THE INFLUENCE OF ARTIFICIAL AGEING ON ABRASIVE WEAR OF SiC and Al_2O_3 PARTICULATE METAL MATRIX COMPOSITES.

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Abstract

Abrasive wear behaviour of unreinforced and particulate reinforced 6061 Aluminium alloy metal matrix composites (MMCs) was investigated under two-body abrasion conditions using a pin-on-drum machine. The abrasive wear rates were determined in the as-fabricated, solution treated and artificially aged conditions, to determine the effect of variations in matrix hardness. The results indicate that increasing ageing time, up to peak ageing, increases hardness levels and lowers the wear rates of these materials. Reinforced 6061 MMC appears to have enhanced the ageing kinetics compared with unreinforced 6061 alloy as indicated by higher levels of hardness achieved in the reinforced materials at shorter ageing times. At similar hardness levels, it was observed that all of the MMCs which were aged for longer periods of time exhibited greater wear resistance than those aged for shorter periods. As a result, the wear rates of composites were seen to be less dependent of hardness and more dependent upon ageing time.

Introduction

Aerospace and automotive applications have provided the main driving force for the development of light alloy Metal Matrix Composites (MMCs) [1]. This is because aluminium MMCs have good combinations of high strength, stiffness and wear resistance compared with similar unreinforced alloys. The increase in strength and stiffness is due to the incorporation of ceramic fibres or whiskers [2-5] and improvement in the wear properties is attributed to particle reinforcement [6-9]. Most of the studies on abrasive wear to date have concentrated on the type, volume fraction, size and geometry of the reinforcement with relatively less attention devoted to the effect of matrix microstructure on wear behaviour [10]. To improve understanding of the wear behaviour in MMCs, it would also be useful to identify the role of other parameters such as bulk hardness and microstructure on wear resistance.

A linear relationship has been shown to exist between the wear resistance and bulk hardness for a range of pure metals [11,12]. However, the wear resistance of heat-treated steels is found to be lower than pure metals of the same hardness level [11]. Also, a non-linear relationship is known to exist between hardness and wear resistance when a single steel is heat treated to different levels of hardness [12]. This indicates that microstructure may play an important role in the wear of materials. Moore [13], in his investigation on wear of ferritic steels, proposed that wear resistance is not only related to bulk hardness, but also related to the microstructure.

The effects of ageing on abrasive wear rate (the inverse of wear resistance) have been reported by some investigators to improve the microstructure of the matrix and consequently the wear resistance of the MMCs [14-17]. The best wear resistance has been attained at Peak-hardness for 2124 Aluminium alloy. However, MMCs can become more wear resistant when overaged, compared with the underaged materials of the same hardness [10,14]. Wang and Rack [10] proposed that alloys without reinforcement exhibit similar trends in wear resistance to MMCs in the underaged (UA) and overaged (OA) condition i.e. a decrease in wear rate in the OA condition usually exists. This therefore suggests that the matrix microstructure may influence abrasive wear to a significant extent. However, various reinforcements are reported to enhance the ageing kinetics in MMCs compared with monolithic alloys [10,16,18,21].

It is customary to attempt correlation of abrasive wear resistance (the inverse of abrasive wear rate) with hardness. The load dependence of Vickers micro-hardness is complex and not clearly understood even in monolithic alloys [19]. Some authors [20] have observed that in the case of particulate Metal Matrix Composites, with fine particles at all loads the indenter will cover a number of particles because of size and morphology, whereas with large particles with the same volume fraction, use of a lower indenter load can avoid encompassing particles within the indentations and thus the particles not interfering with matrix hardness. A load of 50g was considered to give a fairly good estimate of hardness from this point of view [20].

In the present investigation the influence of reinforcement and artificial ageing response in both unreinforced and reinforced 6061 is considered with reference to their mechanical and wear properties. While the present research is continuing, results obtained so far show some interesting trends, as detailed in the results section below .

Material and experimental procedure

The materials used in this investigation were cylindrical pins (approx. 6 mm x 30 mm long) machined from 19 mm diameter extruded rods of unreinforced and particulate reinforced 6061. The reinforced 6061 consists of 10, 20^v/o SiC and 10, 20^v/o Al_2O_3. The SiC composites were manufactured by a powder metallurgy route by California Consolidated Technology, and the Al_2O_3/6061 was produced via liquid metallurgy route by Duralcan. All the rods were supplied by Comalco Research Centre, Victoria. More details about the materials are reported elsewhere [20].

Twenty four pins in total were tested. The different conditions that were used include (i) solution treatment (S.T.) at 530°C and water quench (ii) S.T. plus natural aging for 20 hours at room temperature, followed by 0.5, 4 and 8 hours artificial aging at 175°C, and (iii) as-fabricated specimens. Subsequent to thermal ageing treatment the specimens were placed in a freezer to prevent further natural ageing.

Measurements of the abrasive wear rate were made in air at ambient temperature (17-25°C). The apparatus used was the pin-on-drum machine shown schematically in Figure 1. The device utilises a dead weight load of 66.7 N at a sliding speed of 43.82 mm sec^{-1} and a sliding distance of 12.62 m. The pin rotates about its (vertical) axis at 20 rpm to maintain even wear. The pin also moves across a rotating 0.5 m diameter drum surfaced with 80μm Alumina abrasive paper (parallel to the drum axis) and follows a helical path. The test pins were each initially run-in over about half the test path length before any weight loss measurements were taken, to achieve a uniform contact surface before testing. Prior to and after each test run, pins were cleaned in ethanol in an ultrasonic cleaner, dried and weighed using a digital balance to the nearest 0.1 mg. For each test run, the pin traces a helical path of 12.62 m being continually exposed to fresh abrasive. Four such test runs were performed on each pin, and an average weight loss was determined. In between these test runs, a reference pin (Bisalloy 80 quenched and tempered steel-Hv 265) was also abraded over one complete 12.62 m path length to account for any variation in the abrasive paper characteristics which could influence the wear rate. A calibration factor k was then determined once all the test and reference pins had been abraded, for the purpose of compensating for variability in the abrasive cloth. From the weight loss measurements of the reference pin for each sheet abrasive cloth, the average weight loss for the test material was adjusted using the following equation:

$$W_1 = W_2 \times k \qquad (1)$$

Where:

W_1 = Corrected weight loss of material (CWL)

W_2 = Average actual weight loss of material (AWL)

K = Calibration factor (Ave. wt. loss of Standard Pin) /actual weight loss of standard pin per abrasive paper.

The abrasive wear rate was evaluated on the basis of weight loss per unit distance of sliding. From the weight loss the volume loss can be calculated by using density data for each test material. Thus the wear rate and wear resistance may be expressed as follows:

$$A_r = V/d \qquad (2)$$

Where:

A_r = Wear rate (cm^2)

V = Volume loss (cm^3)

d = Sliding distance (cm)

and this may be normalised by using

$$A_r = V/dA \quad \text{[DIMENSIONLESS]} \qquad (3)$$

Where:

A = contact area (cm^2)

and wear resistance = $(\text{wear rate})^{-1}$

Subsequent to wear testing, all specimens were again refrigerated until the Vickers microhardness tests were performed. Between 8 - 10 measurements of microhardnesss were taken diagonally across each specimen to obtain an average value. The Vickers microhardness indentations were taken after the wear tests in case the microstructure may have been somewhat altered during abrasion. The temperature of the pin wear surface was constantly monitored with an alumel chromel thermocouple during the wear tests to determine the magnitude of heating effects during abrasion. The maximum temperature recorded in any of the tests was 30°C. The sectioned surfaces of the pins were then metallographically prepared to No. 1200 SiC abrasive paper and polishing was further carried out on 3μm, and 1μm synthetic suede diamond abrasive cloth. Final polishing was carried out using silica suspension on the polishing pad which produced scratch-free-surfaces for further wear studies.

Discussion

The correlation between actual weight loss (W_2) and corrected weight loss (W_1) for unreinforced and reinforced 6061 in the as-fabricated, solution treated and artificially aged condition is shown in Figures 2-6. The dotted lines represent an ideal correlation between AWL and CWL, where the gradient is unity. An increase in ageing time for 6061 indicates a negative deviation in AWL and CWL (figure 2). This trend also applies for all the MMCs shown in figures 3-6.

The values of AWL for the test pins shown in figures 7 and 8, in general correlated with the trend of CWL values in figures 9 and 10. Figures 7 and 8 represent AWL values for 6061/MMCs as a function of ageing time and in the as-fabricated condition respectively. Figures 9 and 10 represent CWL values for 6061/MMCs as a function of ageing time and in the as-fabricated condition respectively. The AWL and CWL values are larger for Al_2O_3/6061 as compared with SiC/6061. In general CWL values were slightly higher than the AWL values as indicated in figures 2-6. The reason for this is that AWL is dependent upon the calibration factor K from equation (1). K values generally ranged from 0.93 - 1.08. The majority of the values of K were greater than 1. Three specimens were outside this range and disobeyed the general rule. 10 and 20^v/o Al_2O_3/6061 in the as-fabricated condition attained K values of 1.16 and 1.34 respectively. Control alloy 6061 which was solution treated and naturally aged at room temperature for 20 hours and artificially aged for 0.5 hours at 175°C showed a K value of 0.61. It is obvious that higher K values increase the CWL, whilst lower K values lower the CWL value. Two possible reasons for the large scatter in these K values are (i) the vertical movement of the shaft, which has a dead load upon it, being constrained by high frictional effects, and (ii) The abrasive paper may not have been tightly secured to the drum, and adhesive material may still be present beneath the abrasive cloth due to the previous bonding. As a result the pin could dig deep in the paper and introduce variability in abrasion rate.

