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The Effect of Alloying, Processing and Heat Treatment on the Wear Resistance of Al-Cu-Mg-Ag Alloys

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Abstract

In this study, eight aluminum-based alloys with two levels of weight percentages of copper, magnesium, and silver were cast and hot rolled. The alloys were processed at two conditions; hot rolled solely or hot rolled and aged to peak condition (T6). Statistically designed experiments were carried out to investigate the wear resistance of the aluminum -based alloys. The study investigated the following process variables: the effect of the level of alloying, the processing condition, the level of applied load, and the test duration on the wear performance and weight loss as a response variable. Analysis of variance (ANOVA) was carried out to define the significant factors. The means effect and interactions plots were extracted, and the regression model was developed and experimentally validated. The weight percentages of Cu and Ag, applied load, and test duration were found to be significant. The wear resistance improved with increasing percentages of Cu, Mg and Ag and the peak aging. The regression model represented the experimental results properly.

Keywords: wear resistance, aluminum alloys, hot roll, peak aging, statistical analysis.

1. Introduction

Wear resistance improvement is a crucial objective for aluminum alloys due to the existence of high demand on friction related applications that mandates the use of lightweight materials. Aluminum is a light metal and can be strengthened and hardened by alloying, heat treatment and cold working. Aluminum alloys are characterized with high strength-to-weight ratio, and this paved the way to their utilization in aviation and automotive industries. Their mechanical and tribological properties are basically influenced by the materials crystal structure [1]–[3]. They can be improved by alloying, formation of composites, heat treatment, and hot and cold working processes [4]–[6]. Aluminum can be alloyed with copper, manganese, silicon, magnesium, and zinc. The addition of silicon improves the castability and abrasion resistance, while the addition of copper and magnesium improve the mechanical properties. Also, specific alloying elements such as nickel and titanium are added to improve the hot hardness and corrosion resistance, respectively [7], [8]. The strength of these alloys can be improved by cold working and heat treatment. The tensile strength range of aluminum and its alloys is from 70 MPa for pure aluminum to 560 MPa for Al-Li-Cu-Mg heat treated alloy [9].

E. Scharifi et al. [10] investigated the effect of hot tensile deformation for heat treated AA7075 alloy and found that the aging time increased the hardness. A. Al-Obaisi et al. [11] investigated the effect of alloying elements (Cu, Mg, and Ag) and aging conditions (under-aged and peak-aged) on the mechanical properties at different testing temperatures. The peak-aged conditions produced higher yield and tensile strength compared to the under-aged conditions at different testing temperatures. The wear resistance is greatly affected by the crystal structures; FCC, BCC and HCP. The wear resistance and the coefficient of frictions of FCC lanthanum is higher than that of HCP structure of the same element [1]. M. Taher et al. [12] investigated the effect of the chemical composition of silver-aluminum alloys on the development of crystal structure. They found that the crystal structure changes from FCC to HCP to finally HCP + FCC with the increase of Al percentage in Ag. This transformation is accompanied with an increase in hardness and decrease in the wear rate. Precipitates of $MgZn_2$ and MgZn are commonly found in Al-Zn-Mg alloy. These precipitates significantly increase the mechanical and tribological properties because of structure refinement which occurs due to dislocations restrictions [13]. H. Sevik et al. [14] studied the effect of different levels of silver on the wear resistance of ZA-12 alloy. They found that the wear resistance was enhanced, and the coefficient of friction was decreased by the increase of silver percentage. These improvements were due to the increase of β-dendrites and the decrease of the eutectic zinc due to the addition of silver. F. Bertelli et al. [15] investigated the mechanical properties and the wear resistance for Al-Sn-Cu and Al-Sn-Si alloys. The alloys were solidified in a water-cooled apparatus to produce different dendrite length arm

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spacing. The wear resistance increased for samples that were taken far from the cooling side.

Mechanical and tribological properties can be improved using many techniques, such as heat treatment and coatings using ceramics or nickel-phosphorous for aluminum alloys [16], [17]. Moreover, powder milling with the addition of silver to AA2014 aluminum alloy led to the formation of hard precipitates which improved the wear resistance for AA2014 aluminum alloy [18]. The addition of ceramic particles to the metallic alloys lead to the formation of metal-matrix composites which improve the mechanical and tribological properties of the composites. M. Nagaral et al. [19] investigated the addition of micro-B_4C particles with different percentages to Al2024 aluminum alloy. They reported that the mechanical properties in terms of hardness, yield and ultimate tensile strengths increased with the increase of percentage of ceramic particles. M. Ayvaz et al. [20] investigated the wear resistance of 6013 aluminum alloy samples after artificial aging heat treatment at different temperature for different intervals. The condition of heat treatment temperature of 200 ℃ for 4 h produced the highest wear resistance compared to aging at 180℃ for different times.

As presented earlier, the effect of the alloying elements, heat treatment, applied load and the load application time during the wear test were extensively investigated experimentally in many published research articles. However, there exists a lack of statistical analysis for the experimental results and the parameters that influence the wear resistance. This has motivated the current work to investigate the significant factors and to reveal the interaction between the parameters and finally to develop a regression model for the response variable presented by the weight difference.

