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The effect of enhanced solid solubility on the microstructure and mechanical properties of Al-Cr solid solution by powder metallurgy process

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Abstract

Al-Cr alloys are usually used in home appliances, automotive, marine and aerospace applications as these possess superior properties like high strength-to-weight ratio, good corrosion resistance and workability. In Al-Cr alloys, chromium has severely limited strengthening effects due to its relatively low solid solubility in the aluminium matrix. The high content of chromium in Al matrix leads to the discontinuous precipitation with coarse Al_7Cr intermetallic phase. In this study, powder metallurgy (P/M) technique followed by microwave assisted sintering was adopted for the synthesis of Al-xCr (x = 0, 2.5 and 5 wt%) alloys to enhance the solid solubility of Cr. Specimens were sintered at 560 ºC for one hour and cooled inside the microwave atmosphere. Sintered specimens were hot extruded and characterized in terms of the mechanical properties. Mechanical characterization showed that the addition of Cr as alloying element leads to an increase in microhardness, 0.2% tensile yield strength (TYS) and ultimate tensile strength (UTS) of the Al-alloy. However, the ductility of the Al-alloys was significantly decreased by the incorporation of Cr particulates in the aluminium matrix.

Keywords: Al-Cr system, powder metallurgy technique, hybrid microwave sintering, mechanical properties.

Introduction

An increasing demand for the fuel consumption reduction and exhaust emissions limitation in automobile and aerospace industries has led towards an increased trend of using light alloys for structural components in many production areas [1]. The high performance and low specific weight materials are required in a very vast range of applications, for example in thermal management and precision devices. Aluminium (Al) alloys have good mechanical properties, high thermal conductivity and are easy to cast [2]. The density of aluminium is only 2.7 g/cm^3, which is approximately one-third of the steel (7.83 g/cm^3) [3]. Aluminium has been found as the most common metal among many other metals on the earth, constituting nearly about eight percent of the earth's crust [4]. Properties like lightness, strength, conductivity, formability, durability and finishability made aluminium alloys different from the other metallic alloys [5].

Al-based alloys reinforced by different metals like nickel (Ni), magnesium (Mg), chromium (Cr), cobalt (Co), titanium (Ti) etc. have been successfully fabricated by the casting methods or by powder metallurgy techniques [6][7]. Many important properties of an alloy, such as its mechanical strength, creep resistance and magnetic properties are affected by the presence of the other components in the metal matrix and their orientations in the microstructure. The main purpose of adding Cr in Al alloys is a prevention of recrystallization and grain growth that refine the grains [8]. If during casting, the Cr amount exceeds the minimum liquid solubility, then undesirable coarse Al_7Cr constituent will be formed in the multi-component alloy [9]. In spite of many investigations concerning the constitution of the Al-Cr alloy system, it is not known sufficiently as yet. Among all the aluminium alloys, Al-Cr system is mainly used as primary material for an aircraft's structural components, like frames for example [10]. High-strength aluminium alloy parts become increasingly necessary for aircraft and automotive parts due to significant weight savings [11].

Some of the previous methods of producing aluminium-chromium alloys with different compositions have been studied. Audier et al. [12] used three Al-Cr alloys in which Cr was varying from 17, 20 to 25 At% for verifying the lattice structure and phase of Al-Cr compounds. The alloys were prepared by melting the constituent elements in an inductive crucible under an argon atmosphere. Cao et al. [13] produced Al-Cr alloy ingots of around 20 g with composition of $Al_{11}Cr_2$ by melting at 1100 °C for 10 hrs. Subsequently, the ingots were cooled at different rates of 300, 100, 20 and 2 °C/h. Stein et al. [14] prepared 5Al-Cr alloys from the highly pure metals by using arc-melting process in an argon gas atmosphere. After that, the melted alloys were drop cast into cylindrical shaped copper mould. Hu et al. [15] prepared three specimens of the Al-Cr binary alloys with the 23, 25 and 27 At% Cr composition. Each specimen had a weight equal to 1 g, approximately. Specimens were prepared in an arc-melting furnace with the argon gas atmosphere. In order to improve the homogeneity of specimens, they were five times re-melted. Almeida et al. [16] used 14.9 ± 5.5 wt.% Cr content for the preparation of the Al-Cr alloys by using laser alloying technique. The laser melting was performed at scanning speeds of 5 and 40 mm/sec using CO_2 laser with beam power of 2 kW. Specimens were re-melted to eliminate undissolved Cr and for microstructure homogenization. However, after this formation mechanism, a discontinuous precipitations were found. Grushko et al. [17] has also produced Al-Cr alloy system with constitution of above 75 At% of Al. The constituent elements were melted by levitation induction in a water-cooled crucible which was in an argon atmosphere. The variety of manufacturing processes and significantly better mechanical properties of aluminum-based materials made them promising for industry usage, and therefore, more research on new materials development should be performed in the future.