Figure 9 shows CWL as a function of ageing time and it can be seen that CWL generally decreases from ST to ageing up to 8 hours. The AWL and CWL for the as-fabricated MMCs in Figures 8 and 10 show an increase for Al_2O_3/6061 and a decrease for SiC/6061.

As mentioned earlier the high K values for as-fabricated 10 and 20^v/o Al_2O_3 ie. 1.16 and 1.34 possibly arising from the experimental conditions increased the CWL values, but if these values were close to unity, then the AWL values of these two materials would only be slightly lower.

Figures 11-15 show the variation in wear rate with matrix hardness at different ageing times for both unreinforced and reinforced 6061. Since this investigation involved ageing for times up to a maximum of 8 hours for all materials, only a comparison of UA and PA conditions can be made. Although the line of best fit indicates a general trend of decreasing wear rate with increasing matrix hardness, the wear rate is in fact less dependent on the hardness and more dependent upon ageing time as explained below. For example, unlike the MMCs, unreinforced

6061 increased in hardness with increasing ageing time up to PA condition. Figure 16 illustrates a direct dependence of hardness on the ageing time. From figure 11, unreinforced 6061 shows a very low wear rate in the solution treated condition. The trend in wear rate is parallel to that of $20^{v}/o$ Al_2O_3/6061 in the PA condition. For other ageing times, it seems that the wear rate of unreinforced 6061 is higher than that of MMCs. However, from figure 16 the hardnesses of unreinforced 6061 after 4 and 8 hours ageing are considerably lower than those for the corresponding ageing periods for the MMCs. Unreinforced and reinforced materials usually undergo some natural ageing prior to artificial ageing. The natural ageing at room temperature may enhance the ageing kinetics and allows the PA hardness to be attained in a shorter period [10,16]. The ageing kinetics of MMCs can be enhanced in comparison to unreinforced 6061, since the reinforced matrix has a much greater density of dislocations than the unreinforced control alloy [16]. The acceleration in ageing kinetics is attributable to the decrease in incubation time required for nucleation and the increase in solute diffusivity and hence precipitation growth rate resulting from the increase in the matrix dislocation density due to the mismatch of coefficient of thermal expansion between matrix and reinforcement [21,22]. From figures 12-16 it can be seen that the incorporation of reinforcement in the 6061 alloy (a) decreases time for maximum hardness and, (b) also decreased the wear rate. Figure 16 shows a decrease in hardness between solution treatment and 0.5 hours ageing for 10 and $20^{v}/o$ Al_2O_3/6061 and a decrease in wear rate is also associated with the decrease in hardness levels as shown in figures 12 and 13 respectively. The wear rate is at its minimum in the PA condition for MMCs. For all the MMCs observed in the present work in the PA condition, the following are placed in order of decreasing to increasing wear rates: 6061 reinforced with $20^{v}/o$ SiC, $20^{v}/o$ Al_2O_3, $10^{v}/o$ SiC and $10^{v}/o$ Al_2O_3. Figure 17 shows an increase in hardness for SiC/6061 as compared with Al_2O_3 for as-fabricated MMCs. The as-fabricated MMC matrix hardness values are much lower in comparison to that of MMCs in the aged condition as shown in figures 16 and 17. Figure 18 shows a progressive increase in wear resistance from 0 to $20^{v}/o$ particulate reinforcement. From this graph, it can be seen that the effect of reinforcement on wear resistance is beneficial. Also wear resistance is further improved upon longer ageing for both O to $20^{v}/o$ of reinforcement. The lowest wear rate is shown by the $20^{v}/o$ SiC/6061 in the PA condition. The $10^{v}/o$ Al_2O_3 in the as-fabricated condition exhibited the highest wear rate, while the lowest wear rate for the same material was achieved after 8 hours ageing. There is a greater scatter in results of wear resistance for the $10^{v}/o$ Al_2O_3 between points 1 and 5.

Figure 19 shows hardness as a function of volume fraction. There is an increase in matrix hardness from $0^{v}/o$ to $20^{v}/o$ reinforcement. There is a greater increase in hardness by increasing particle volume fraction from 10 to $20^{v}/o$ in the case of SiC/6061 than there is for the same increase in the Al_2o_3/6061. For instance, except for the solution treated condition, the increase in hardness produced by increasing from 10 to $20^{v}/o$ SiC/6061 is approx. 17% for all levels of treatment, while for 10 to $20^{v}/o$ Al_2o_3/6061 the increase is almost nil. For the as-fabricated materials the percentage increase for 10 to $20^{v}/o$ Al_2O_3/6061 and for 10 to $20^{v}/o$ SiC/6061 is approx. 18%. Wang and Hutchings found that $20^{v}/o$ of SiC whisker reinforcement in the PA condition, can lead to up to 60% increase in the indentation hardness [10]. Indeed, this increase in indentation was observed for most of the SiC/6061 when compared to the unreinforced 6061. This increase in hardness , however, did not contribute proportionately to a decrease in wear rate. Therefore a comparison of microhardness results for both unreinforced and reinforced matrix alloys may not be a true indicator of the accelerated ageing phenomenon [20,21]. Transmission electron microscope studies are in progress to study the microstructural aspects as a function of the ageing time and composition of the composites.

Conclusions

1. A linear relationship between actual and corrected weight loss was observed for the majority of unreinforced and reinforced 6061 materials.

2. The weight loss decreased with increasing ageing time in all of the materials examined.

3. No simple relationship seems to be obvious between matrix hardness and wear rate.

4. Prolonged ageing within the experimental conditions increases the wear resistance. At equivalent hardness levels, the wear resistance in the overaged condition is higher than that in the underaged condition.

5. An increase in volume fraction of particulate reinforcement increased the wear resistance. This effect is more pronounced in the case of SiC/6061 than in the Al_2O_3/6061 material. An increase in volume fraction of reinforcement also increased the matrix hardness, but maximum hardness in both 10 and 20^v/o SiC/6061 was attained at 4 hours of ageing, whereas the rest of the materials reached maximum hardness at 8 hours ageing. However, despite the decrease in hardness of 10 and 20^v/o SiC/6061 in the PA condition, minimum wear rates were reached at PA for all the materials.

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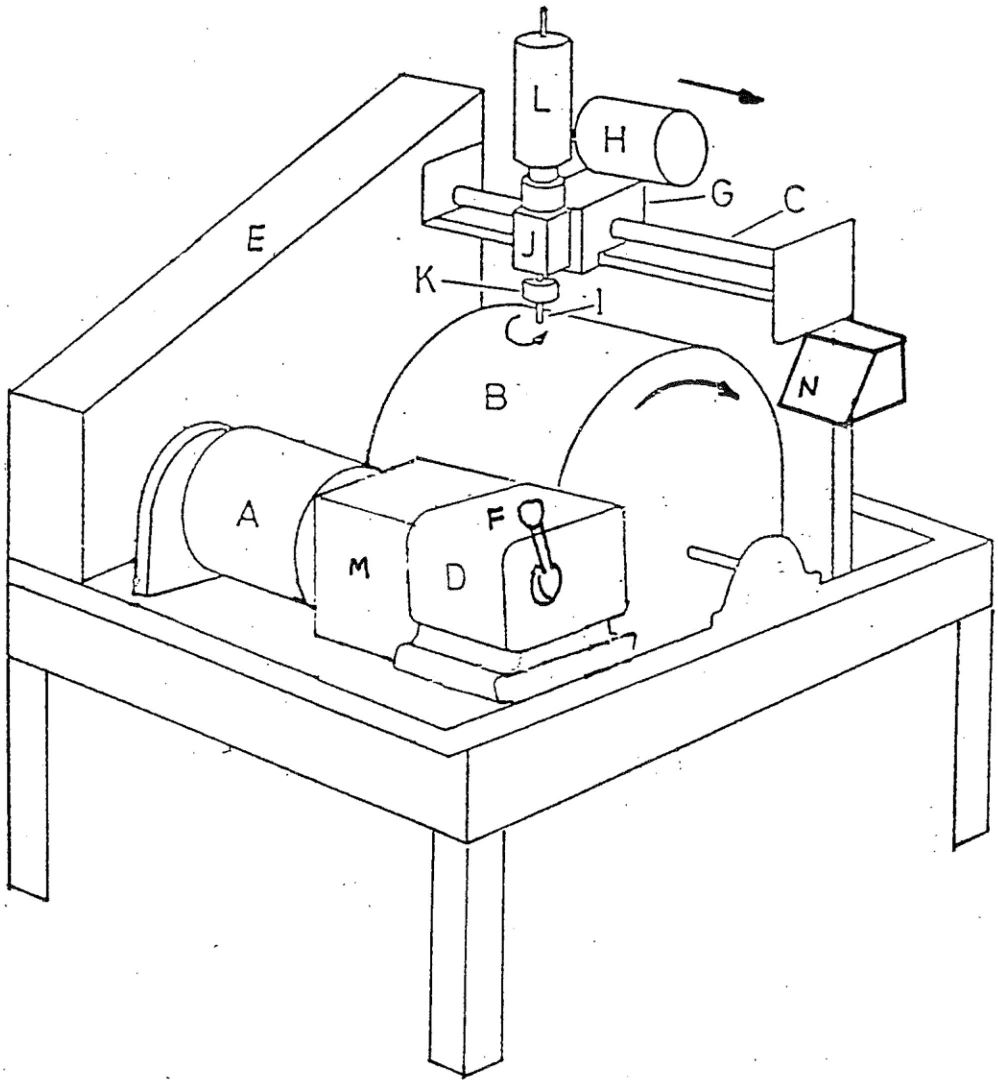

Figure 1. The pin-on-drum wear machine.

