CHARACTERIZATION AND HEAT TREATMENT INVESTIGATIONS ON TUNGSTEN CARBIDE REINFORCEMENT IN AL2024 ALLOY FOR ENHANCED MECHANICAL PROPERTIES

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Abstract

This study aimed to explore the impact of varying weight percentages of tungsten carbide (WC) reinforcement dispersed in an Al2024 solid solution. The homogenization of WC particulates (β-phase) within the Al2024 solid solution (α-phase) was achieved using the stir casting technique. Following casting, the specimens underwent a three-stage heat treatment process, including solutionizing, water quenching, and artificial ageing, with durations of 1, 3, 5, and 7 hours. Microstructure analysis and ultimate tensile strength investigations were carried out on both the as-cast and heat-treated specimens, following ASTM standards. The results highlighted that incorporating 8% WC by weight into the Al2024 solid solution with a 7-hour ageing duration significantly influenced the mechanical properties. Particularly, the presence of a lamellar eutectic microstructure (WC) played a vital role in altering the mechanical properties of the Al2024 alloy. The study focused on a comprehensive analysis of the composite material's microstructure and phase composition to gain insights into the interaction between WC particles and the Al2024 matrix during the heat treatment process.

Keywords: Al2024-Alloy, Tungsten carbide, Lamellar eutectic microstructure, Precipitate Hardening.

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1. Introduction

Composites are inhomogeneous, anisotropic, and have wide engineering applications, viz., aircraft construction, truck trailers, tennis rackets, etc., but are not limited to [1]. The unique property of strength-to-weight ratio and the advantage of flexibility in design have led to substitutions for many conventional engineering materials [2–4]. In the broad classification of composites, metal matrix composites are structural materials with light weight that have a matrix of low-density metal alloys like Ti, Mg, Al, Cu, etc. and consist of particles or fibers of ceramics like nitrides, oxides, carbides, etc. as reinforcements [5-8].Ceramic-reinforced Aluminium Metal Matrix Composites (AMMCs) have attracted attention because of their characteristic isotropic properties, relatively low costs, and excellent mechanical properties like specific strength and good wear resistance [9, 10]. The properties and quality of AMMCs are controlled by the percentage of reinforcement, the uniform distribution of reinforcing agents into the matrix phase, and the method of fabrication of composites [11–13]. Further mechanical properties can be tailored by subjecting it to a proper heat treatment process.
Among various aluminium alloys, the 2000, 6000, and 7000 series are quite popular choices for their better formability characteristics and the option for modification of the strength of the composites through heat treatment [14–18]. Typical aluminium heat treatment methods are annealing, homogenization, solutionized heat treatment, natural ageing, and precipitation hardening [19]. In the literature, it is observed that there is an improvement in the mechanical and wear properties of composites due to the influence of ceramic particles and their distribution in the base matrix [19–22].

Earlier investigations showed that the heat treatment process plays a significant role in raising microhardness. The composites with 15.0% SiC and 3% B_4C by weight and an 8-hour ageing duration have more wear resistance [23]. Azmi Rahmat stated that age-hardened 6061 with Alumina silica continuous fibers as reinforcement had a stronger and faster hardening effect than the unreinforced alloy treated under the same conditions [24]. In recent years, much attention has been drawn to the Al2024 aluminium alloy.

Al2024 is one of the most promising alloys in the aluminium alloy series and is reported to exhibit high strength, high ductility, and good machinability. It is stereotypically used in the aerospace industry, manufacturing rivets, truck wheels, and machine screw parts [25]. It has been found that mechanical properties often deteriorate (cracks, reductions in hardness and tensile strength, etc.) at elevated temperatures, making it difficult to predict the uncertainty. Also, the effect of artificial ageing duration and precipitate hardening mechanisms on the addition of different wt.% of WC in Al2024 solid solution has not been investigated yet.

Considering the aforementioned research limitations, this study aimed to conduct an experimental investigation to examine the mechanical behavior of Al2024 solid solution with dispersed WC particulates at varying weight percentages (2, 4, 6, and 8 wt.%). The primary objective was to develop an improved composite material that enhances the Ultimate Tensile Strength, potentially serving as a viable substitute for the conventional Al2024 alloy.

