

Effect of Cr Addition on Mechanical Properties and Wear Rate of Cast Al-Cu Alloy

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Abstract

Objectives: This paper investigates the effect of Cr addition on hardness, tensile properties and wear behaviour of Al-4.5Cu alloy A206. **Methodology:** The base alloy was melted and stirred well, fine Cr powder added in required amount, in oil fired pit furnace and poured into a permanent cast iron mold. The cast specimens were solution heat treated at 540°C for 4 hrs and were aged at 170°C for 17 hrs and 20 hrs. The as-cast and aged specimens were subjected to microstructure and EDAX evaluation followed by hardness, tensile and wear testing. **Findings:** The microstructure analysis and EDAX analysis reported an irregularly distributed polyhedral structures that appear blocky due to the phase formation of Al-Cr-Mn-Fe-Si. The hardness, ultimate tensile strength and yield strength were found to increase, reach a peak value and then decrease upon further chromium addition in aged condition. The wear rate decreased with increasing hardness and coefficient of friction remained constant with time. **Application/Improvements:** Evaluate the effect of Cr in Al alloys on the mechanical strength and wear properties.

Keywords: Al-Cu Alloy, Cr Addition, Heat Treatment, Tensile Properties, Wear Rate

1. Introduction

Al-Cu alloys are high strength alloys which are heat treatable used in various applications like cryogenic storage tanks, steering knuckles, engine pistons, brake valves, missile fins, aircraft structures and oil pumps. These alloys have an excellent thermal conductivity, diffusivity properties and electrical conductivity as they are made up of two metals namely Al and Cu that are most widely used in electrical wires and heat sinks. These alloys respond very well to precipitation heat treatment comprising of solution treatment also called as soaking followed by artificial aging. These alloys are used in making shapes that involve external pressure in form of gas, air with the help of a piston by processes such as pressure die casting, squeeze casting, hot isostatic pressing leading to a high strength of the product due to residual plastic stresses created by strain hardening effect. These residual stresses aid in heat treatment by acting as driving force for nucleation of the coherent metastable

θ” solute particles to occur which leads to precipitation hardening.

It has been studied that Al-4.5Cu reaches its peak hardness when homogenized at 540°C for 4 hrs and aged at 170°C for 17 hrs¹. A maximum hardness of 70 HV was observed upon aging for 17 hrs after which the hardness kept reducing. The effect of Cu and Ge on solid clustering of Al-Mg-Si alloys upon aging studied, where it was seen that Cu slows down the clustering kinetics at early stages then it increases². More Mg and Si compared to Ge speed up the kinetics of clustering dependent on the solute vacancy interaction and their jump frequencies. He observed an increase of 5 HV by adding Cu compared to the one without Cu addition. The effect of Mg/Si ratio on the natural aging of Al-Mg-Cu-Si alloys mentions that further natural aging after artificial aging lowers the hardness more in case of high Mg/Si ratio due to coarsening of the β” particles that strengthen the alloy upon aging³. A maximum drop of 14 HV was observed after 2 weeks and 1 day for Mg/Si equal to 2. Solid clustering of

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Cu-Mg solute particles was studied at early stages of high temperature ageing of Al-Cu-Mg alloys containing high Mg/Cu ratio, which increases the peak hardness due to vacancy stabilization observed by positron annihilation spectrometry⁴. It was seen that Mg creates nucleating sites for coherent solutes due to the formation of Cu-Mg vacancy complexes that act as embryo for nucleation⁵. An observation was made that Mn reduces tensile strength of Al-Cu-Mg-Ag A201 alloy as it leads to brittle failure of the alloy due to the presence of a phase $Al_{20}Cu_2Mn_3$ leading to micro-cracking⁶. In Al-Cu-Li, Zr deficiency forms Al_3Zr which saw lesser Zr interaction with the strengthening metastable phase upon homogenization, thus leading to segregation of Zr and formation of separate Zr particles and Zr-Mn particles due the atomic misfit⁷. The effect of equal channel angular pressing (ECAP) processed semi solid casting on A356 was studied⁸. It was observed that ECAP treatment followed by semi-solid casting lead to better hardness and wear properties, where the semi-solid casting had a hardness of 85 HV while the conventional casting only had 75 HV. The wear rate was lesser for the semi-solid cast alloy with a wear rate of 19.4 mm³/m compared to the conventionally cast alloy with a wear rate of 22.6 mm³/m under a load of 20 N and a sliding distance of 5 km. The effect of spray forming on the wear properties of Al-12Si and Al-20Si was studied⁹. The spray formed alloys had superior hardness and better wear properties compared to the chill cast alloys. Their wear analysis is compared later with the findings of the current study.