A: Electric motor (drives drum)
B: Drum
C: Lead screw driven synchronously by E
D: Variable speed gearbox
E: Toothed rubber belt
F: Gearbox control lever
G: Specimen carriage

H: Small electric motor rotates K
I: Specimen
J: Keyed linear bearing
K: Chuck
L: Dead-weight
M: Flexible coupling
N: Control panel

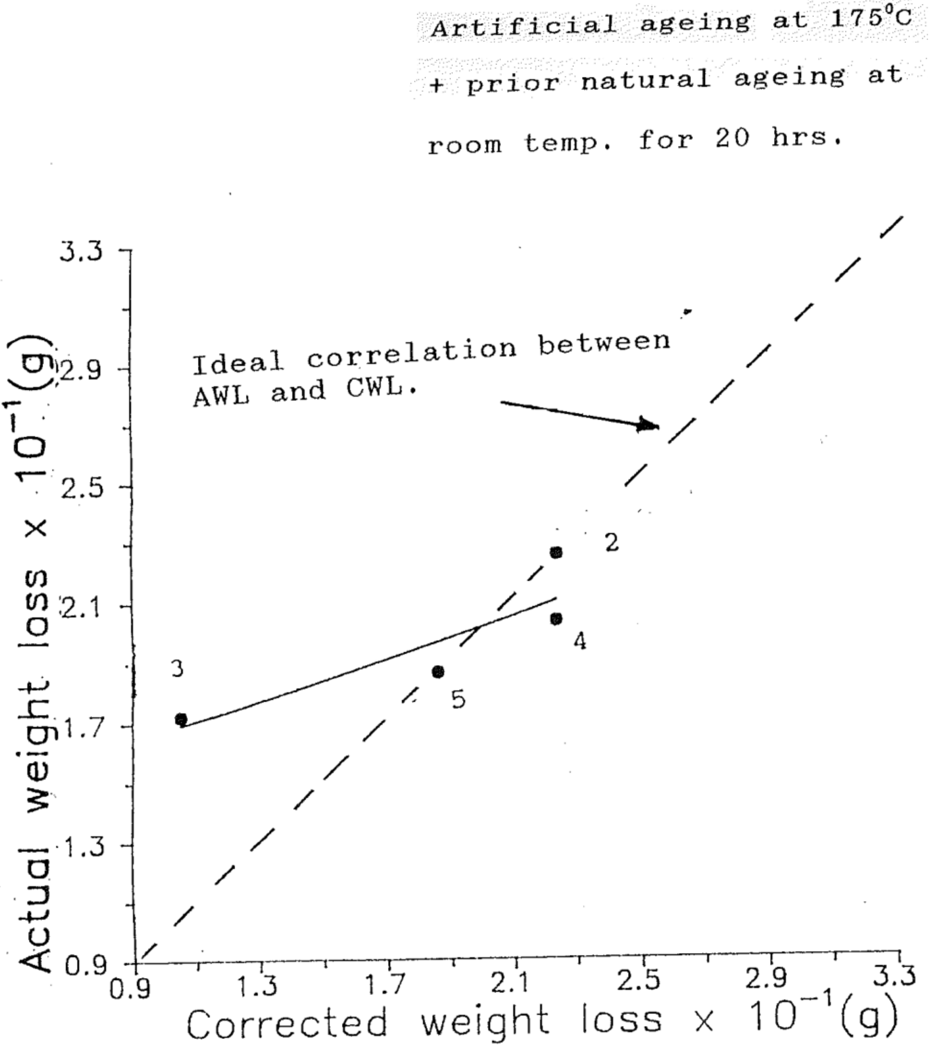
Artificial ageing at 175°C
+ prior natural ageing at
room temp. for 20 hrs.

Figure 2. Correlation between actual weight loss and corrected weight loss for 6061 at various ageing times.

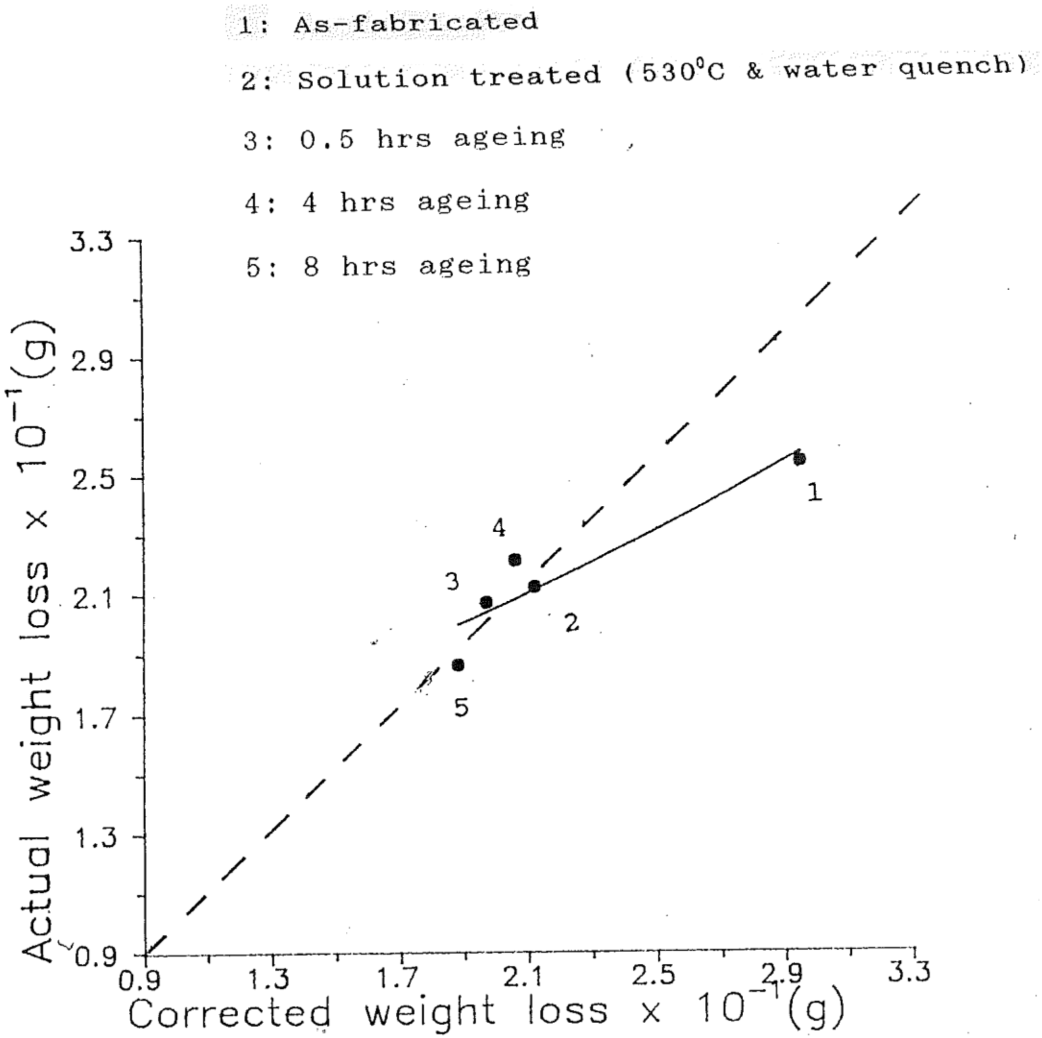
1: As-fabricated
2: Solution treated (530°C & water quench)
3: 0.5 hrs ageing
4: 4 hrs ageing
5: 8 hrs ageing

Figure 3. Actual weight loss vs corrected weight loss for $10^{v}/o$ Al_2O_3/6061 at various ageing times.

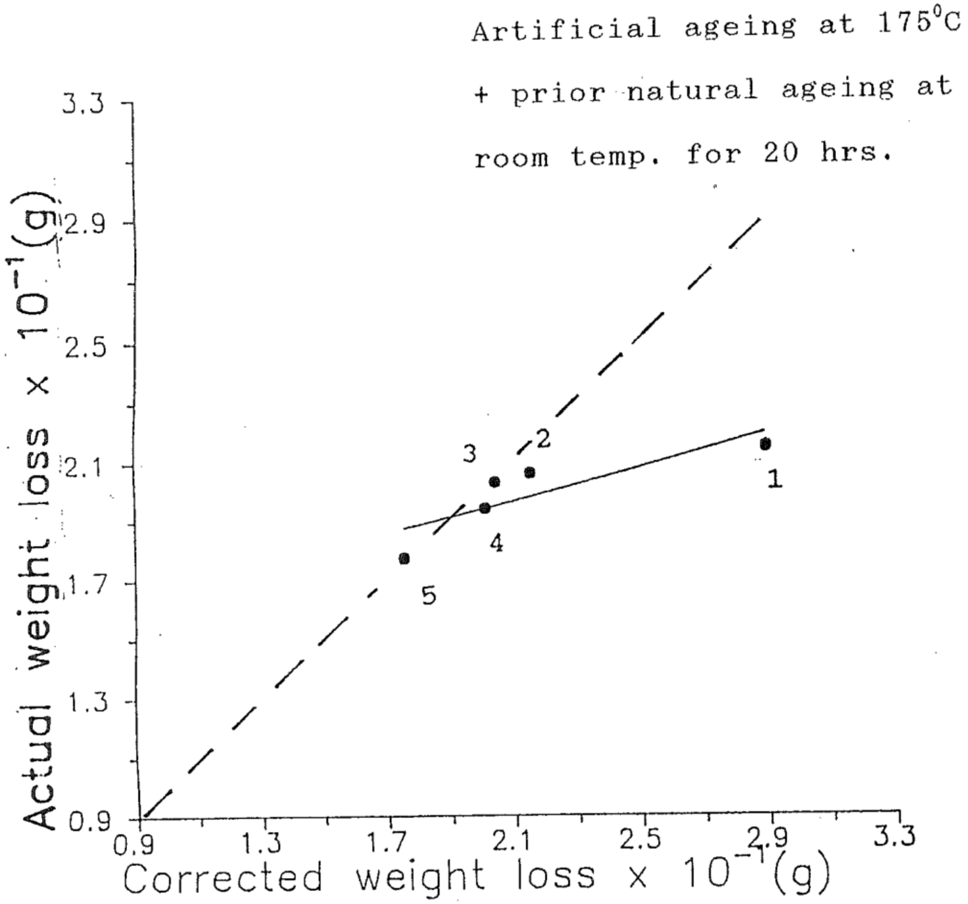

Figure 4. Actual weight loss vs corrected weight loss for 20^V/O Al_2O_3/6061 at various ageing times.