2. Experimental Procedure

2.1 Material selection and Composite preparation

As a matrix phase, a commercial Al2024 alloy was explored. Table 1 shows the chemical composition of Al2024. The tungsten carbide (WC) particulates are considered dispersed phases and homogenized with the solid solution of Al2024 alloy. The average size of the WC particulates is in the range of 30–40 mm. The stir casting technique [26] was used to homogenise the matrix. The stir casting equipment is shown in Fig. 1. The temperature of the crucible was maintained at 650±5 ^{o}C. The solidification of the final composite was done at ambient temperature. The composite specimens were prepared by adding 2, 4, 6, and 8 wt% WC to an Al2024 solid solution.

Table 1 Chemical Composition of Al2024 alloy

Element	Cu	Mg	Mn	Fe	Si	Cr	Zn	Al
Wt. %	4.3	1.3	0.4	0.4	0.3	0.1	0.3	93

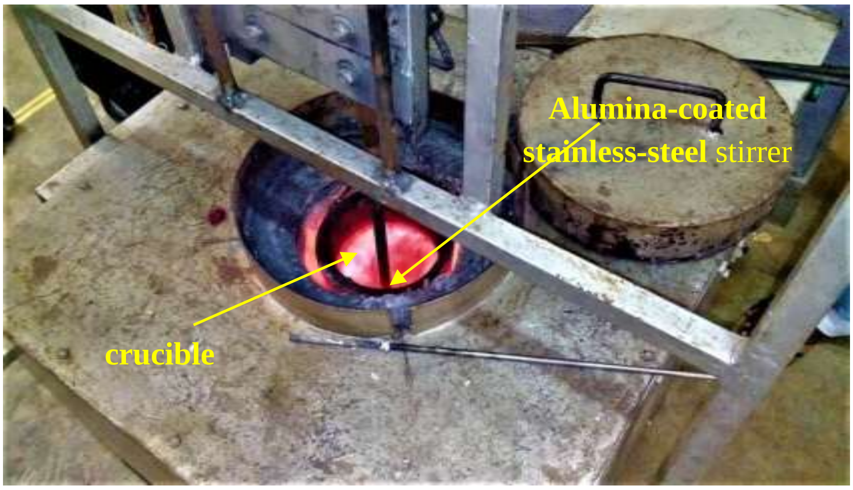

Fig.1 Stir casting setup

2.2 Heat treatment process
Two sets of specimens were prepared for each test. The first set of specimens was treated as as-cast specimens. The second set of specimens was subjected to heat treatment and is called as heat-treated specimens. The heat treatment process was carried out in three steps: solutionizing, water quenching, and artificial ageing. The processes of heat treatment are indicated schematically in Fig. 2.

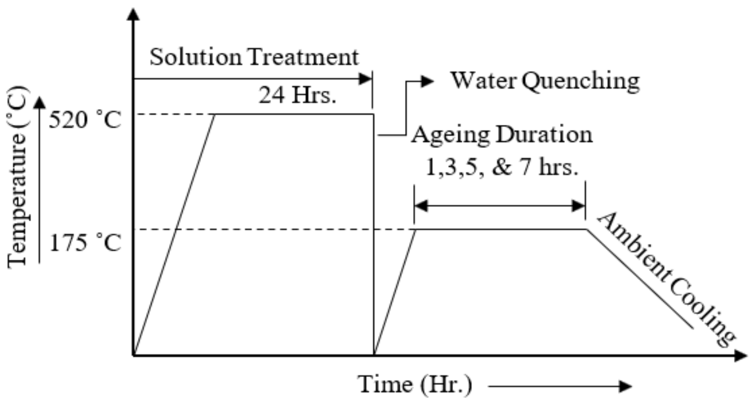

Fig. 2 Heat treatment cycle

2.3 Characterization of the Composite Specimens

Microstructure and elemental characterization of as-cast and heat-treated specimens were carried out using SEM and EDS techniques. The specifications of the SEM and EDS machines are given in Table 2.

Table 2 SEM and EDS Machine Specifications

MODEL	Hitachi SU 3500
Resolution	30 nm
Magnification	up to 3,00,000 X
Detector	SE, BSE, and EDS
Accelerating voltage	0.3 to 30 kV
Variable pressure range	6 to 650 Pa
Cold stage	up to - 25 ◦C
Coating	Carbon and gold

2.4 Tensile test

A tensile test was conducted on cast and heat-treated specimens as per ASTM E8M standards [27]. The machine specifications are shown in Table 3. The dimensions of the test specimen and actual specimens are shown in Figs. 3, 4, and 5, respectively. Three test trials were conducted on each as-cast and heat-treated specimen, and its average value was recorded. The specifications of the tensile testing machine are shown in Table 3. The dimensions of the tensile test specimen as per the ASTM E8M standard are shown in Fig. 3. The actual as-cast and heat-treated specimens are shown in Figs. 4 and 5, respectively.