2. Experimental Work

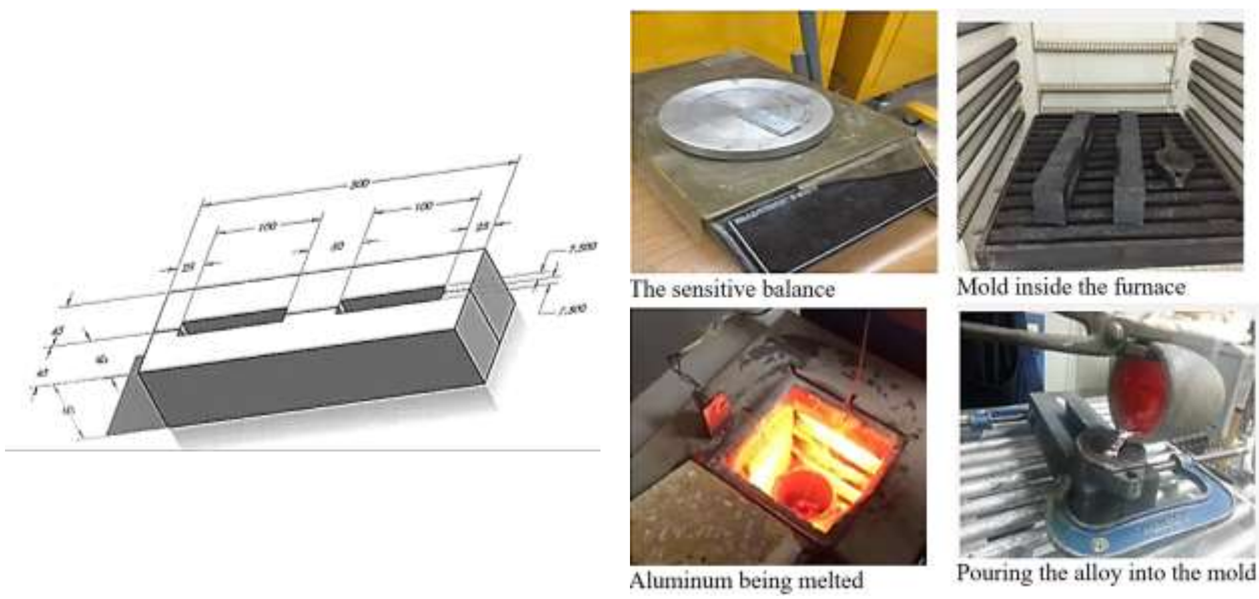
This section explains the process of manufacturing the samples and subsequent rolling followed by heat treatment and finally wear resistance experiments. The samples preparation is composed of casting followed by homogenization treatment then hot rolling, some of the samples were then subjected to aging to peak condition (T6). The wear test is carried out at two levels of loads and application time. This paper is an extension research for pervious published paper in reference [11], [21].

2.1. Alloys Synthesis

Firstly, pure aluminum and different weight percentages of copper, magnesium and silver elements are added to the electric furnace that was heated to 750^{o}C. Two levels of Cu, Mg and Ag are used to manufacture 8 alloys as shown in table (1). The tool steel die was preheated to 150^{o}C, and its cavity (sample dimensions) has the dimensions of 100×15×60 mm^3. Figure (1) shows the mold shape used and dimensions and the casting steps. All produced samples were homogenized at 540^{o}C for 24 hours to eliminate micro-cracks and homogenize the structure, before hot rolling.

Table 1. The chemical composition of the eight alloys which are performed for this study.

ALLOY SERIES	WT. % CU	WT. % MG	WT. % AG	WT. % AL
1	3.0	0.5	0.3	Balance
2	5.0	0.5	0.3	Balance
3	3.0	1.0	0.3	Balance
4	5.0	1.0	0.3	Balance
5	3.0	0.5	0.6	Balance
6	5.0	0.5	0.6	Balance
7	3.0	1.0	0.6	Balance
8	5.0	1.0	0.6	Balance



(a) (b)

Figure 1. (a) Mold cavity dimensions, (b) casting and heat treatment processes

2.2. Hot rolling

All samples were hot rolled after homogenization. The sample thickness was decreased from 15mm to 3mm with a reduction ratio of 80% at a rolling speed of 20 rpm as shown in Fig. (2-a). The samples were maintained at 450℃ in an external furnace for 15 minutes before rolling while the roller's temperature was maintained at 170℃. Figure (2-b) shows the samples before and after rolling, while Figure (2-c) shows the samples that were cut from the rolled plate for wear testing.

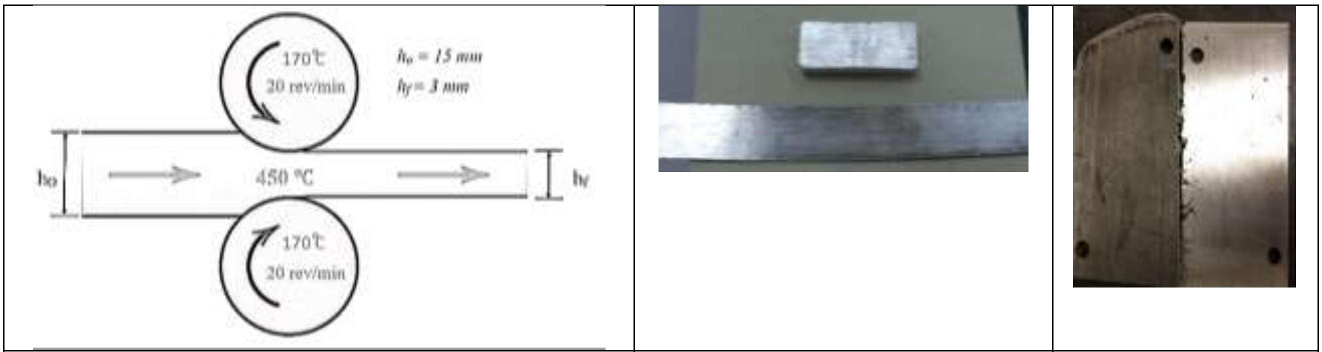
2.3. Aging Treatment

Firstly, solution treatments at 540 ℃ for alloys of 5% Cu and at 500℃ for alloys of 3% Cu were carried out. Then, all alloys were quenched in agitated water medium. The aging conditions for these alloys were depicted from previous work [21]. The alloys were subjected to age hardening process in a salt bath of 50% potassium nitrate (KNO_3) and 50% sodium nitrite ($NaNO_2$) at a temperature of 190℃ for different durations to reach peak hardened conditions. The samples were water-quenched after aging.

2.4. Wear test

Sliding wear tests according to ASTM A29 were implemented using sliding stainless steel-440C (HRC 62) ball with 10 mm diameter as a counter face as shown in Fig. (3). Wear test conditions are stated in table 2. Fig. (3-b) shows a sample that was subjected to wear tests. The sample weight was measured before and after each wear test and the difference is taken as an output for this test. Before weighing, the samples were cleaned by forced air and swabbed by ethanol. The higher and the lower weight loss samples were imaged using SEM "Vega3 Tescan".

Two levels of composition of copper, magnesium and silver, processing conditions (hot rolled or aged to peak condition), applied load, and load application duration were selected during the experimental investigation as shown in table 3. Minitab 17 software was used to generate the array and the statistical analysis.



(a) (b) (c)

Figure 2. Rolling process and conditions, (b) rolled sample (c) polished and unpolished samples before wear testing

(a) (b)

Figure 3. (a) pin-on-disc machine used for wear test, (b) The sample that is subjected to wear testing.