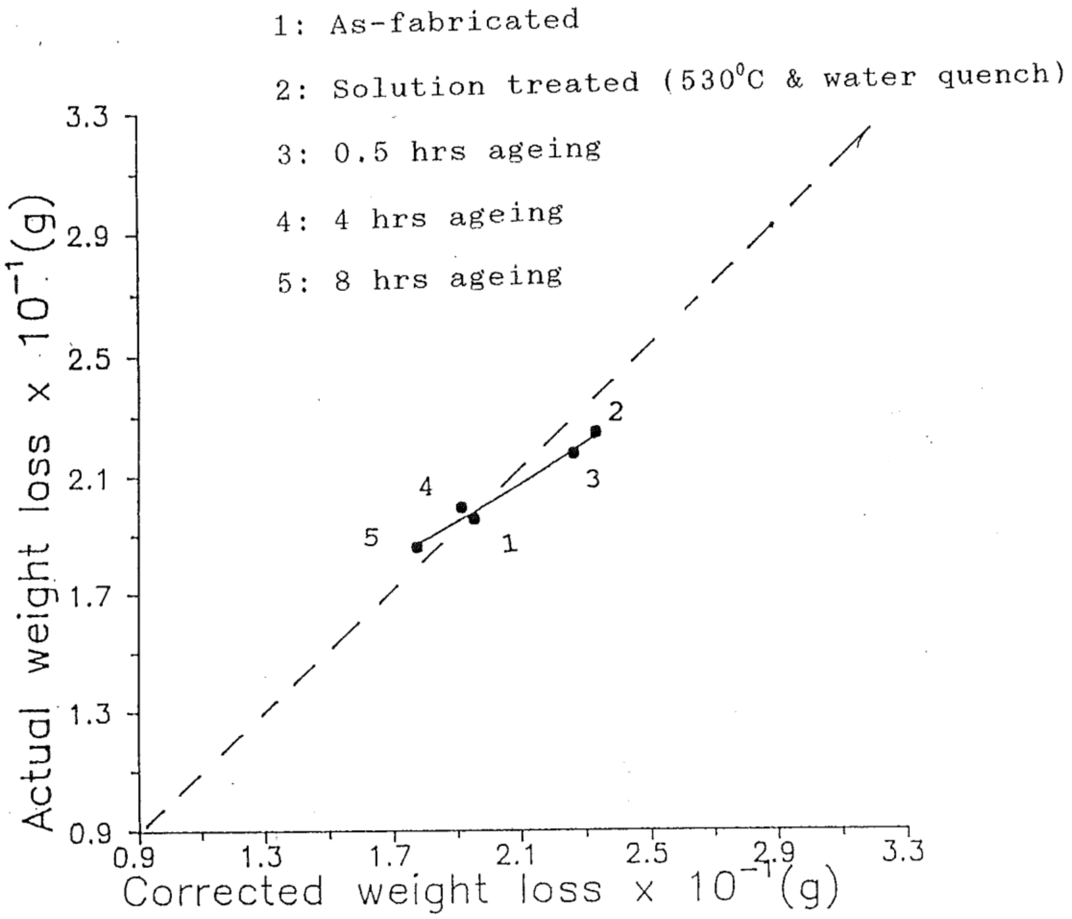

Figure 5. Actual weight loss vs corrected weight loss for 10^V/O SiC/6061 at various ageing times.

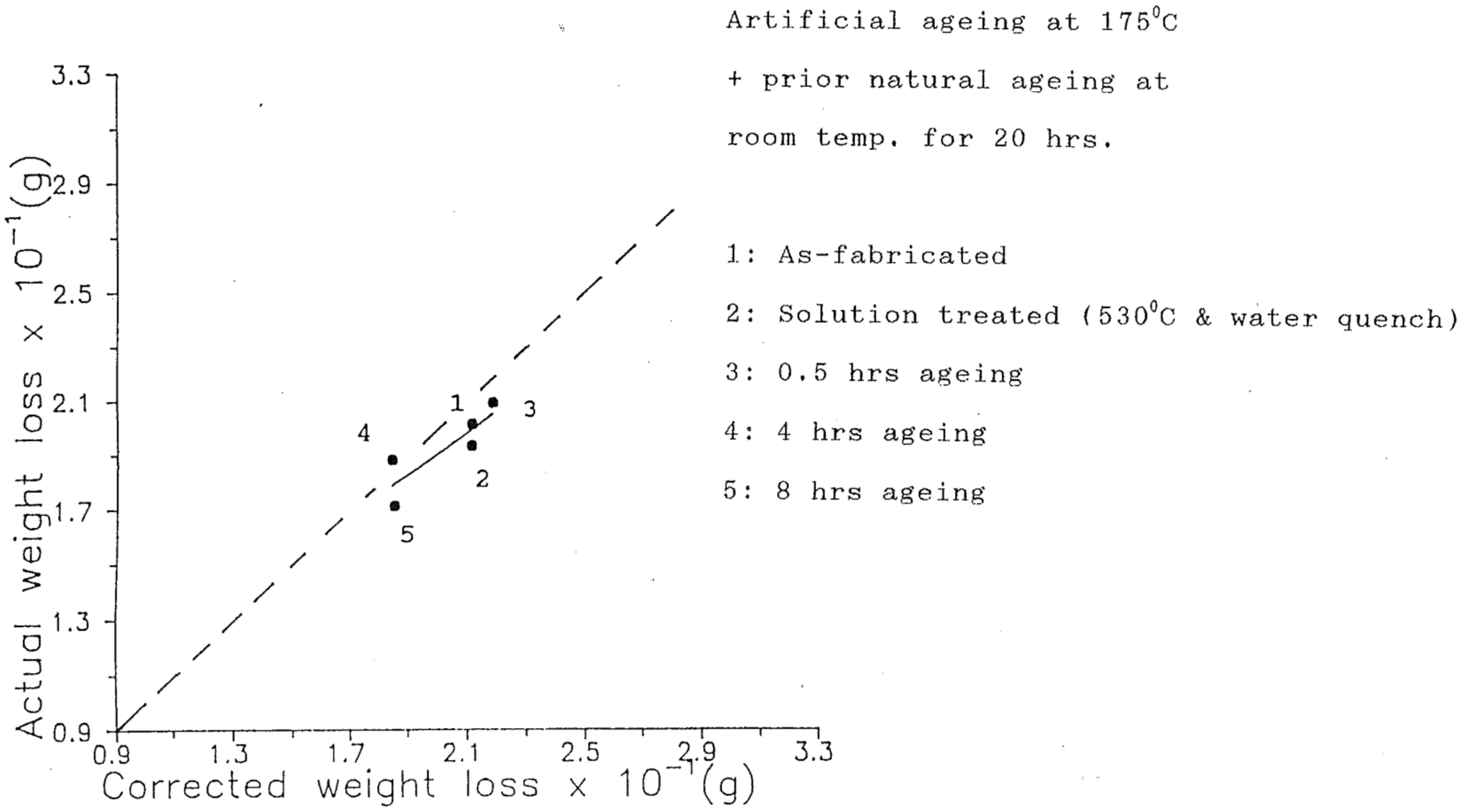

Figure 6. Actual weight loss vs corrected weight loss for $20^{v}/o$ SiC/6061 at various ageing times.