Effect of Cr addition to Al alloys is not studied by many authors, Cr addition to Al-Cu alloys has not been studied yet. The effect of Cr and Zr (zirconium) alone and together in Al matrix with 0.4% Zr and 0.8% Cr on the hardness upon varying the aging sequence was studied¹⁰. Solution treated Al-0.8Cr had a maximum hardness of 48 HV, upon aging at 450°C the hardness kept decreasing but when 0.4% Zr was added further to the above alloy, a peak hardness of 58 HV was observed when aged at 400°C at 24 hrs. Effect of Cr on the tensile strength of Al secondary foundry alloys was studied for which the maximum tensile strength of 146 MPa was observed for 0.1% Cr addition in the base alloy¹¹.

2. Materials and Processing

The base aluminum alloy Al-4.5Cu was melted in an oil fired pit furnace in an argon atmosphere and alloyed with elements like Mg, Mn, to the specification of A206. Then

the alloys with Cr were prepared by further addition of Cr in form of small chips at 1100°C and stirred well for 45 min and the temperature was lowered to 750°C and poured into a permanent cast iron mold. The alloys thus, obtained were Al-4.5Cu, Al-4.5Cu-0.1Cr, Al-4.5Cu-1Cr, Al-4.5-2Cr.

Small specimens were cut and prepared to a size of 10×10×5 mm size to carry out micro-structure and micro-hardness testing. For observing the micro-structure, the specimens were polished and etched using 0.5% HF solution. The specimens were observed under Lyzer Instruments optical microscope at 100X magnification, micro-structures were taken using Dewinter software.

Specimens were prepared for tensile test as per ASTM B557M with a gauge diameter of 6.25 mm and gauge length of 31.75 ± 0.25 mm. Specimens for hardness and tensile test were solution treated at 540°C for 4hrs followed by aging at 170°C for 17 and 20 hrs. All the alloys were tested in as cast condition, after solution treatment, and after aging. Hardness was measured using Wolpert Wilson (Germany) Vickers hardness tester at 500 gm load. Tensile test was conducted using Auto-Instruments UTM.

Ducom pin-on-disc tribometer was used, for conducting dry sliding wear. The disc used was EN 31 alloy steel that had a hardness of 60 HRC, surface roughness of 0.15µm. The specimens for the wear rate were machined to a diameter of 6 mm and length of 32 mm with a hemispherical end. The testing was carried out as per ASTM G99 standards with a sliding distance of 1.5 km for 10 min and a load of 2kg. The track width was taken as 110 mm, rpm of 494 was calculated.

3. Results and Discussion

The results obtained to evaluate various properties of the alloys in various conditions are mentioned as follows:

3.1 Chemical Composition Analysis

The chemical composition of the base alloy was found using emission spectrometer which is given in Table 1.

3.2 Microstructure Examination

The as cast micro-structure of the base alloy is shown in Figure 1 that shows dendritic structures. Homogenization and aging leads to disappearance of the dendrites leading to the formation of nuclei of the coherent metastable θ'' solute particles along with appearance of grain boundaries as shown in Figure 2. The coherent particles lead

to the increase in hardness upon aging to a certain peak time beyond which a decline in the hardness is observed showing signs of overaging as shown in Figure 3 where the grains are coarser than in Figure 2. The intermetallic phase formed along the grain boundaries is CuAl_2 phase that is also formed while casting. The micro-structure of the Cr added alloy show blocky patches that are the phases formed by Cr, Mn, Fe, Si with Al as intermetallics as seen in all the micrographs of the alloys that are added with Cr.