Table 2. wear test conditions

Description	Speed	Track length	Separation distance between tracks	Direction
Specification	10 mm/s	50 mm	5 mm	Reciprocating

Table 3. Process variables

Parameter	wt.% Cu (A)	wt.% Mg (B)	wt.% Ag (C)	Processing Conditions (D)	Load – N (E)	Duration - hr (F)
Level (1)	3	0.5	0.3	Hot rolled	20	0.5
Level (2)	5	1	0.6	peak aged	60	2

3. Results and discussions

The effect of weight percentage of copper, magnesium and silver, the processing conditions (hot rolling and peak aging), applied load, and the load duration on the weight difference between the sample before and after the wear tests are shown in table 4. A 2-levels full factorial design for the six process variables is implemented.

Figure 4 shows the effect of the process variables of Cu, Mg and Ag percentages, processing conditions, applied load and the loading time on the sample weight loss. It is clear that the increase in the loading time increases the weight loss especially with the hot rolled condition. The peak aging improves the wear resistance greatly compared to the hot rolled samples. The higher percentage of Ag reduces the weight loss which means that the wear resistance is improved. Generally, the percentage of 5% Cu improves the wear resistance compared to the lower level.

Table 4. the effect of process variables on the weight difference.

No.	Input parameters						Weight diff. (gm)	No	Weight diff. (gm)						Weight diff. (gm)
	Cu %	Mg %	Ag %	Processing Condition	Load (N)	Duration (hr)			Cu %	Mg %	Ag %	Processing Condition	Load (N)	Duration (hr)	
1	3	0.5	0.3	1	20	0.5	0.0093	33	3	0.5	0.6	1	20	0.5	0.0039
2	3	0.5	0.3	1	20	2	0.0298	34	3	0.5	0.6	1	20	2	0.0118
3	3	0.5	0.3	1	60	0.5	0.0227	35	3	0.5	0.6	1	60	0.5	0.0123
4	3	0.5	0.3	1	60	2	0.0765	36	3	0.5	0.6	1	60	2	0.0473
5	3	0.5	0.3	2	20	0.5	0.0049	37	3	0.5	0.6	2	20	0.5	0.0019
6	3	0.5	0.3	2	20	2	0.0155	38	3	0.5	0.6	2	20	2	0.0068
7	3	0.5	0.3	2	60	0.5	0.01439	39	3	0.5	0.6	2	60	0.5	0.0037
8	3	0.5	0.3	2	60	2	0.0436	40	3	0.5	0.6	2	60	2	0.0137
9	5	0.5	0.3	1	20	0.5	0.0089	41	5	0.5	0.6	1	20	0.5	0.0079
10	5	0.5	0.3	1	20	2	0.0302	42	5	0.5	0.6	1	20	2	0.0185
11	5	0.5	0.3	1	60	0.5	0.0207	43	5	0.5	0.6	1	60	0.5	0.015
12	5	0.5	0.3	1	60	2	0.0564	44	5	0.5	0.6	1	60	2	0.0533
13	5	0.5	0.3	2	20	0.5	0.0041	45	5	0.5	0.6	2	20	0.5	0.0012
14	5	0.5	0.3	2	20	2	0.0097	46	5	0.5	0.6	2	20	2	0.0054
15	5	0.5	0.3	2	60	0.5	0.0111	47	5	0.5	0.6	2	60	0.5	0.0036
16	5	0.5	0.3	2	60	2	0.0314	48	5	0.5	0.6	2	60	2	0.0093
17	3	1	0.3	1	20	0.5	0.0132	49	3	1	0.6	1	20	0.5	0.0054
18	3	1	0.3	1	20	2	0.036	50	3	1	0.6	1	20	2	0.015
19	3	1	0.3	1	60	0.5	0.0292	51	3	1	0.6	1	60	0.5	0.0095
20	3	1	0.3	1	60	2	0.0729	52	3	1	0.6	1	60	2	0.0304
21	3	1	0.3	2	20	0.5	0.0056	53	3	1	0.6	2	20	0.5	0.0025
22	3	1	0.3	2	20	2	0.0217	54	3	1	0.6	2	20	2	0.0131
23	3	1	0.3	2	60	0.5	0.0144	55	3	1	0.6	2	60	0.5	0.0093
24	3	1	0.3	2	60	2	0.0559	56	3	1	0.6	2	60	2	0.0313
25	5	1	0.3	1	20	0.5	0.0041	57	5	1	0.6	1	20	0.5	0.0047
26	5	1	0.3	1	20	2	0.0135	58	5	1	0.6	1	20	2	0.0146
27	5	1	0.3	1	60	0.5	0.0118	59	5	1	0.6	1	60	0.5	0.0138
28	5	1	0.3	1	60	2	0.0364	60	5	1	0.6	1	60	2	0.0426
29	5	1	0.3	2	20	0.5	0.0012	61	5	1	0.6	2	20	0.5	0.0027
30	5	1	0.3	2	20	2	0.0033	62	5	1	0.6	2	20	2	0.0091
31	5	1	0.3	2	60	0.5	0.0022	63	5	1	0.6	2	60	0.5	0.0061
32	5	1	0.3	2	60	2	0.0065	64	5	1	0.6	2	60	2	0.022

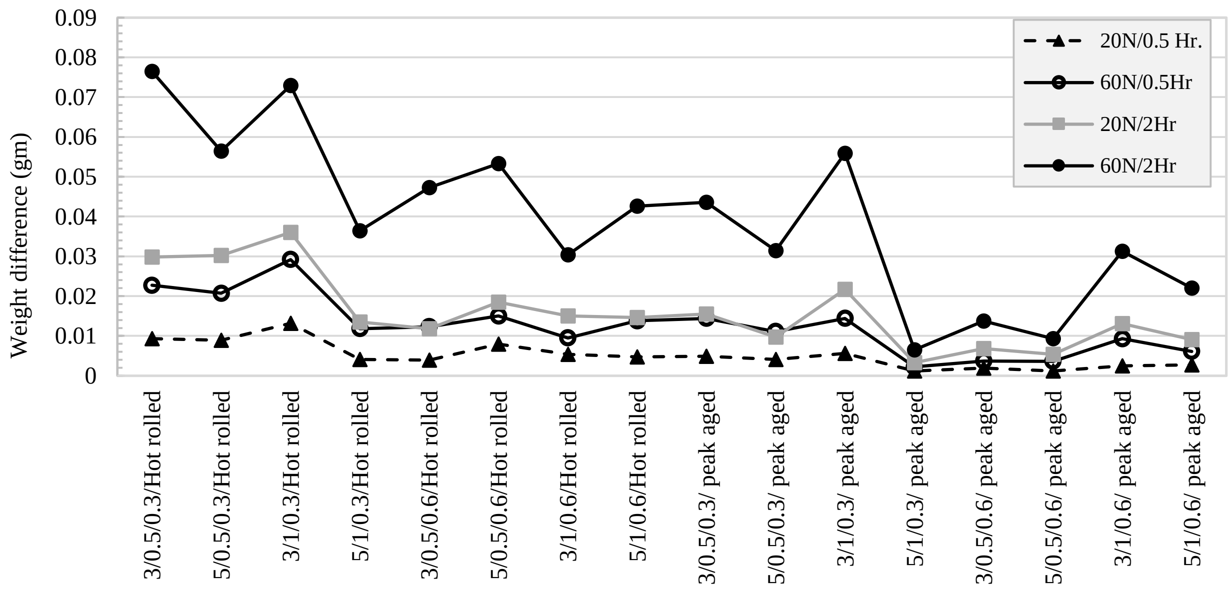


Figure 4. weight difference between the sample weights before and after the wear test at the used conditions