Table 3 Tensile testing Machine specifications

MODEL	**TUE-C-400**
Measuring Capacity(kN)	400
Measuring Range (kN)	0 - 400
Least Count (kN)	0.04
Accelerating voltage	8 to 400
Resolution of Piston Movement (mm)	0.1
Over all dimensions approx. (mm)	2100 x 800 x 2060
Weight approx. (kg.)	2100

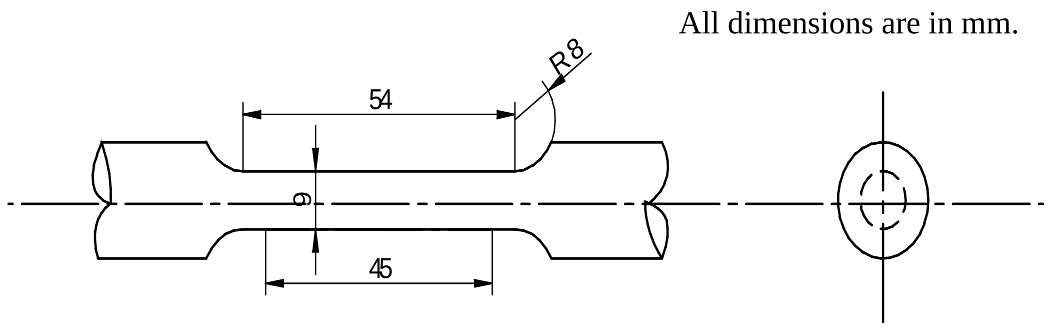

Fig.4 As casted Tensile test specimens

Fig. 5 Heat treated tensile test specimens

3. Results And Discussion

3.1 Characterization of as casted and heat treated specimens

The SEM micrographs of as-cast and heat-treated specimens are shown in Fig. 6. The element analysis of as-cast specimens is shown in Fig. 7. It has been found that Copper (Cu) exists as a major element at 4.3% by weight in a native Al2024 alloy, which may augment the specific strength and accelerate precipitate hardening, sometimes also referred to as artificial ageing. Precipitate hardening is often seen as promoting hardness. It has also been reported that during plastic deformation, precipitate acts as an obstacle to dislocate the grains or grain boundaries; consequently, high stress is required to induce plastic deformation [28]. Also, it has been found and reported that the presence of 1.3 wt.% magnesium (Mg) can augment strain hardening but is susceptible to grain boundary attack and can be improved by a heat treatment process [29]. The other binary elements present in the native Al2024 alloy are shown in Table 1. A distinct grain boundary is observed in the case of as-cast specimens irrespective of varying wt.% of WC, and it is attributed to the sound, homogeneous casting. The solid solution grains of Al are bounded by bright intermetallic precipitates, Al_2Cu and Al_2Cu/Al eutectic (lamellar morphology), as identified in refer to Fig.6 (a) to (g) [30]. A nominal carbon deposit is observed at the interfaces of the grain boundary. Relatively more carbon deposits were observed at higher wt.%, i.e., in the present case, 8 by wt.%WC. On the other hand, dispersion of WC particulates was found to nucleate locally after the heat treatment process. The clusters of WC particulates are mostly observed in cases of 4 and 8% after the solutionizing process. The reason for such abnormalities may be attributed to uneven solidification. With the increase in wt.% of WC and under the heat treatment process, the grain boundary was found to be amalgamated, and at the same time, the WC particulates were observed to be precipitated out of the alloy. Strains at grain boundaries are observed in the saturated Al2024 α-solid solution, acknowledged with local precipitate on the surface, which is attributed to an increase in the solubility limit in the α solution. With the increase in wt.% of WC, β phase in α solid solution, the formation of precipitate was found to be more significant and observed to improve the hardness, and this is mainly due to precipitation hardening and the strength of the AS-HT specimen; refer to Fig. 6 (g).