Table 1. Spectroscopy result of the base alloy

Elements	% Composition
Al	94.75
Cu	4.5
Mg	0.19
Mn	0.22
Ti	0.19
Fe	0.1
Si	0.04



Figure 1. As cast base alloy.

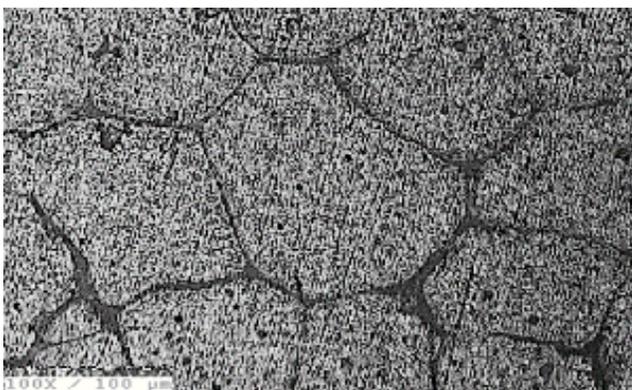


Figure 2. Base alloy- 17hrs of aging.

As cast Al-4.5Cu-0.1Cr does not show any appearance of grain boundaries, only dendrites are seen as in Figure 4. The effect of aging Al-4.5Cu-0.1Cr for 17 hrs as shown in Figure 5 has not resulted in the appearance

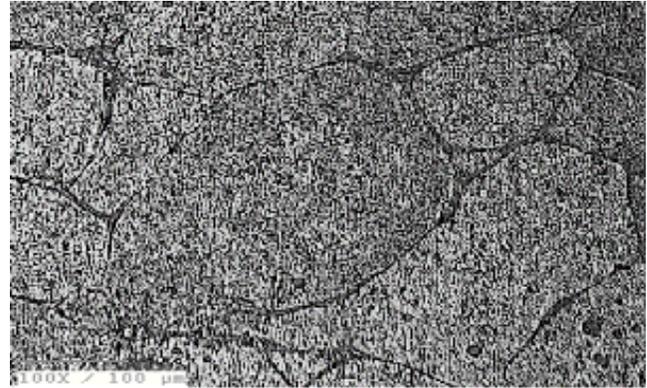


Figure 3. Base alloy aged at 20 hrs.

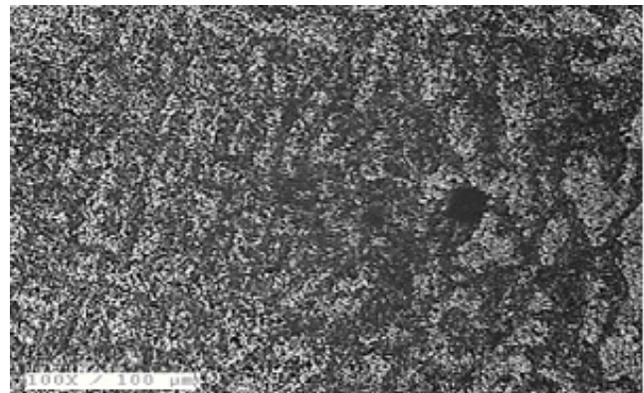


Figure 4. Al-4.5Cu-0.1Cr as cast.