Figure 5 shows SEM images for the worn surface topography for the sample under the following conditions: Cu 5%, Mg 1%, Ag 0.3%, peak aged, 20N, 0.5hr that represent the case of lowest material removal (Fig. 5 (a)) and the sample with the following conditions: Cu 3%, Mg 0.5%, Ag 0.3%, hot rolled, 60N, 2hr that represent the case of highest material removal (Fig.5 (b)). Figure 5(a) exhibits smooth surface morphology without striations. Due to the lower applies force, smooth abrasion roughness appeared. While the high applied force in case of samples shown In Fig. 5(b), the surface is featured with roughness due to high plastic deformation and delamination which is usually associated with low hardness. The mixture of plate-like debris and smooth surface indicates a mixture of abrasion and adhesion wear mechanisms [22].

3.1. Statistical analysis and ANOVA

The statistical analysis confirms that the results are normally distributed, and the residuals are fairly scattered. The analysis of variance for the weight difference was carried out and ANOVA results are shown in table 5. The addition of copper and silver, processing condition, application loads, and the loading time are significant factors. Only the addition of the magnesium is the insignificant factor, however its interaction with other variables is significant. The interactions up to three factors are also investigated. The second level interactions of copper percentage independently with each of Mg content, Ag content, applied load, and the test duration are significant. Moreover, the interactions of Mg with Ag and processing condition and the interactions of silver weight percentage with the applied load and testing time are significant.

It has been reported that the addition of small amount of silver to Al-Cu-Mg alloy can significantly influence the age hardening mechanism due to the formation of **Ω** phase which improves the alloy mechanical properties and thermal stability [21], [23]. This physical effect appears in the significance of age-hardening mechanism interaction. However, the addition of silver to Al-Cu alloy did not exhibit a significant effect on the mechanical properties which points to the need for the existence of Mg in the alloy system along with the Ag addition to precipitate the **Ω** phase, as previously reported [21]. The significance of Mg and Ag interaction clears this correlation. Peak-aging mechanism increases the mechanical properties in terms of yield strength and hardness which in turn enhances the wear resistance and reduce the weight loss due to the friction tests [11].

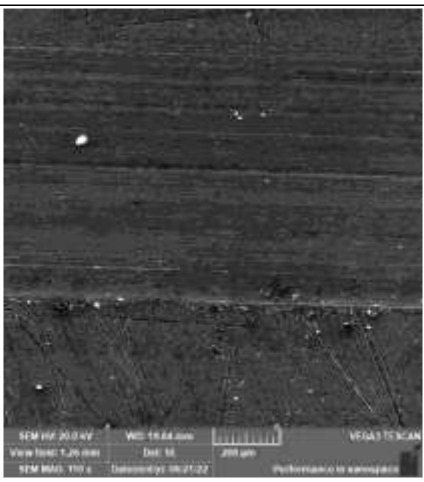
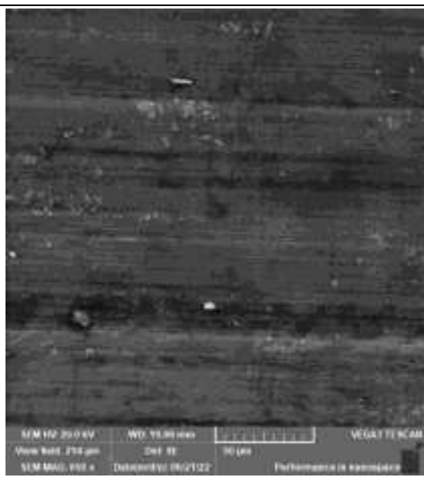
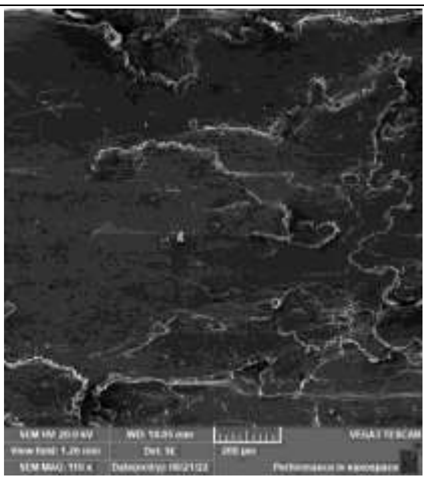
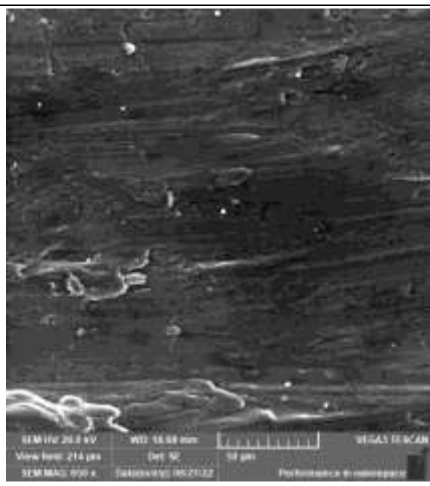
Magnification = 110 X	Magnification = 650 X
	
(a) Worn surface for Cu 5%, Mg 1%, Ag 0.3%, peak aged, 20N, 0.5Hr at two different magnifications.	
	
(b) Worn surface for Cu 3%, Mg 0.5%, Ag 0.3%, hot rolled, 60N,2Hr at two different magnifications.	

Figure 5. SEM images samples of (a) lower and (b) higher weight loss.