Therefore, this research is focused on developing a high strength aluminium alloys with enhanced mechanical properties by designing a new compositions of Al alloys. A design of new alloy will be achieved by adding the particular alloying element (Cr) which exhibits very low solubility in aluminium even at elevated temperature. Powder metallurgy technique will be used for producing these alloys. Among the advantages of this technique one can indicate an extension of solid solubility and refinement of grain sizes. The extension of solid solubility of Cr, that belongs to the low diffusivity elements, in aluminium will enable to form the high strength alloys with better mechanical properties.

Materials and Methods

The materials synthesized in this project were the aluminium based alloys with Cr as alloying element. The aluminium powder used was of 18 μm average grain size (Alfa-Aesar company). The chromium powder used was of 6 μm average grain size (Alfa-Aesar). The scanning electron microscopy (SEM) images of the Al and Cr powders are shown in the images a and b of Figure 1, respectively.

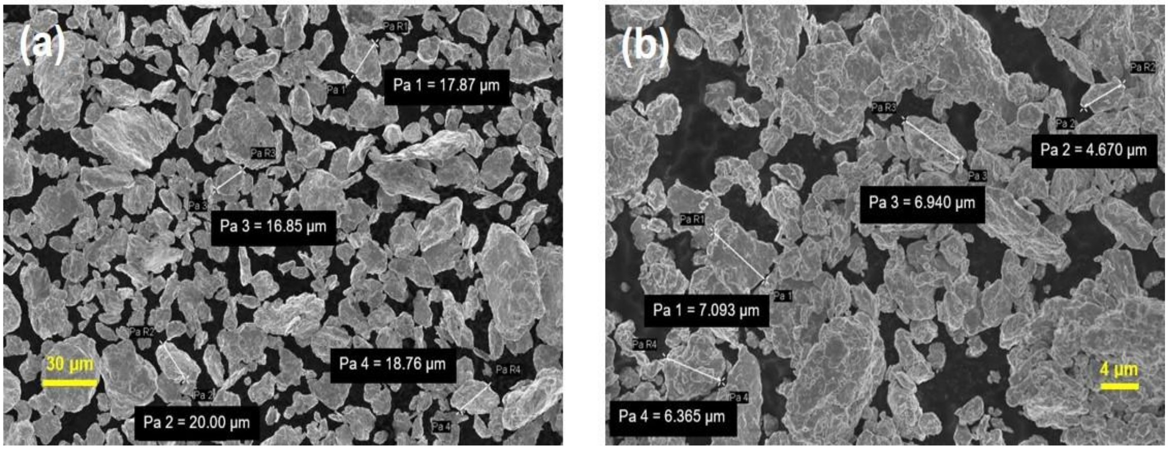

Fig. 1. SEM images of the aluminium (a) and chromium powder (b)