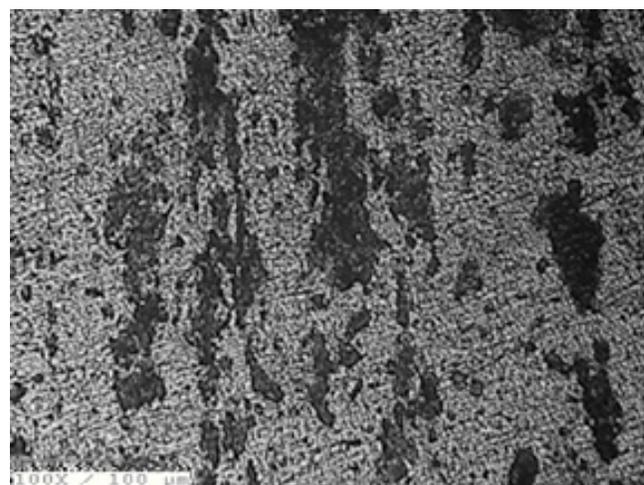


Figure 5. Al-4.5Cu-0.1Cr aged for 17 hrs.

of grain boundaries but dendrites have disappeared and small coherent θ'' nuclei are visible. These phases result in the strengthening effect of the alloy increasing the hardness.

Figure 6 shows the microstructure of Al-4.5Cu-0.1Cr alloy. From Figure 6 it is understood that further aging for 20 hrs improves the hardness of the alloy due to formation of more fine coherent metastable phases, and it also results in formation of grain boundaries.

3.3 Identification of Phases

Energy Dispersive Spectrometry was used to find out the phases present in the matrix and ensure the amount of Cr added meets the desired value. From the phases formed obtained from EDS and the hardness result obtained it is concluded that at higher concentrations of Cr it forms the brittle, irregularly distributed brittle Al-Cr-Mn-Fe-Si phase (which acts as a site of stress concentration mentioned in) and $Al_{20}Cu_2Mn_3$ as observed, thus at lower percentage it is not formed and it participates in solid solution strengthening in addition to the precipitation hardening effect of aging which sees high hardness for Al-4.5Cu-0.1Cr. Figure 7 shows the EDS plot of concentration vs the work potential for Al-4.5Cu-0.1Cr alloy. Figure 8 shows the various element compositions in weight percent and atomic weight percent. It is seen that the Cr content is as desired which is 0.1%. Figure 9 shows the EDS plot for Al-4.5Cu-1Cr, Figure 10 shows the composition of the constituent alloy with Cr content almost equal to 1%. In Figure 11, the EDS plot of the element concentration peaks is shown for Al-4.5Cu-2Cr, Figure 12 shows its chemical composition without much variation in Cr content from the desired value of 2%.

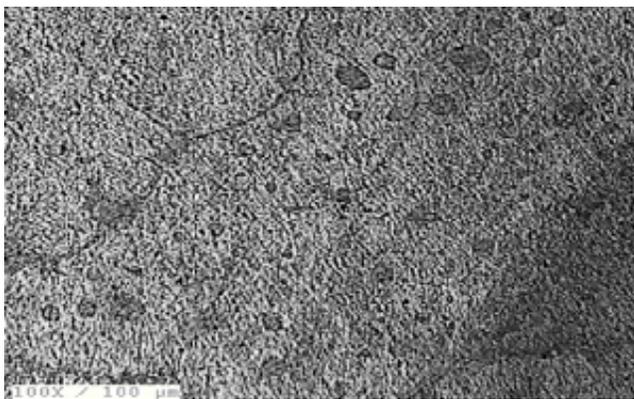


Figure 6. Al-4.5Cu-0.1Cr aged 20 hrs.

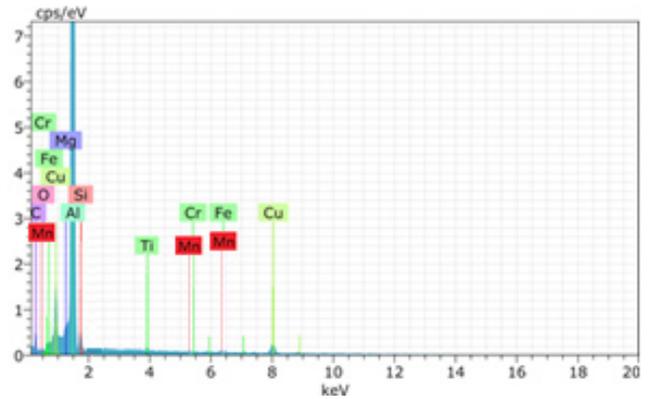


Figure 7. EDS result for Al-4.5Cu-0.1Cr.