3.2. Main effect plot

The main effect plot shows (Fig. 6 (a)) the testing duration, applied load and the processing conditions have the larger effect on the wear rate followed by the weight percentages of the copper and the silver. On the contrary, the percentage of magnesium has the least effect. The wear rate measured represented by the weight difference for the aluminum alloys decreases by about 45% by increasing the Cu weight percentage from 3% to 5% and increasing the Ag percentage from 0.3% to 0.6%. The peak aging heat treatment improves the wear resistance compared to the hot rolled condition. However, the weight loss percentage decreases by about 40% for the peak aged samples compared to their hot rolled counterpart. The increase of the applied load from 20N to 60N increases the weight loss percentage due to wear by about 60%. The testing duration of 2 hours increases the wear rate by about 80% compared to the duration of 0.5 hour.

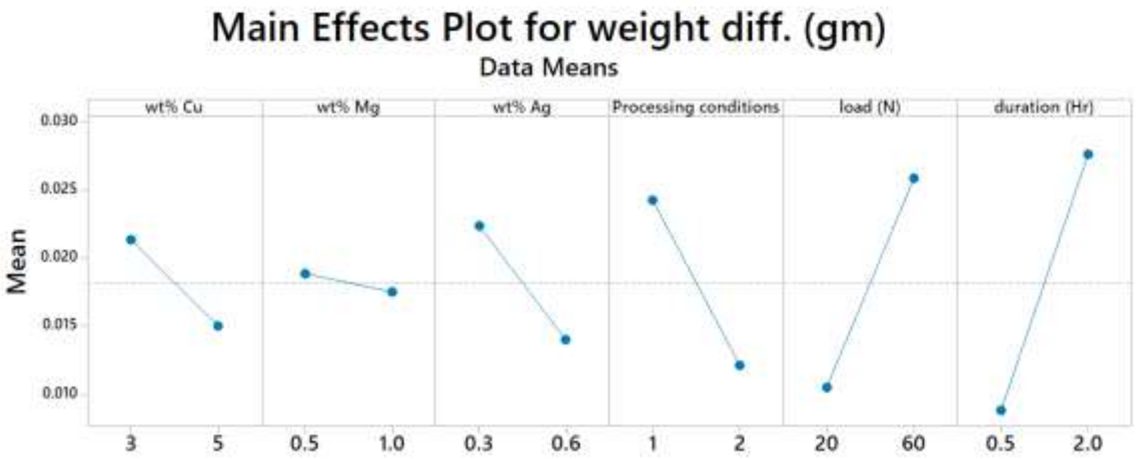
3.3. Interaction plot

Figure 6 (a) shows the interaction plots. The interaction between copper and magnesium percentages is significant as shown in table 5. The interaction plot confirms this significance. At the low Cu percentage, there is no difference between the two levels of Mg. But with the higher level of 5% Cu, the high level of Mg (1%) reduces the wear weight loss compared to the Mg percentage of 0.5%. Regarding the interaction of the copper and silver, there is no difference between the two levels of copper in case of high silver level of 0.6% while at the low silver weight percentage, the weight loss due to the wear test decreases greatly when the Cu weight percentage increased form 3% to 5% .

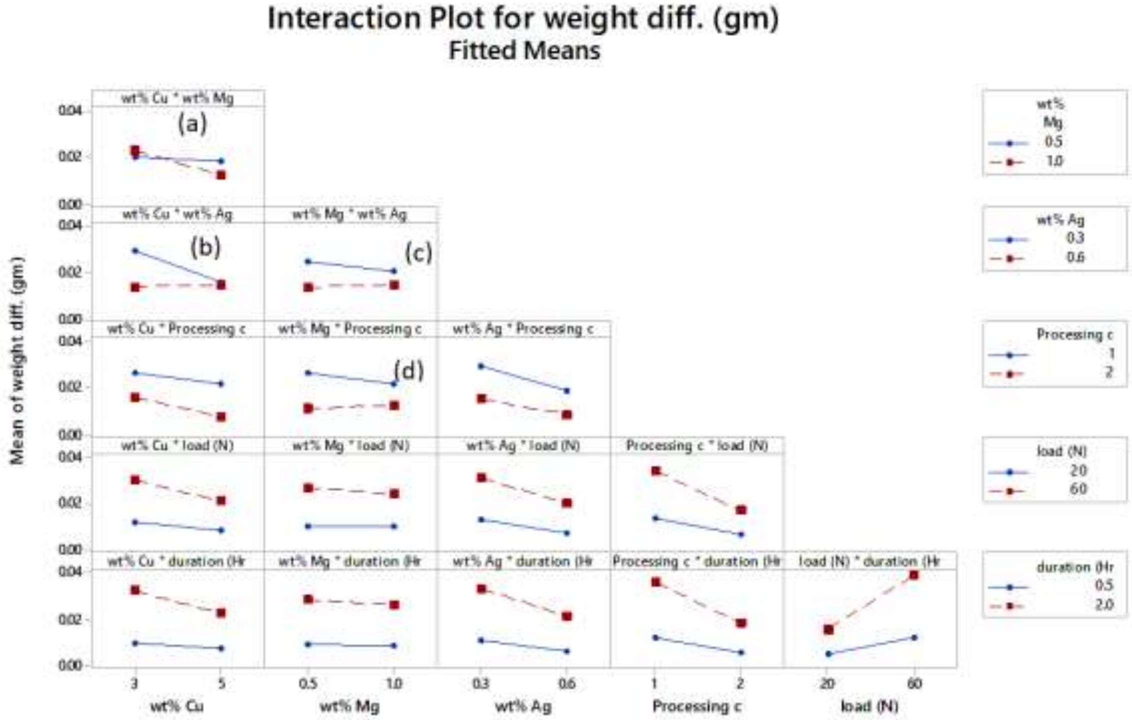
The interactions of magnesium weight percentage with the silver percentage and hardening mechanisms affect significantly the wear resistance. With reference to the interaction of Mg and Ag percentages, the two levels of Mg percentage has no effect on the weight loss when the level of 0.6% Ag was used. Whilst, the high level of Mg of 1% decreases the weight loss compared to the level of 0.5% Mg when the lower level of Ag of 0.3% was used. In case of the peak aged samples, the two level of Mg has the same effect on the weight loss percentage. When the hot roll mechanism was carried for some samples, Magnesium percentage of 1% decreases the weight loss compared to the addition of 0.5% Mg.