Three types of specimens were fabricated by using Powder Metallurgy microwave assisted sintering route: pure Al, Al-2.5% Cr, Al-5.0% Cr (all are in wt.%). Firstly, weighted powders were put into a ball-milling jar with ball to powder weight ratio (BPR) of 10:1. Balls used in this blending process were of stainless steel and had 5 mm diameter. The milling was performed at 200 rpm for 2 hrs. Subsequently, the mixed powders were filled into the steel die. The quantity of powders feed required was calculated based on the alloy elements density and desired size of the green compacts. The die was compressed under a pressure of 550 MPa using the hydraulic universal testing machine (UTM) at room temperature. The load was maintained about 1 minute on the die, and then, the billets were ejected safely from the die. The size of cylindrical green compacts manufactured was about 36 mm in diameter and 36 mm in height. The billets obtained after compaction were uniform and with no agglomeration or segregation observed. All the green specimens compacted in solid form were kept inside the microwave for sintering. Then, the specimens were heated up to 560°C and annealed at this temperature for 1 hour, and subsequently, allowed to cool inside the microwave atmosphere. Sintered cylindrical billets of 36 mm diameter were hot extruded at 350°C temperature into 8 mm diameter of cylindrical rod by using Hot extrusion machine. The extrusion ratio (which is the ratio of initial to final cross-sectional area) for this process was kept equal to 20.25:1. After hot extrusion, the cylindrical rods were cut into pieces of required length by using wire EDM. Microhardness measurements of the specimens were conducted to obtain the adequate hardness values for both the matrix and interface of matrix-reinforcement. A digital microhardness tester which was equipped with an indenter of facing angle 136° was used for this test. The Vickers hardness test was carried out at room temperature (25°C) with the loading speed of 50 μm/s, loading force of 0.10 Kgf, and dwell time of 10 s. Tensile properties were determined by using an automated universal testing machine (UTM). The dog-bone tensile specimens were made by using the mini-CNC lathe machine. The specimens were of 25 mm of gauge length and 5 mm of nominal diameter, Figure 2. Strain rate used for this test was equal to 1 mm/min for all specimens investigated. Tensile tests were carried out at room temperature (25°C). The following mechanical properties were determined using the tensile stress-strain curves: (a) 0.2 % tensile yield stress; (b) ultimate tensile strength; and (c) ductility.

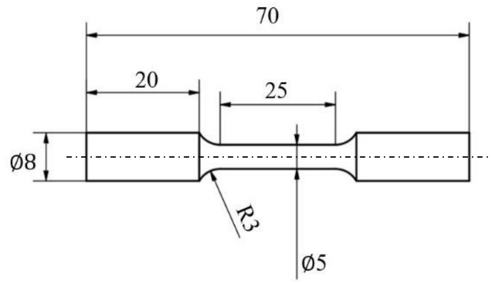

Fig. 2. Engineering drawing of the specimen used in tensile tests (units in mm)

Results and Discussion

Five indentations were carried out for each specimen in order to determine microhardness either at the matrix or reinforcement interface. The average values are shown in Figure 3 with error bars reflecting the calculated standard deviation. An increasing trend of hardness with the increase of percentage content of Cr in aluminium is nearly exponential, as it is shown in Figure 3. The percentage increase in hardness for alloy containing 5% Cr particulates (90.89%) was higher than that for 2.5% Cr particulates (28.83%) obtained. Such result can be attributed to the higher content of the harder reinforcement particulates of Cr, and as a consequence, more localized matrix deformation during indentation.

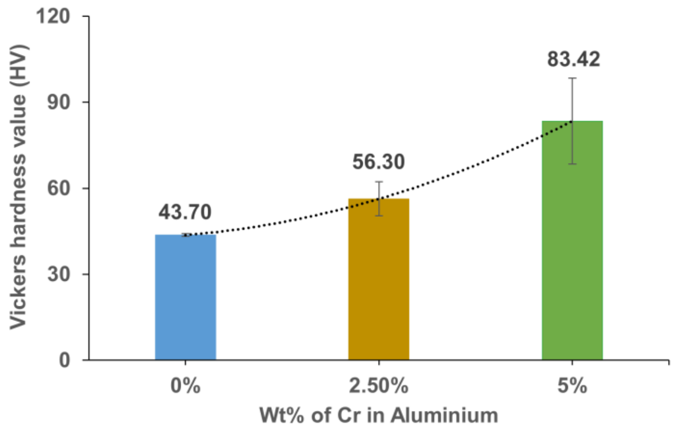

Fig. 3. Variation in Vickers hardness

The stress-strain characteristics of the three specimens: pure Al, Al-2.5%Cr, Al-5.0%Cr are plotted in Figure 4 using the data obtained from the automatic UTM. It is clearly seen, that the pure aluminium formed by the powder metallurgy exhibits a very good ductility, nearly 22%. The results captured from the tensile tests are shown in Table 1. The conventional yield point (0.2% TYS) for the Al-2.5% Cr is around 50% higher than that for the pure Al obtained. Similar result was achieved for Al-5.0% Cr, however, in comparison to the Al-2.5% a slight decrease of this parameter can be observed. Similar tendency represents variation of the UTS; however, differences are significantly lower (around 16%). The ductility is significantly reduced for both alloys as compared to the pure aluminium. The increase in the 0.2% TYS and UTS of aluminium by the addition of Cr particles can be attributed due to the following reasons:

- good interfacial integration that enables efficient load transfer from the matrix to reinforcement;
- uniform distribution of the Cr particles in the Aluminium matrix;
- small size of the Cr particles.

