium alloy WE54 in the initial state and after heat treatment.**

Fig. 6. Zmiany współczynnika tarcia  $\mu$  stopu magnezu WE54 w stanie dostawy i po obróbce cieplnej

## CONCLUSIONS

- Precipitation hardening of the magnesium alloy caused changes in its mechanical properties (increase in hardness and Young's modulus). The highest hardness of 1.18 GPa was found for the

solution-treated alloy at a temperature of 545°C, quenched in ice water and then aged at 250°C for 24 h. The solution treatment process itself caused a ca. 20% decrease in hardness of alloy WE54 compared to its as-received condition.

- The first stage of precipitation hardening, i.e. overageing of the magnesium alloy, caused a more than twofold reduction in the specific wear rate and linear wear, and a reduction of the friction coefficient.
- Changes in the mechanical properties after ageing of the alloy enhanced its tribological properties, i.e. a reduction in the specific wear rate by 3 to 4 times was observed, as well as a 1.7–3.2-times reduction in the linear wear and a 20% reduction of the friction coefficient compared to the initial material.
- The most advantageous results were obtained for the alloy subjected to solution treatment at 545°C for 8 h, with quenching in ice water with a temperature of 0°C and ageing at 250°C for 24 h, i.e. the extension of the ageing time above this value caused overageing of the alloy and deterioration of its functional properties.
- It was found that as the load imposed on the friction pair increased (2-10 N), the specific wear rate decreased, while linear wear increased, and the friction coefficient was reduced.

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