Table 5. ANOVA table (if P-Value < 0.05, the factor is significant)

Term	Effect	Coef.	SE Coef.	T-Value	P-Value
Constant		0.018200	0.000528	34.47	0.000
Wt.% Cu	-0.006318	-0.003159	0.000528	-5.98	0.000
Wt.% Mg	-0.001400	-0.000700	0.000528	-1.33	0.194
Wt.% Ag	-0.008418	-0.004209	0.000528	-7.97	0.000
Processing conditions	-0.012200	-0.006100	0.000528	-11.55	0.000
load(N)	0.015431	0.007715	0.000528	14.61	0.000
Duration (hr)	0.018819	0.009410	0.000528	17.82	0.000
wt.% Cu*wt.% Mg	-0.004357	-0.002178	0.000528	-4.13	0.000
wt.% Cu*wt.% Ag	0.007062	0.003531	0.000528	6.69	0.000
wt.% Cu* Proces. conditions	-0.001768	-0.000884	0.000528	-1.67	0.103
wt.% Cu*load (N)	-0.002737	-0.001369	0.000528	-2.59	0.014
wt.% Cu*duration (hr)	-0.003625	-0.001813	0.000528	-3.43	0.002
wt.% Mg*wt.% Ag	0.002431	0.001215	0.000528	2.30	0.027
wt.% Mg* Proces. conditions	0.003063	0.001531	0.000528	2.90	0.006
wt.% Mg*load (N)	-0.001143	-0.000572	0.000528	-1.08	0.286
wt.% Mg*duration (hr)	-0.000782	-0.000391	0.000528	-0.74	0.464
wt.% Ag* Proces. conditions	0.001932	0.000966	0.000528	1.83	0.076
wt.% Ag*load (N)	-0.003012	-0.001506	0.000528	-2.85	0.007
wt.% Ag*duration (hr)	-0.003775	-0.001888	0.000528	-3.58	0.001
Proces. conditions*load (N)	-0.004819	-0.002410	0.000528	-4.56	0.000
Proces. Conditions*duration	-0.005731	-0.002865	0.000528	-5.43	0.000
load (N)*duration (hr)	0.008038	0.004019	0.000528	7.61	0.000
wt.% Cu*wt.% Mg*wt.% Ag	0.003500	0.001750	0.000528	3.31	0.002
Cu Ag* Proces. Conditions	-0.001838	-0.000919	0.000528	-1.74	0.091
wt.% Cu*wt.% Ag*load (N)	0.003018	0.001509	0.000528	2.86	0.007
wt.% Cu*wt.% Ag*duration (hr)	0.003557	0.001778	0.000528	3.37	0.002
Mg Ag* Proces. Conditions	0.002218	0.001109	0.000528	2.10	0.043
wt.% Mg* Proces. Con.*dur.	0.002556	0.001278	0.000528	2.42	0.021
Proces. *load (N)*duration	-0.002512	-0.001256	0.000528	-2.38	0.023



(a)



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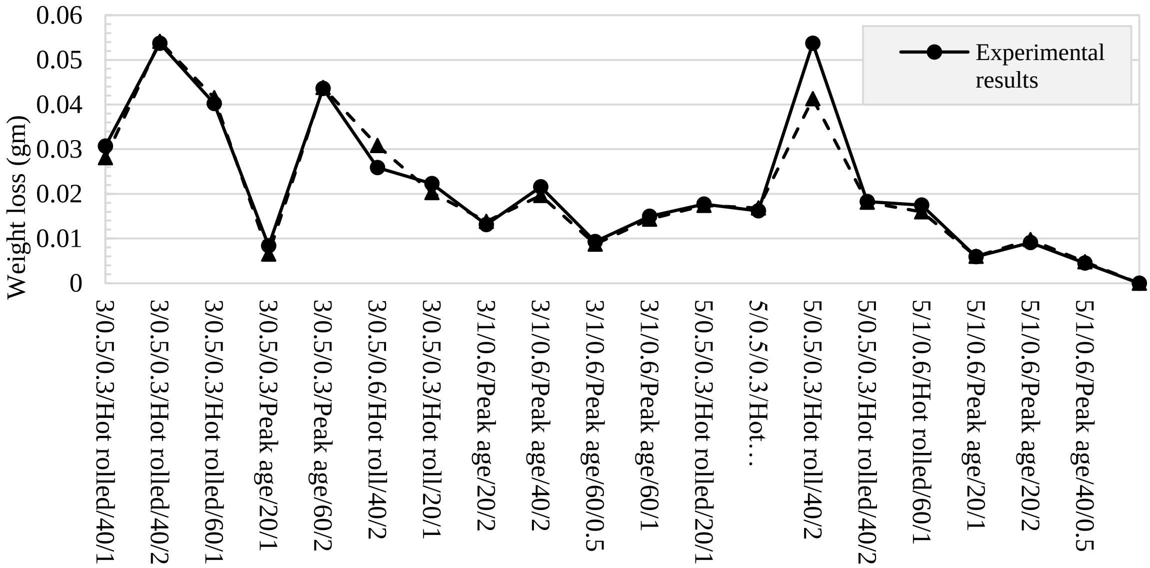

(c)

Figure 6. (a) the main effect plot for the main factors., (b) the interactions plot for the affecting factor on wear weight loss, (c) the comparison between the experimental and predicted results for the weight difference during wear tests.

3.4. Regression model for the weight difference

The regression shown in Eq. (1) was developed form the statistical analysis for the experimental results shown in table 4. A, B, C, D, E, F are the weight percentages of copper, magnesium, silver in addition to the processing condition, applied load, and test duration, respectively. Processing condition levels are the hot rolled substituted in the model with (1) and peak age with (2). The model efficiency is evaluated with the high coefficient of determination (R squared: 97.1%) and adjusted R squared (95%).

This regression model was validated through a set of newly designed experiments similar to the previous experimental setup. The alloys composition levels and the processing conditions were used in this set of validation experiments at different levels of applied loads and testing durations. Table 6 shows the condition levels for the verification experiments. Figure 6 (c) shows the results of the weight difference for the validation experiments due to the wear test compared to the predicted values calculated from the model using Eq. (1). The error between the experimental and predicted values was calculated and then the percentage of this error relative to the experimental results was documented in table 6. In most experiments, the error percentages are within acceptable values. This means that the regression model (Eq. (1)) for the weight loss based on the experimental conditions expresses the conditions effect on the weight loss properly.