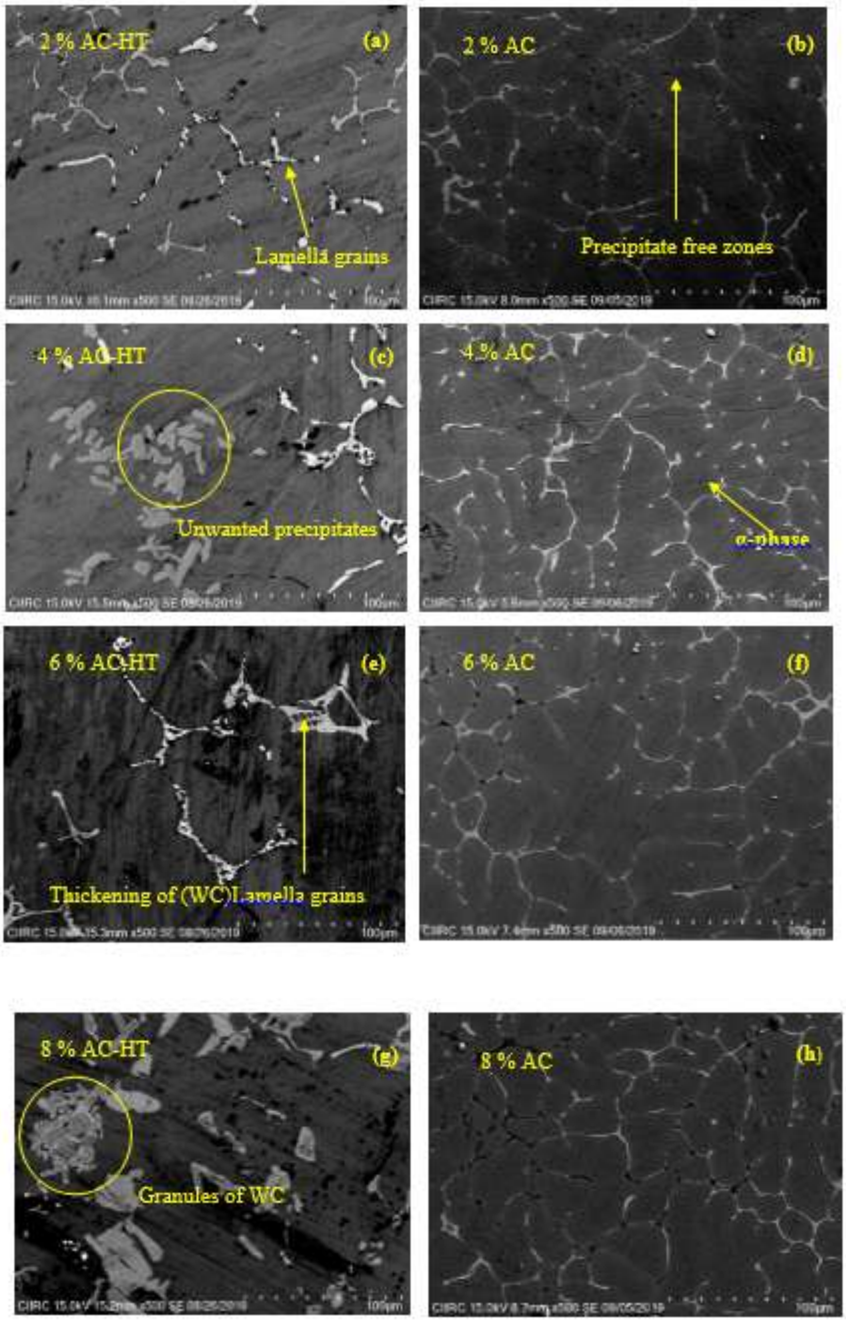

Fig.6 SEM micrograph of as casted heat-treated (AC-HT)and as casted (AC)specimens.