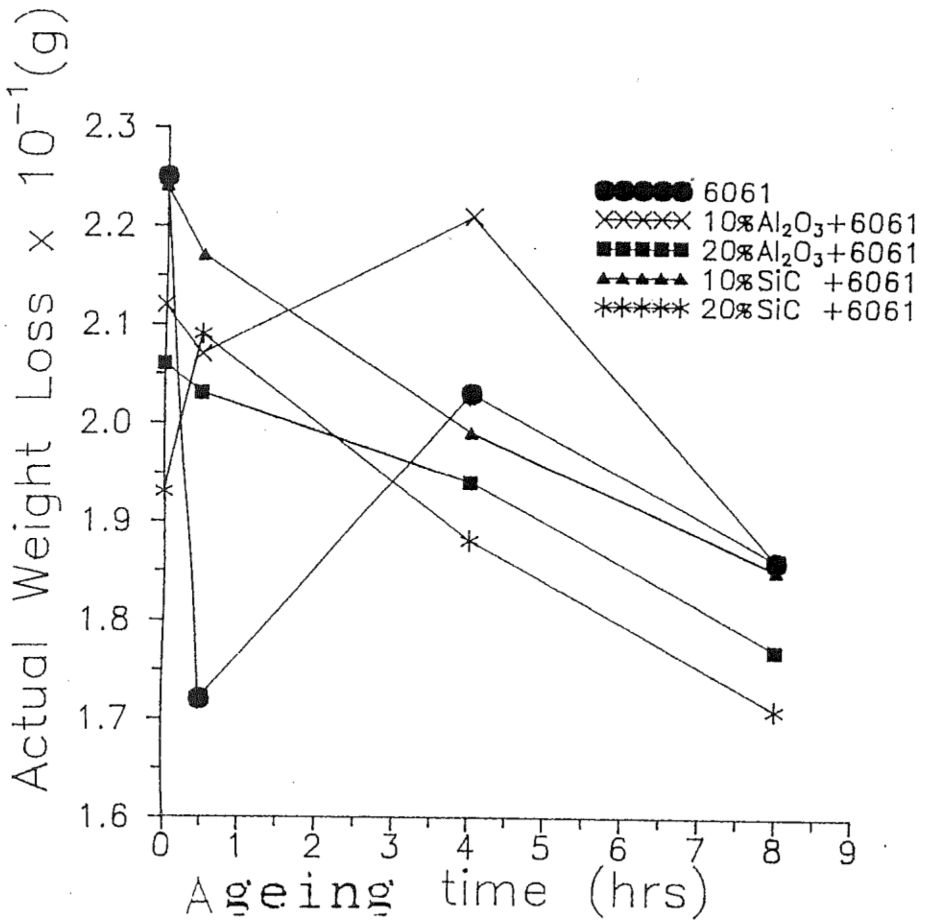

Figure 7. Variation of actual weight loss as a function of ageing time (at an ageing temp. of 175°C) for the 6061 MMCs and control alloy.

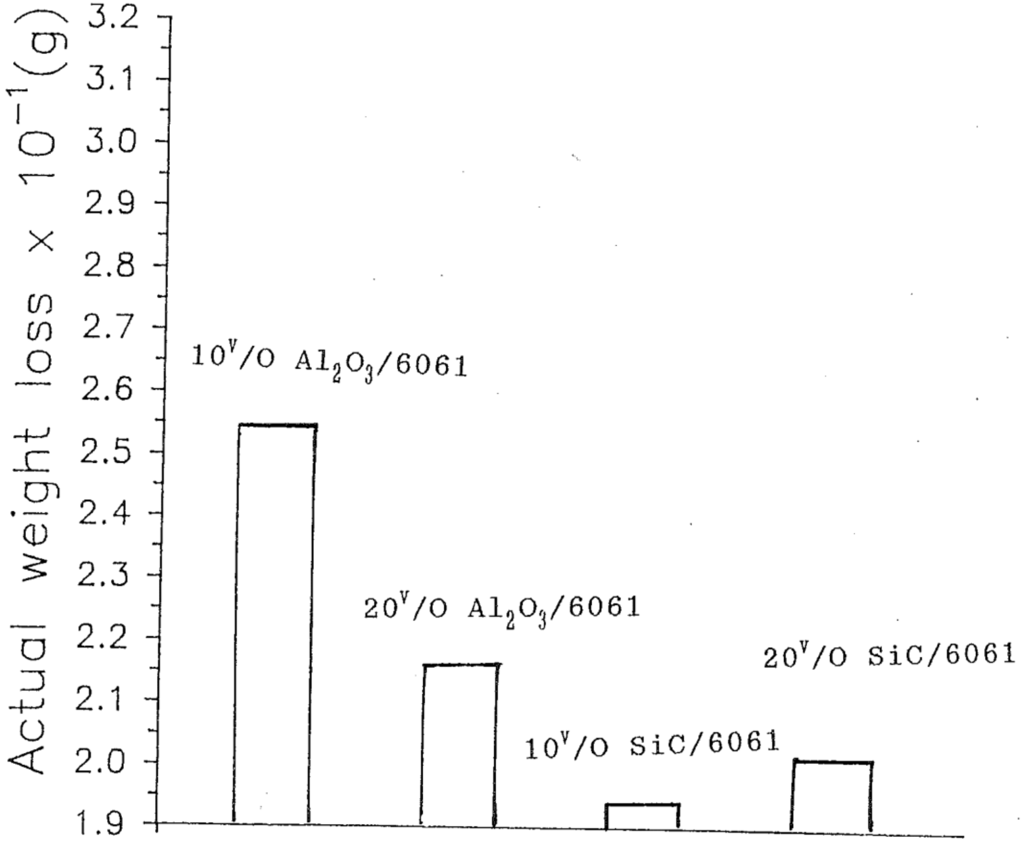

Figure 8. Actual weight loss for 6061 MMCs in the as-fabricated condition.

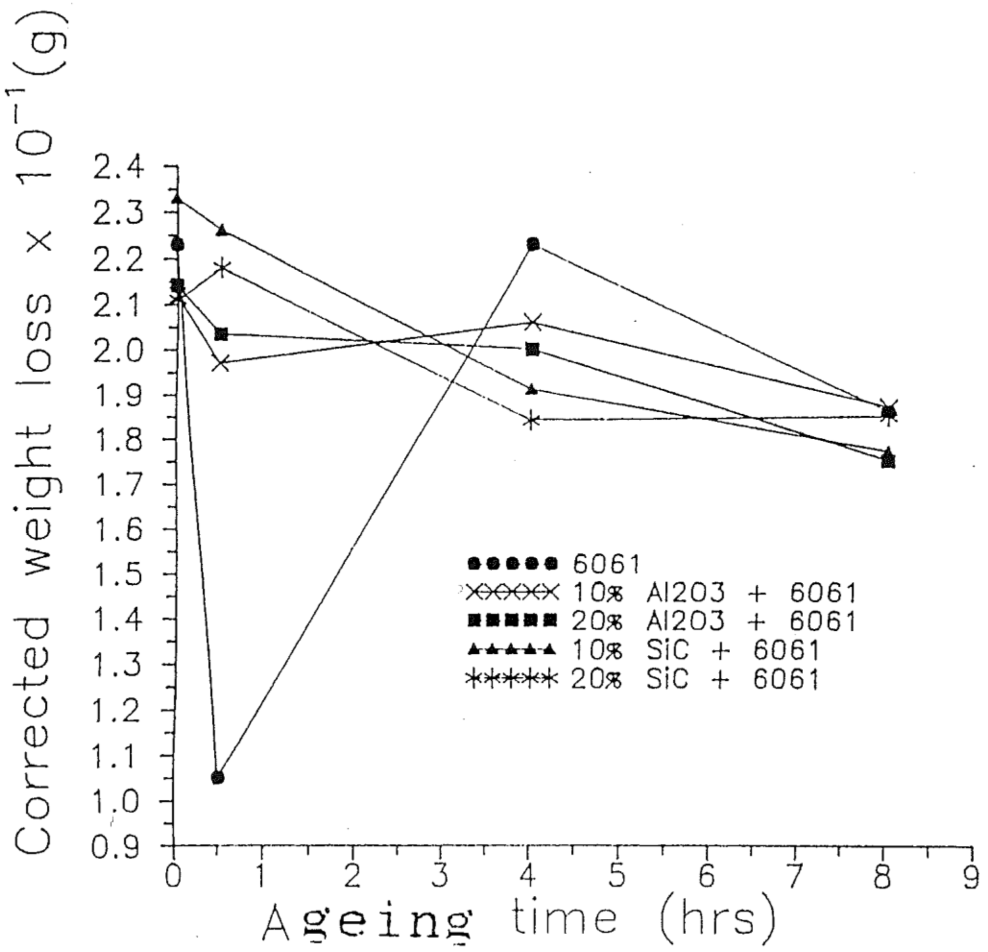

Figure 9. Variation of corrected weight loss as a function of ageing time (at an ageing temp. of 175°C) for the 6061 MMCs and control alloy.

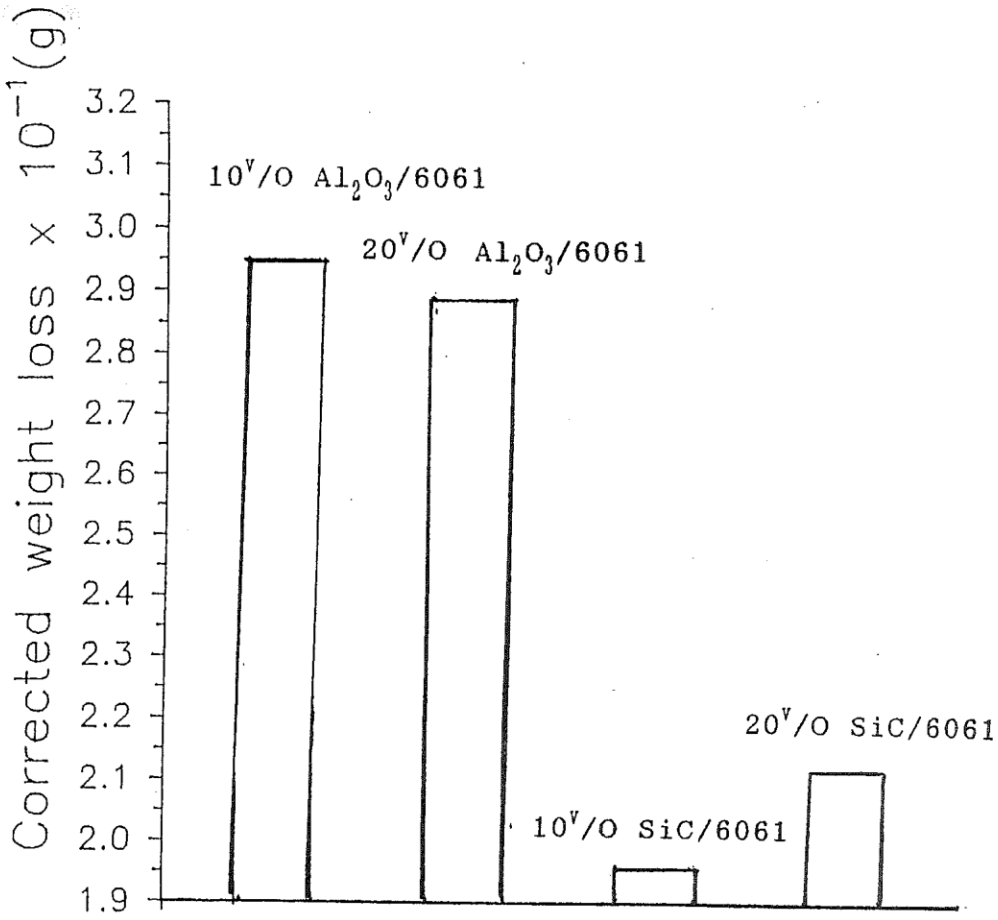

Figure 10. Variation of corrected weight loss for 6061 MMCs in the as-fabricated condition.