Table 6. the conditions levels of the experiments for the model verification

Parameter	Wt.% Cu (A)	Wt.% Mg (B)	Wt.% Ag (C)	Processing Conditions (D)	Load (N) (E)	Duration (Hr) (F)
Level (1)	3	0.5	0.3	Hot rolled	20	0.5
Level (2)	5	1	0.6	peak aged	60	2
Level (3)	--	--	--	--	40	1

Figure (7) confirms the results of the statistical analysis especially shown in the main effect plots. In figure (7-a), the weight loss increases linearly with increasing the test duration. By comparing conditions (1) and (2), the peak aging increases the wear resistance greatly compared to the hot rolling. The interaction between test duration and the processing conditions is also clear, where the reduction of weight loss due to the peak aging at high testing duration (2hr) is higher compared to the reduction at lower testing duration (0.5hr).

Figure (7-b) shows the effect of the applied load, Cu Wt. % and Ag Wt.% on the weight loss due to the wear test. Generally, it is clear that the weight loss increases gradually with increasing the applied load. By comparing conditions (3) and (4), the high percentage of silver increases the material wear resistance greatly. Increasing Ag From 0.3% to 0.6% decreases the weight loss by about 42% at applied load level of 20N and 120% at 60N. By comparing conditions (4) and (5), the increase of the copper percentage decreases the weight loss and increases the wear resistance of aluminum alloy with nearly the same amount along the wear test loading rage.

$$\begin{aligned} Weight\ diff.(gm.) &= -0.1288 + 0.02662\,A + 0.1558\,B + 0.1678\,C + 0.0014\,D \\ &+ 0.001589\,E + 0.0658\,F - 0.02971\,AB - 0.0330\,AC + 0.00375\,AD \\ &- 0.000295\,AE - 0.00953\,AF - 0.2430\,BC - 0.0314\,BD - 0.000114\,BE \\ &- 0.02253\,BF + 0.0175\,CD - 0.002514\,CE - 0.0800\,CF - 0.000032\,DE \\ &- 0.01117\,DF + 0.000519\,EF + 0.0467\,ABC - 0.01225\,ACD \\ &+ 0.000503\,ACE + 0.01581\,ACF + 0.0592\,BCD + 0.01363\,BDF \\ &- 0.000167\,DEF \end{aligned} \tag{1}$$

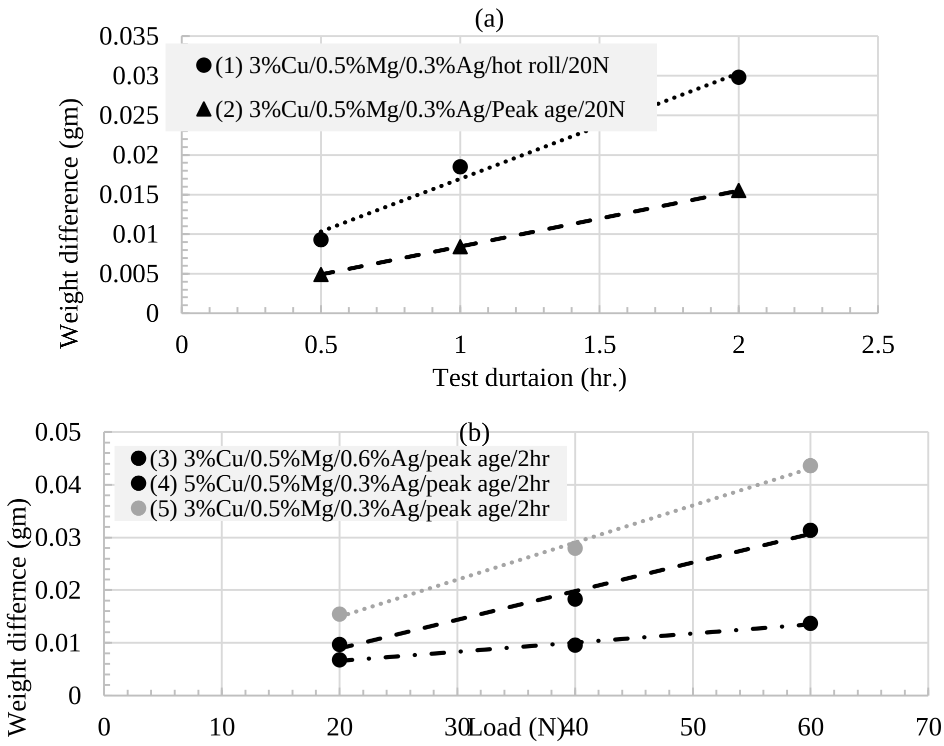

Figure 7. (a) the effect of the test duration on the weight difference at different levels of processing conditions and Mg percentage levels (b) the effect of applied load on the weight difference at different levels of Cu and Ag percentages.

Figure (8) shows the effect of Mg on wear resistance. It is observed that with the higher silver content, increasing the Mg content, from 0.5 to 1.0 wt% improves the wear resistance in the peak aged condition. This is due to the fact that during age hardening of Al-Cu-Mg alloy, addition of Ag to the existing Mg promote the formation of Ω precipitate [23]. In the hot rolled condition increasing the Mg content almost consistently improves the wear resistive and this could be due to the solid solution strengthening effect associated with Mg addition.

Figure (9) shows the effect of the processing conditions on the weight loss for different experimental conditions. Generally, peak aging produces lower weight loss compared to the hot rolled condition. For the sake of evaluating the level of improvement achieved by the different alloying conditions, pure aluminum was cast and cold rolled and then tested under similar wear testing conditions of load (20N - 60 N) and time (0.5hr - 2 hr). The figure confirms the superiority of wear resistance for the eight alloys over that of pure aluminum for all testing conditions. As an example, for the testing conditions of 60 N and 2 hr, the level of improvement calculated as : $\frac{\Delta W_{Al}-\Delta W_{alloy(\#)}}{\Delta W_{Al}}$x 100 yielded a value of 91% by comparing the weight loss of pure aluminum to that of alloy 4 (5Cu-1.0 Mg-0.3Ag) in the peak aged condition.