Tab. 1. The results of tensile tests

Specimen	0.2% TYS (MPa)	UTS (MPa)	Ductility (%)
Pure Al	62 ± 2.0	127 ± 4.5	22 ± 1.1
Al-2.5%Cr	93 ± 1.9	145 ± 8.8	9 ± 0.6
Al-5.0%Cr	86 ± 2.5	147 ± 8.6	8 ± 0.5

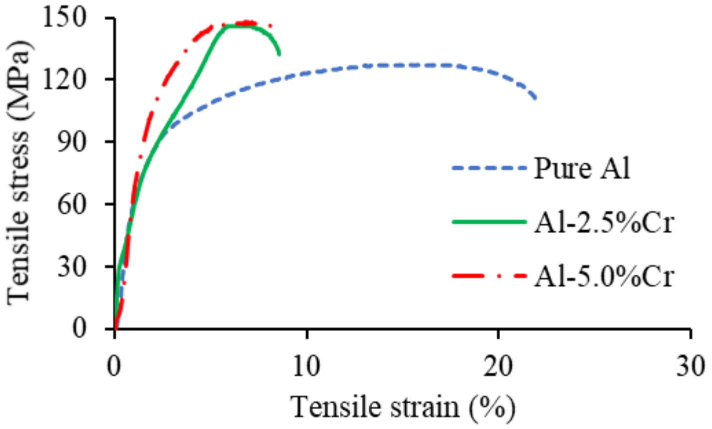

Fig. 4. Tensile characteristics of the pure Al and two aluminium alloys tested

Figure 5 shows the SEM images of both sides of the fractured specimens obtained for the pure Al, Al-2.5%Cr and Al-5.0%Cr. The pure Al showed classic 'cup and cone' fracture that is typical for ductile materials (Figure 5a-b), where a tiny micro-voids are generated near the center, and then, spread out towards the external surface. Contrary to the pure Al, both Al-2.5%Cr and Al-5.0% Cr showed characteristic brittle fracture (Figures 5c-d and 5e-f, respectively) which is in agreement with their very low elongations. The fracture surfaces of Al-2.5%Cr and Al-5.0%Cr exhibited a sharp and bright edges with cleavage-like or orange-peel texture, with no evidence of necking prior to fracture. Furthermore, a few cracked particles and some small shallow dimples can be seen on the surfaces. These are a clear signs of the brittle fracture.

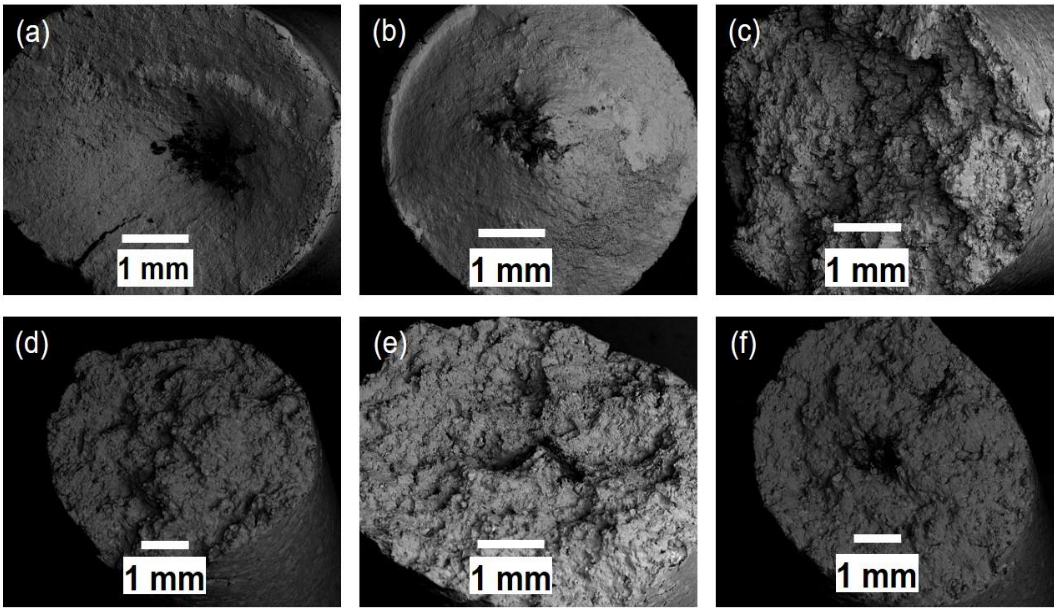

Fig. 5. SEM images of fractured specimens under tension for the pure Al (a, b); Al-2.5%Cr (c, d) and Al-5.0%Cr (e, f)