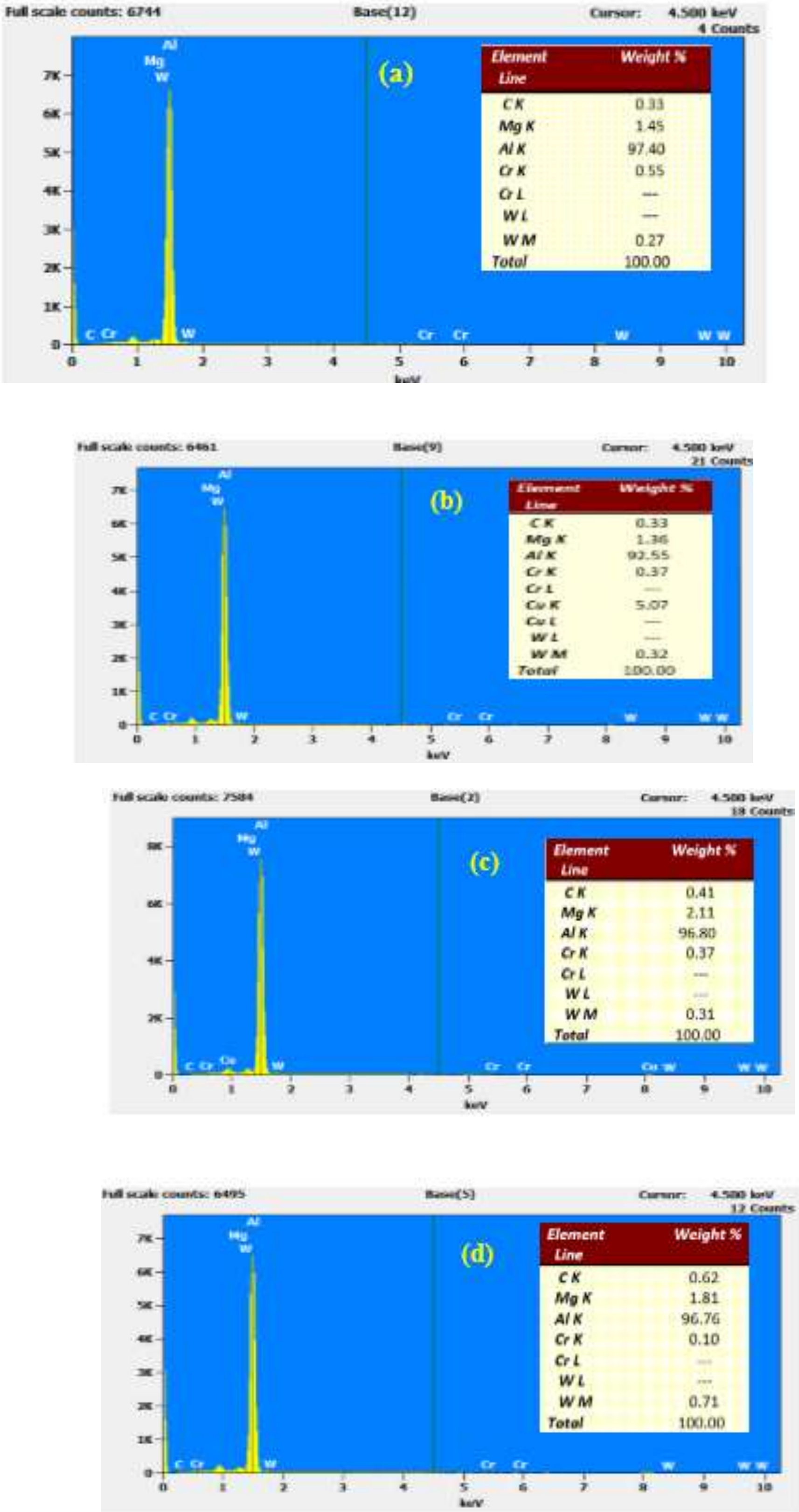

Fig.7. EDS investigations on as casted specimens with different wt. % of WC in Al2024 solid solution (a) 2 (b) 4 (c) 6 (d) 8 wt.%WC.

3.2 Effect of WC dispersion and ageing duration on Ultimate Tensile Strength (UTS) and elongation

From the results, it has been observed that there is an increase in Ultimate Tensile strength (UTS) with the increase in wt.% of WC, β phase in the (Al2024) α -solid solution. The reason for the increase in UTS may be attributed to the formation of graphite structure (C%) at the grain boundary and the lamellar grain structure of the dispersed phase. The grain boundaries serve as barriers to dislocations at the grain boundary [31]. Another reason may be due to a reduction in the inter-spatial distances in the dispersed phase (WC), causing dislocation stacking of WC particulates in the solid solution, thereby restricting the plastic flow. As an effect, enhanced ultimate tensile strength is observed. The other reason may be attributed to the formation of non-uniform localised granules along with ageing duration, which has supplemented extra precipitate hardening of the Al2024 alloy. The variation of UTS with respect to wt.% of WC reinforcement and ageing duration is shown in Fig. 8.

The effect of wt.% WC on elongation is shown in Fig. 9. It has been observed that the percentage elongation of the composites gradually decreases with the increase in wt.% of WC. The reason for this may be the uniform distribution of the lamellar grain structure (WC) in the matrix (refer to Fig. 6 (a), (c), and (e). Thickening of lamellar grains is noticed locally in the matrix, which contributes to extraordinary strain hardening within the alloy. Also, this phenomenon was found to be complemented by the ageing duration. However, a slight increase in the elongation is observed at 8 wt.% of WC, which is attributed to the localised concentration of granule particles causing short-lived precipitate hardening, which resulted in a slight increase in the elongation. Due to the formation of precipitate hardening, no significant distortion or crack in the material was observed, which is found to be the common problem in the alloying process irrespective of as casted and heat-treated specimens. The other elements were not found to have any significant influence on the Al2024 solid solution.