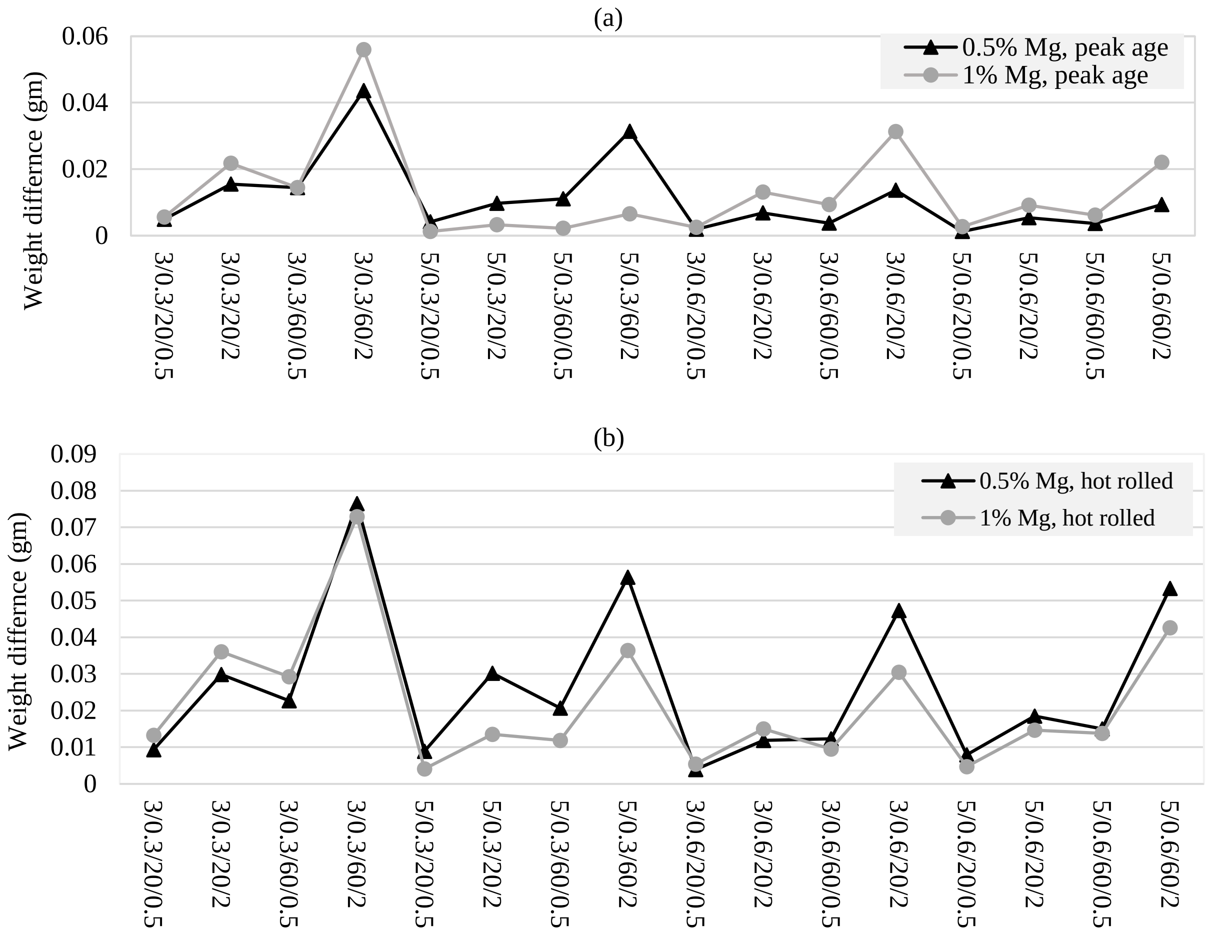

Figure 8. (a) the effect of Mg in case of peak age samples (b) the effect of Mg in hot rolled samples.

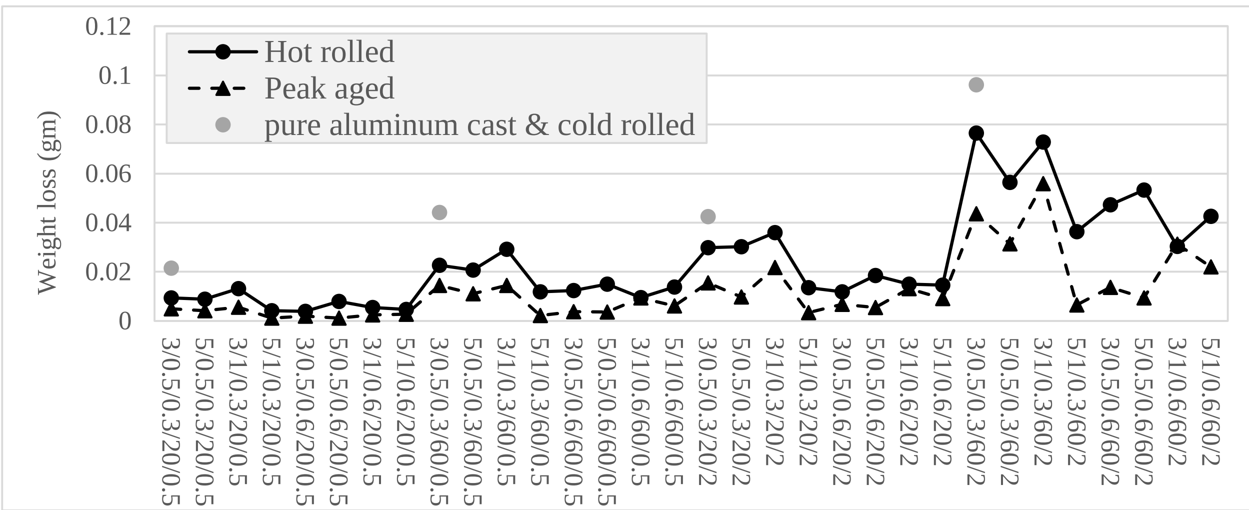

Figure 9. the effect of the processing conditions

4. Conclusions

Eight Al-Cu-Mg-Ag alloys with two levels of copper, magnesium and silver content are cast, homogenized, and hot rolled. Rolled samples were hardened by aging to peak condition. Wear resistance was investigated in terms of the sample weight difference. The wear test was carried out using two levels of applied load and test duration. A regression model was developed and later validated through a new set of experiments. The following conclusions are drawn based on the findings:

1. Addition of copper and silver significantly enhances the wear resistance.
2. Peak aging improves the wear resistance greatly compared to hot rolling.
3. The significant factors and the interaction between the main factors are found using the statistical analysis.
4. All main factors are significant except the magnesium where its significance appears in its interactions with the other factors.
5. Copper has the most effective interactions with the other factors.
6. Peak age effect appears clearly at high applied testing load.
7. A model with high efficiency was derived to correlate with Cu, Mg and Ag percentages, processing conditions in terms of hot rolled or peak aged conditions, applied load and loading time as process parameters and the weight loss as a response variable to indicate the wear resistance. The model is verified experimentally and found that predicted and measured values are close.

CRediT authorship contribution statement

Abdallah Abdelkawy: statistical analysis, Writing – original draft, results analysis. E.A. El-Danaf: conceptualization, Supervising experimental work, results analysis, review draft, Abdulhakim Almajid: supervising experimental work, review draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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