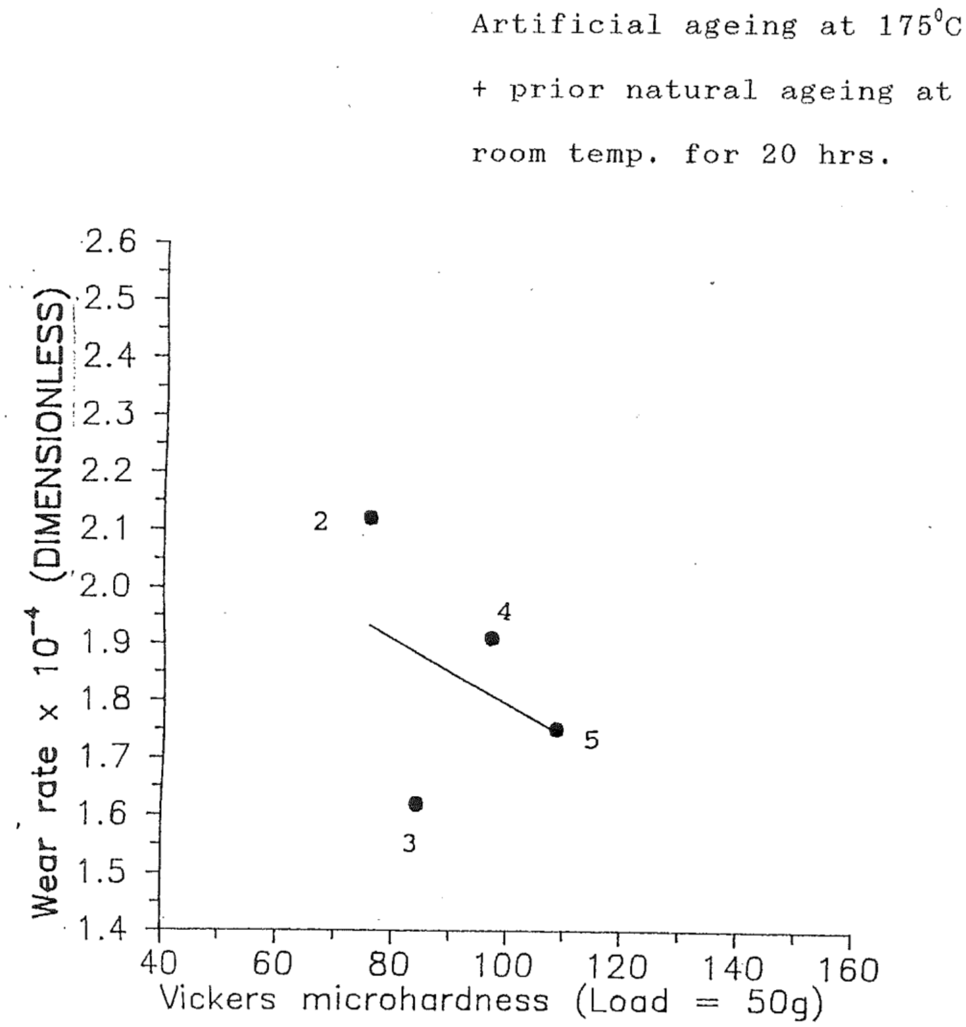

Figure 11. Variation in wear rate with matrix Vickers indentation hardness for 6061 control alloy at various ageing times.

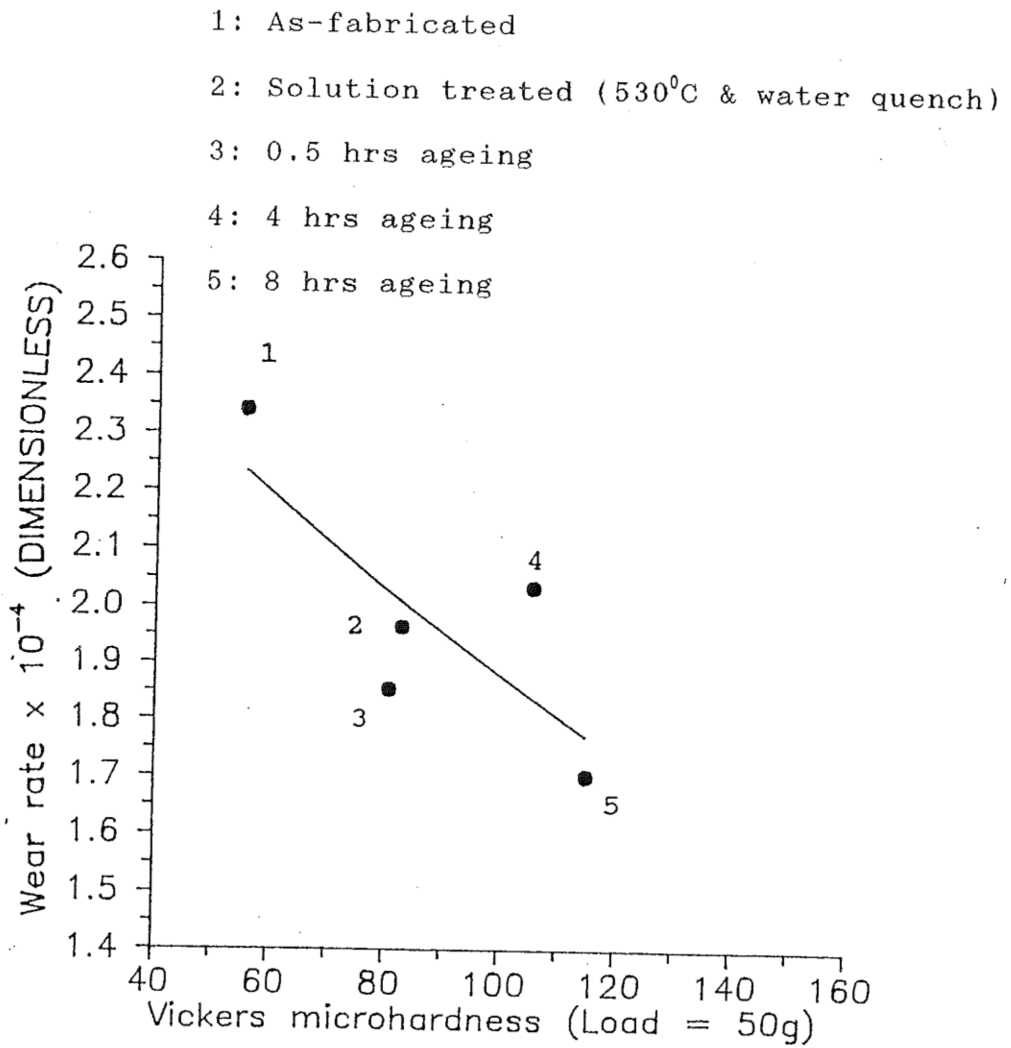

Figure 12. Wear rate vs matrix Vickers indentation hardness for $10^{V}/O$ $Al_2O_3/6061$ at various ageing times.

Artificial ageing at 175°C

+ prior natural ageing at

room temp. for 20 hrs.

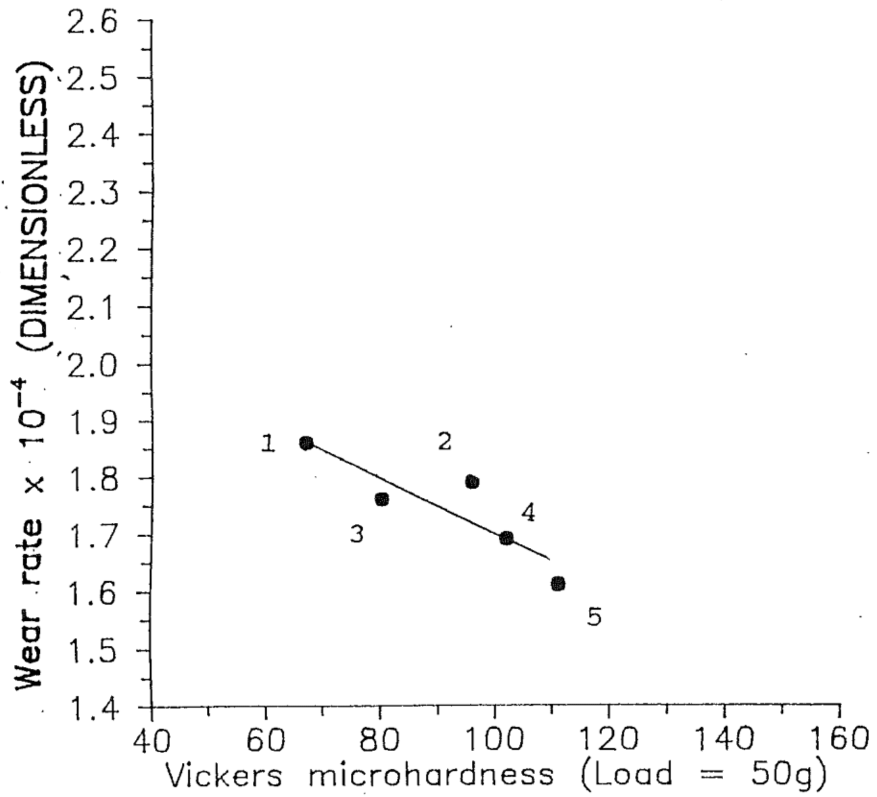

Figure 13. Wear rate vs matrix Vickers indentation hardness for $20^{v}/o$ Al_2O_3/6061 at various ageing times.