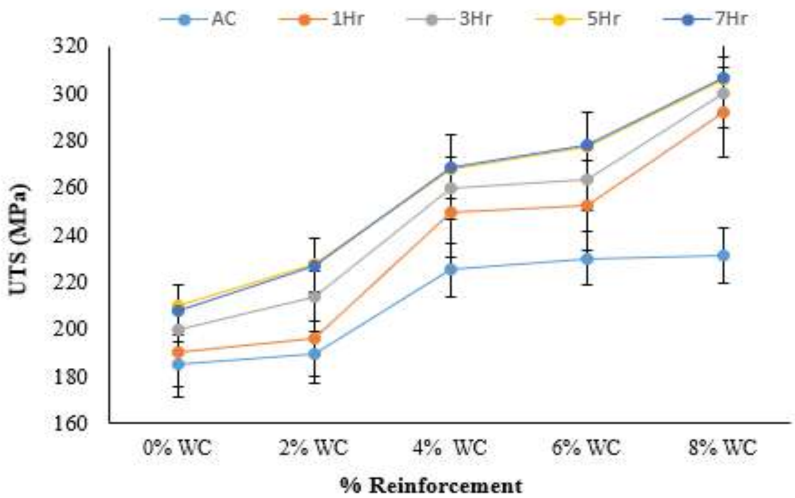

Fig. 8 Effect of reinforcement content and ageing duration on UTS

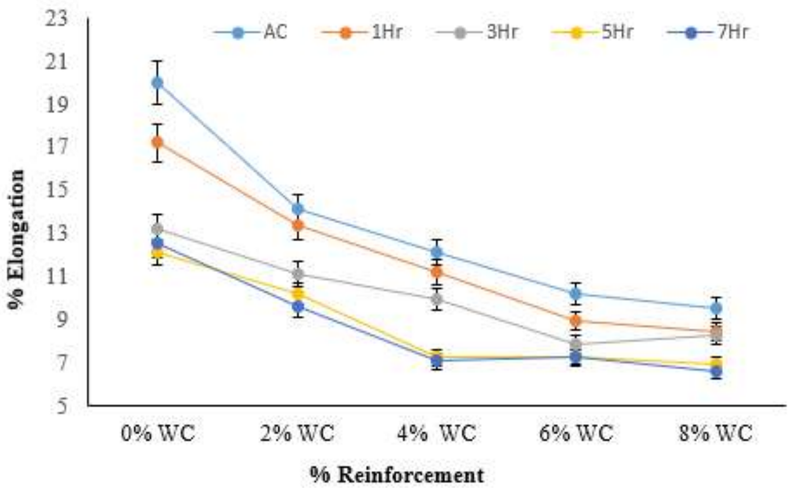

Fig. 9 Effect of WC by wt.% reinforcement with ageing duration on elongation

4. Conclusions

This study focuses on the characterization and mechanical behavior analysis of Al2024 composites containing varying weight percentages of WC. Both as-cast and heat-treated specimens with different ageing durations were investigated. Based on the results and discussions, the following conclusions have been drawn.

1. The aging duration was observed to have a notable impact on the microstructure of the as-cast Al2024 alloy. Specifically, up to 6 wt.% of WC, a distinct lamellar eutectic microstructure was formed. However, at 8 wt.% of WC in the Al2024 solid solution, localized granules precipitation was observed.

2. During the aging process, a lamellar eutectic microstructure consisting of WC precipitates is observed to form from the Al2024 solid solution. This lamellar eutectic microstructure is found to grow thicker as the aging duration increases. Both the lamellar eutectic microstructure and localized granules contribute to the strengthening of the solid solution. Additionally, the presence of WC particles is responsible for inducing lattice distortion along the grain boundaries, effectively hindering dislocation motion. These factors play a significant role in increasing the ultimate tensile strength of the composite material. However, they also lead to a reduction in elongation due to the constrained movement of dislocations and the presence of precipitates.
3. The Al2024 composite containing 8 wt.% of WC particulates, after undergoing a 7-hour ageing process, exhibits a notable increase in ultimate tensile strength compared to the as-casted alloy. The average ultimate tensile strength value is found to be 306.47 MPa.

Conflict of Interest: The authors declare that there is no conflict of interests regarding the publication of this paper.

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