Spectrum: Objects 783				
El	AN	Series	norm. C [wt.%]	Atom. C [at.%]
Al	13	K-series	93.04	97.62
Mn	25	K-series	0.17	0.08
Cu	29	K-series	4.37	1.95
Fe	26	K-series	0.09	0.03
Ti	22	K-series	0.15	0.08
Mg	12	K-series	0.15	0.17
Cr	24	K-series	0.13	0.07
Total:			100.00	100.00

Figure 8. Composition of Al-4.5Cu-0.1Cr.

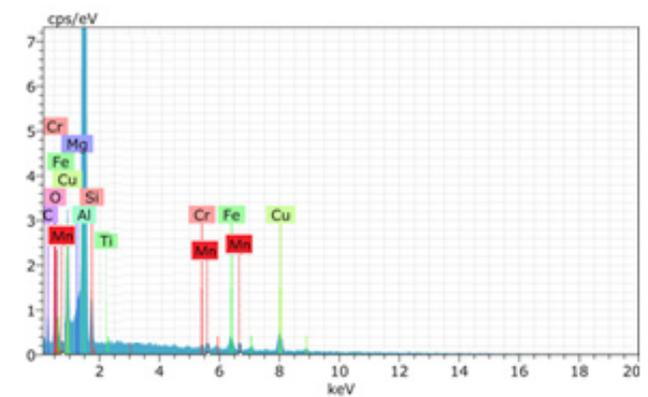


Figure 9. EDS result for Al-4.5Cu-1Cr.

3.4 Hardness

The hardness dependence of the alloy on Cr content is shown in Figure 13. The legends show the various percentages of

Spectrum: Objects 783				
El	AN	Series	norm. C [wt.%]	Atom. C [at.%]
Al	13	K-series	93.73	97.07
Mn	25	K-series	0.19	0.08
Cu	29	K-series	4.50	1.95
Fe	26	K-series	0.11	0.06
Ti	22	K-series	0.12	0.08
Mg	12	K-series	0.15	0.18
Cr	24	K-series	1.20	0.57
Total:			100.00	100.00

Figure 10. Composition of Al-4.5Cu-1Cr.

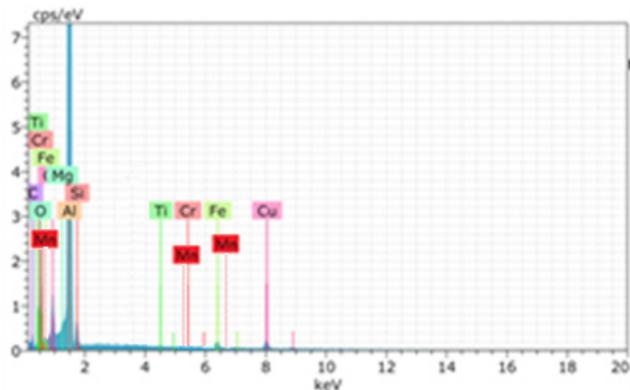


Figure 11. EDS result for Al-4.5Cu-2Cr.

Spectrum: Objects 783				
El	AN	Series	norm. C [wt.%]	Atom. C [at.%]
Al	13	K-series	93.01	96.61
Mn	25	K-series	0.18	0.08
Cu	29	K-series	4.50	1.96
Fe	26	K-series	0.09	0.03
Ti	22	K-series	0.13	0.08
Mg	12	K-series	0.18	0.23
Cr	24	K-series	1.91	1.01
Total:			100.00	100.00

Figure 12. Composition of Al-4.5Cu-2Cr.