1: As-fabricated

2: Solution treated (530°C & water quench)

3: 0.5 hrs ageing

4: 4 hrs ageing

5: 8 hrs ageing

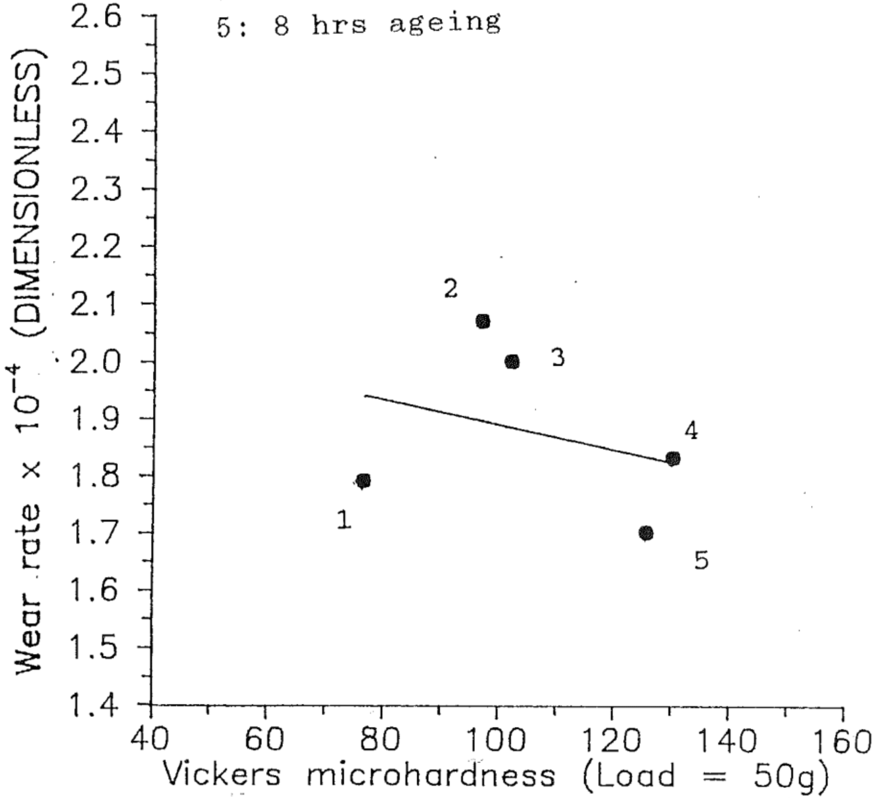

Figure 14. Wear rate vs matrix Vickers indentation hardness for $10^{v}/o$ SiC/6061 at various ageing times.

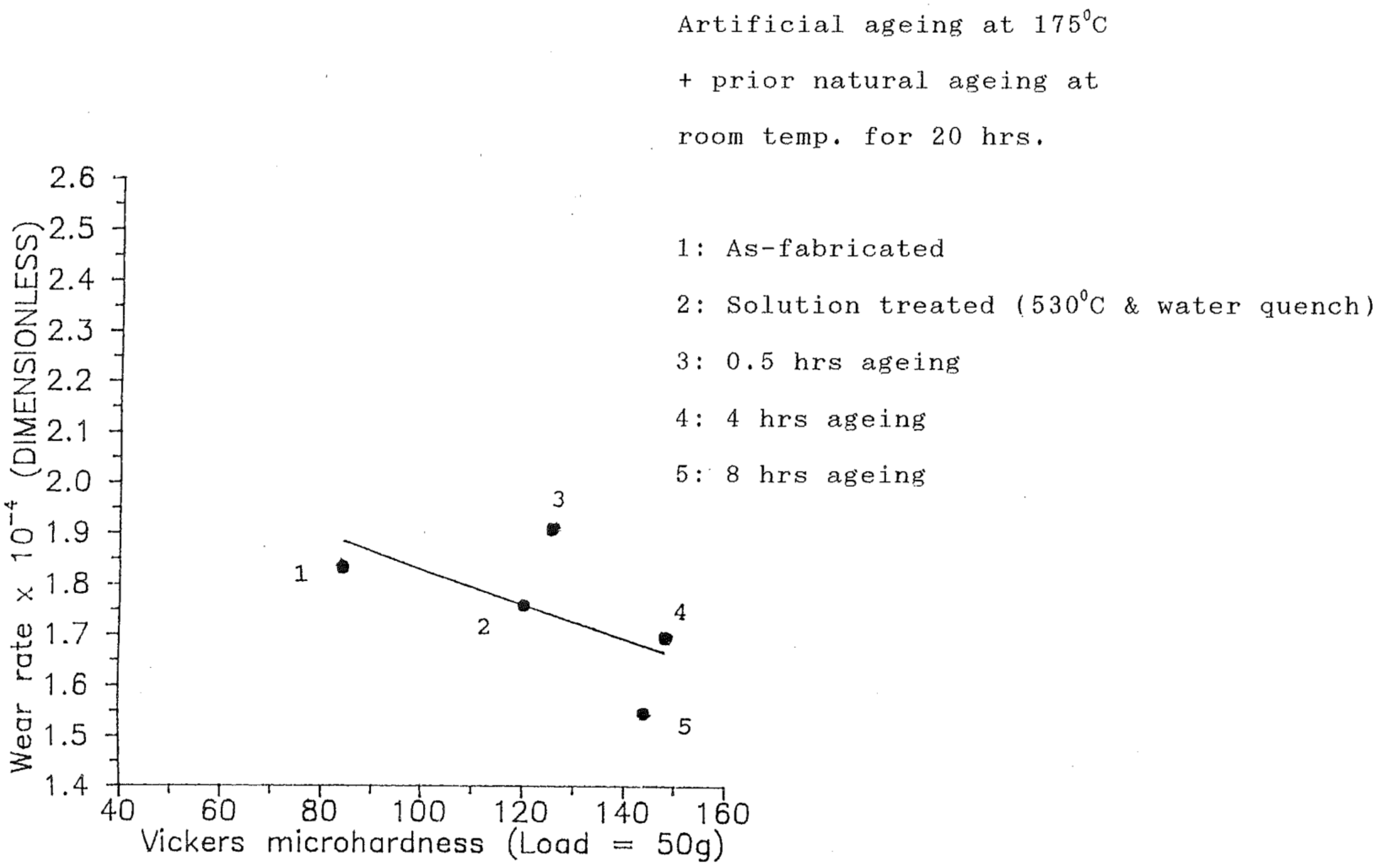

Figure 15. Wear rate vs matrix Vickers indentation hardness for 20^v/o SiC/6061 at various ageing times.

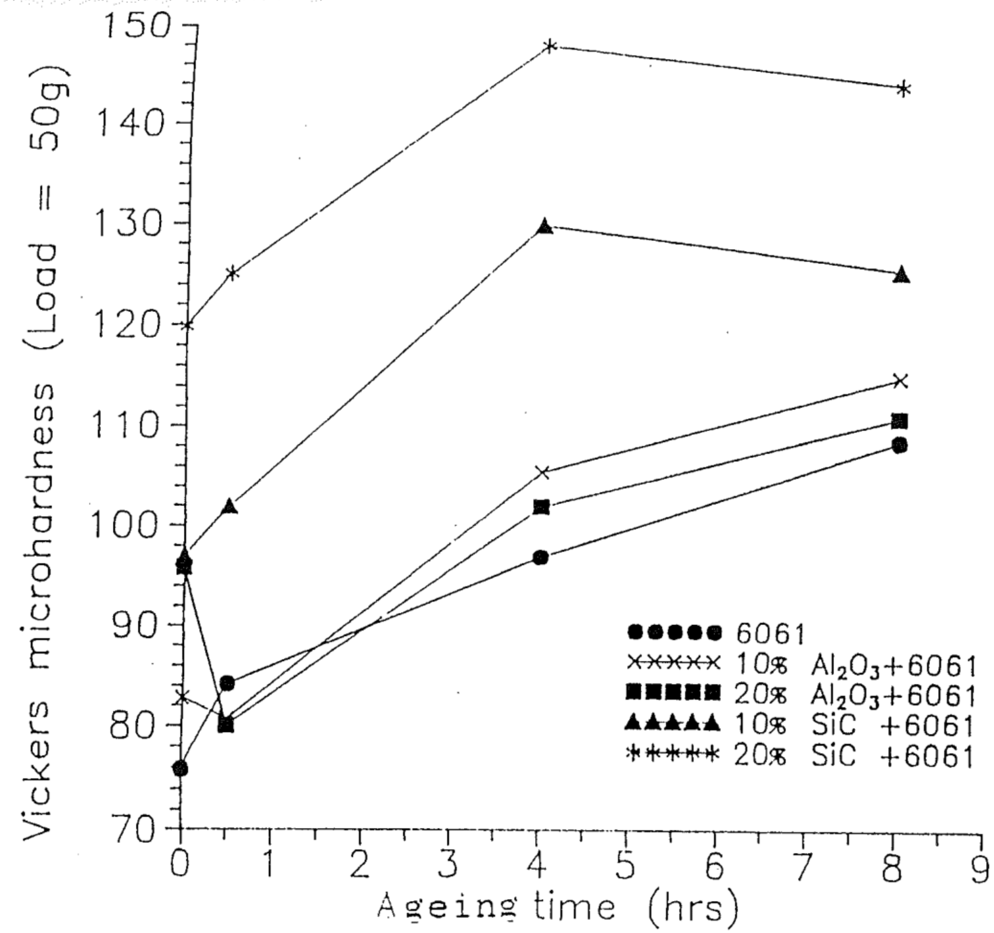

Figure 16. The effect of ageing on the matrix Vickers indentation hardness of 6061 MMCs and the control alloy.