Cr added in the figure. In as cast condition there is not a very significant effect of Cr on the hardness. It is seen that for 0.1% addition of Cr highest hardness upon aged condition is achieved and further addition of Cr reduces the hardness. The hardness dependence on the alloy with Cr content is also shown. In as cast condition there is not a very significant effect of Cr on the hardness. Solution treatment and aging increase the hardness of the alloys as compared to as cast condition. The role played by Cr is consistent with in behaving as a solid solution strengthener. Figure 14 compares previous findings with the current study. Al-4.5Cu-0.1Cr is superior to Al-0.4Zr-0.8Cr and Al-4.5Cu observed as 70 HV when aged for 17hrs.

3.5 Tensile test

Tensile test conducted also showed a similar pattern as observed in case of hardness, which is evident from Figure 15 which shows the variation in the ultimate tensile strength for various treatments and varying Cr contents.

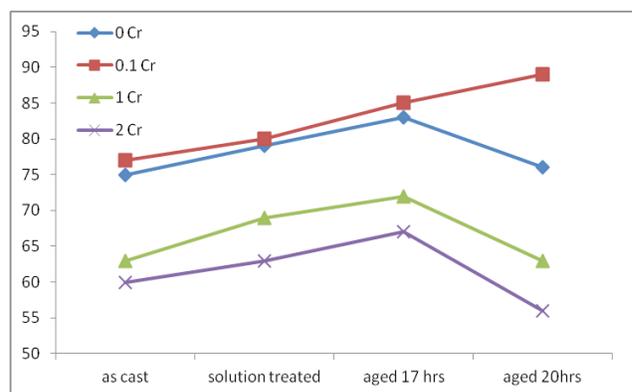


Figure 13. Hardness variation with heat treatment and Cr addition.

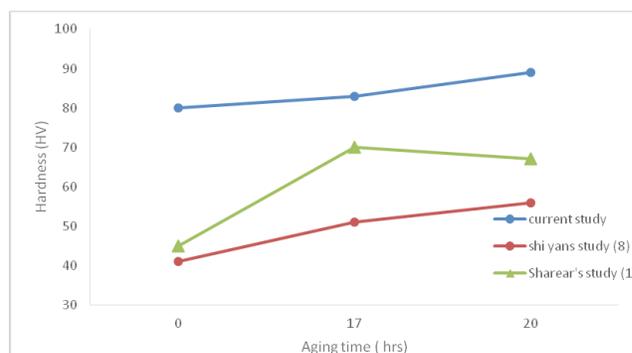


Figure 14. Hardness comparison of previous studies with current study.

Even the yield strength varies in a similar way. This result is consistent with pattern observed in¹¹ on the effect of Cr on the tensile strength of Al secondary foundry alloys. The ductility was found to continuously decrease with the addition of Cr, but the effect of heat treatment has no adverse effect on the ductility. The highest ductility was observed for the aged base metal with 5.6% elongation, compared to 5% in as cast condition. Least ductility was observed for as cast Al-4.5Cu-2Cr with 3.5% elongation and it increases to 3.9% upon aging.

3.6 Wear Analysis

The following section discusses all the observations made from pin-on-disc wear test.

3.6.1 Wear rate

The wear test was conducted for the base alloy and the alloy that gave the highest hardness and tensile strength, which was found to be Al-4.5Cu-0.1Cr aged for 20 hrs. Figure 16 shows the wear plot of Al-4.5Cu-0.1Cr (aged for 20hrs). It

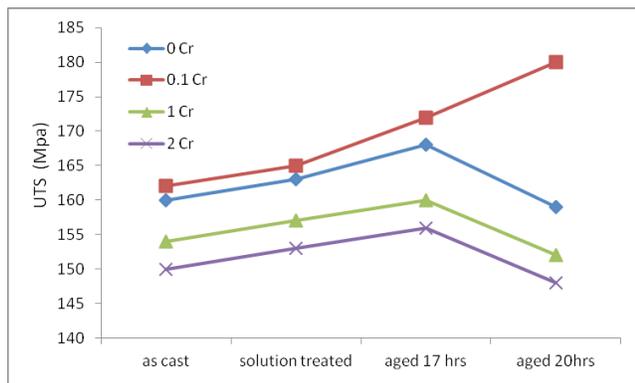


Figure 15. The effect of Cr addition on various conditions.