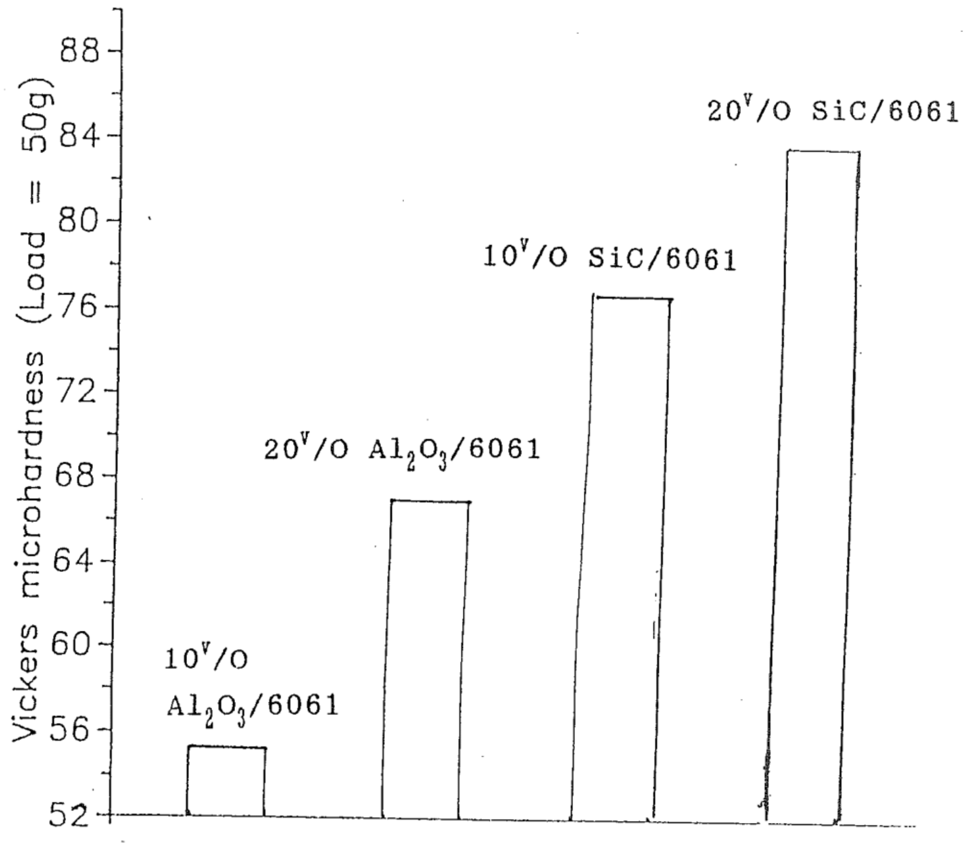

Figure 17. Matrix Vickers indentation hardness for MMCs in the as-fabricated condition.

Artificial ageing at 175°C

+ prior natural ageing at

room temp. for 20 hrs.

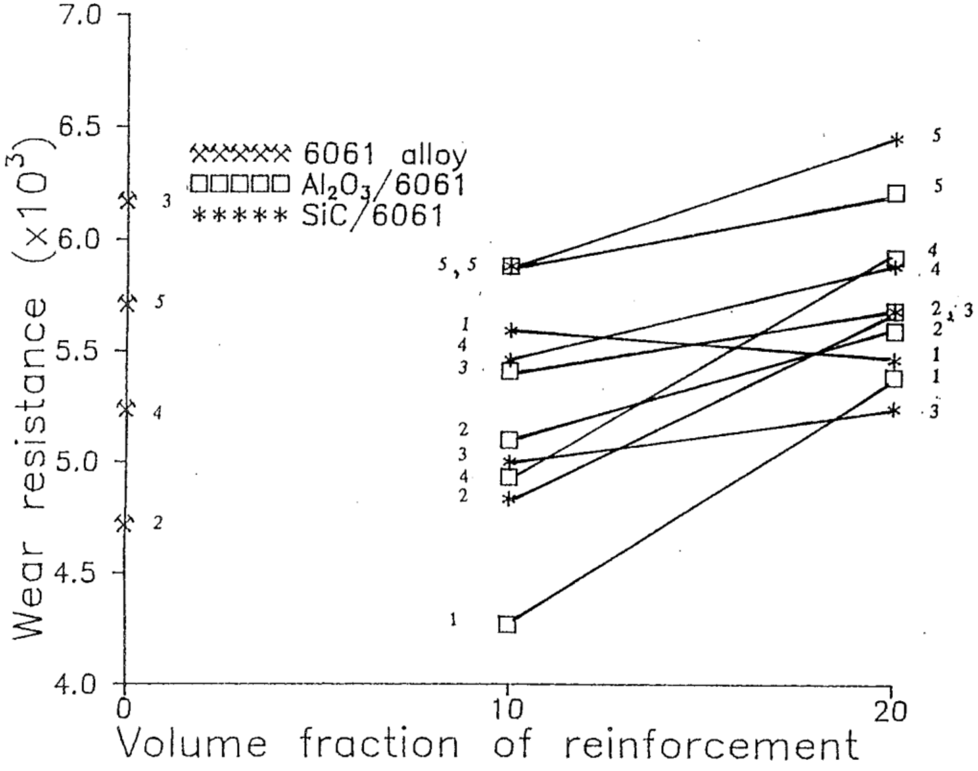

Figure 18. The effect of volume fraction of reinforcement on wear resistance for 6061 MMCs and the control alloy at various ageing times.

1: As-fabricated

2: Solution treated (530°C & water quench)

3: 0.5 hrs ageing

4: 4 hrs ageing

5: 8 hrs ageing

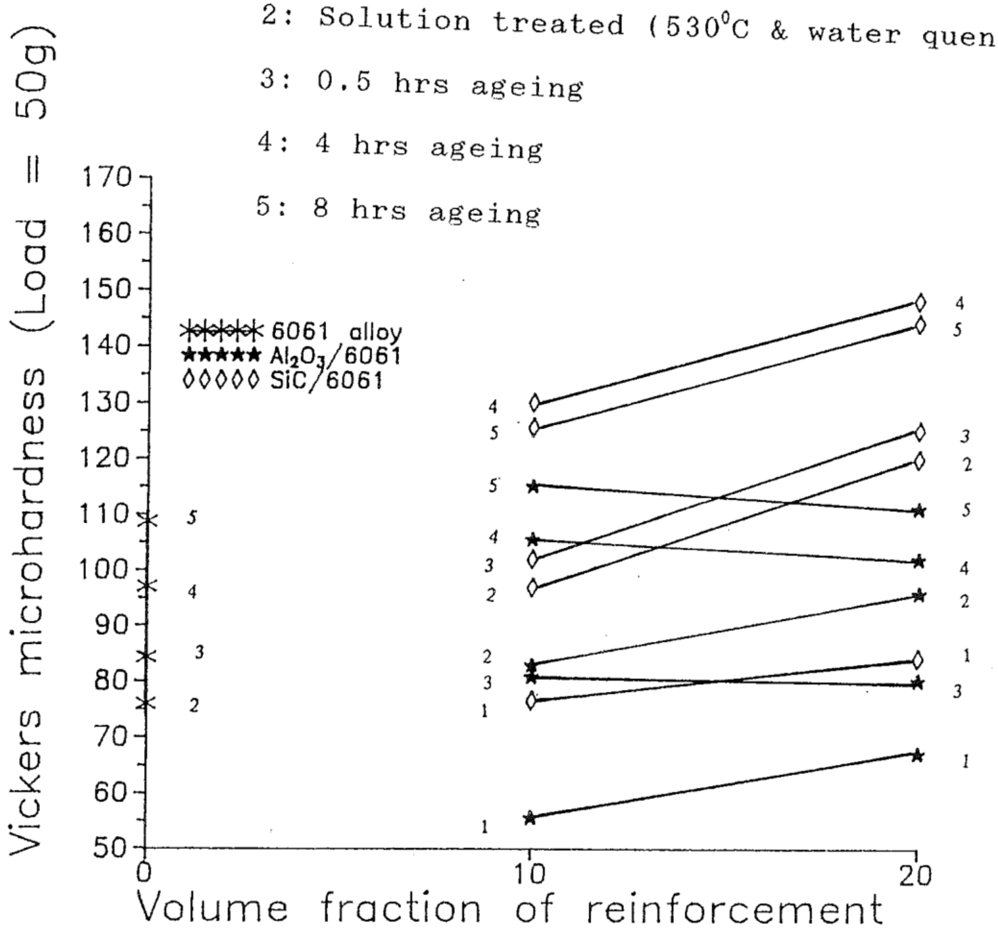

Figure 19. The dependence of volume fraction of reinforcement on matrix Vickers indentation hardness for 6061 MMCs and control alloy at various ageing times.