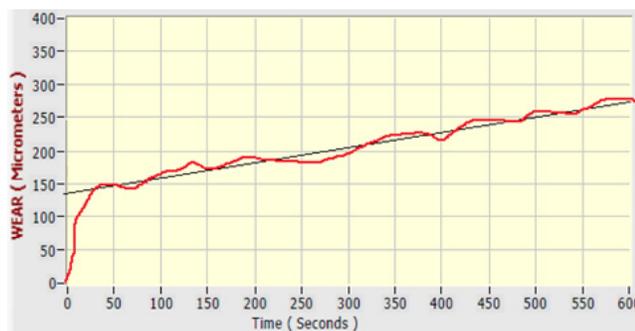


Figure 16. Wear plot for Al-4.5Cu-0.1Cr.

is seen that 20 hrs aged Al-4.5Cu-0.1Cr wears lesser than the as cast base alloy. Thus the wear rate decreases with increasing hardness¹². The wear rate (k_v) of the specimens were calculated in mm^3/m as specified in equation 1, i.e. the ratio of volume worn out (ΔV) and sliding distance (s) thus the equation is:

$$k_v = \frac{\Delta V}{s} =_{1.5 \text{ km}} \quad (1)$$

The base alloy had a wear rate of $9.5 \times 10^{-4} \text{ mm}^3/\text{m}$ whereas the heat treated chromium added alloy Al-4.5Cu-0.1Cr was observed to have a wear rate of $7.04 \times 10^{-4} \text{ mm}^3/\text{m}$ under a load of 20 N and a sliding speed of 2.5 m/s.

The least wear rate obtained for spray formed Al-20Si (SF) alloy out of the other Al-Si alloys studied, is compared with the alloys studied in the current work, shown in Figure 17. It is seen that Al-Cu alloys wear lesser than Al-Si alloys under a load of 20 N and sliding speed of 2.5 m/s.

The coefficient of Friction graph for the 20 hrs aged Al-4.5Cu-0.1Cr is shown in Figure 18. It is seen that it

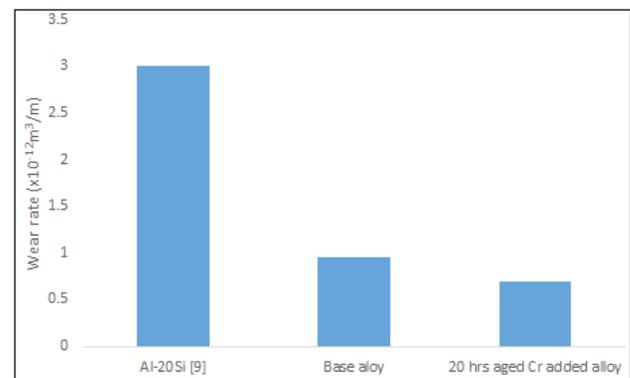


Figure 17. Wear rate comparison of K. Raju with current study.



Figure 18. Coefficient of friction vs time for Al-4.5Cu-0.1Cr.

remains constant with time. It is seen to be around 0.42. The coefficient of friction of the base alloy was 0.4.

4. Conclusion

The conclusions that are drawn from the results are:

- Cr when added at an amount of 0.1% to Al-4.5Cu increases the peak aging time, but reduces the peak aging time of the alloy when further added.
- Al-4.5Cu-0.1Cr is seen to have higher hardness and tensile strength though not very significant in as cast condition but has resulted in solid solution strengthening in addition to precipitation hardening.
- Higher contents of Cr forms a phase with Al and other alloys present to act as stress concentrator leading to failure at lower stress levels.
- Wear rate was observed to decrease with increasing hardness¹²; coefficient of friction remains constant with times which was around 0.4 for the base alloy and 0.42 for Al-4.5Cu-0.1Cr.

5. References

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