Conclusions

The powder metallurgy (P/M) technique can be successfully applied to synthesize the Cr reinforced Al alloys, which lead to extension of solid solubility of Cr in Al. The sintered specimens of Al-Cr alloys displayed extremely high Vickers hardness values at room temperature and significant increase of hardness, that exhibited an exponential character with the increase of Cr content. An addition of Cr to Al matrix increased the 0.2 % TYS and UTS. An opposite effect was observed in the case of ductility of the alloys which decreased significantly in comparison to the pure Al. Both, Al-2.5%Cr and Al-5.0%Cr showed nearly the same level of total strain. The fracture surfaces exhibited the brittle character that corresponds well with the low plastic deformation of these alloys during tensile tests.

References

[1] J. Hirsch, "Aluminium in innovative light-weight car design," *Mater. Trans.*, vol. 52, no. 5, pp. 818–824, 2011.

[2] W. S. Miller *et al.*, "Recent development in aluminium alloys for the automotive industry," *Mater. Sci. Eng. A*, vol. 280, no. 1, pp. 37–49, 2000.

[3] J. R. Davis, *Aluminum and aluminum alloys*. ASM international, 1993.

[4] R. Cobden and A. Banbury, "Aluminium: physical properties, characteristics and alloys," *Talat Lect.*, vol. 1501, no. 11, pp. 144–155, 1994.

[5] C. S. Witharamage, J. Christudasjustus, and R. K. Gupta, "The Effect of Milling Time and Speed on Solid Solubility, Grain Size, and Hardness of Al-V Alloys," *J. Mater. Eng. Perform.*, vol. 30, no. 4, pp. 3144–3158, 2021.

[6] C.-S. Kim, K. Cho, M. H. Manjili, and M. Nezafati, "Mechanical performance of particulate-reinforced Al metal-matrix composites (MMCs) and Al metal-matrix nano-composites (MMNCs)," *J. Mater. Sci.*, vol. 52, no. 23, pp. 13319–13349, 2017.

[7] S. K. Thakur and M. Gupta, "Improving mechanical performance of Al by using Ti as reinforcement," *Compos. Part A Appl. Sci. Manuf.*, vol. 38, no. 3, pp. 1010–1018, 2007.

[8] Y. Liang, C. Guo, C. Li, and Z. Du, "Thermodynamic modeling of the Al–Cr system," *J. Alloys Compd.*, vol. 460, no. 1–2, pp. 314–319, 2008.

[9] J. L. Murray, "The Al-Cr (aluminum-chromium) system," *J. phase equilibria*, vol. 19, no. 4, p. 367, 1998.

[10] P. Rambabu, N. E. Prasad, V. V Kutumbarao, and R. J. H. Wanhill, "Aluminium alloys for aerospace applications," *Aerosp. Mater. Mater. Technol.*, pp. 29–52, 2017.

[11] T. Maeno, K. Mori, and R. Yachi, "Hot stamping of high-strength aluminium alloy aircraft parts using quick heating," *CIRP Ann.*, vol. 66, no. 1, pp. 269–272, 2017.

[12] M. Audier, M. Durand-Charre, E. Laclau, and H. Klein, "Phase equilibria in the Al□ Cr system," *J. Alloys Compd.*, vol. 220, no. 1–2, pp. 225–230, 1995.

[13] B. B. Cao and K. H. Kuo, "Crystal structure of the monoclinic η-Al11Cr2," *J. Alloys Compd.*, vol. 458, no. 1–2, pp. 238–247, 2008.

[14] F. Stein, C. He, and I. Wossack, "The liquidus surface of the Cr–Al–Nb system and re-investigation of the Cr–Nb and Al–Cr phase diagrams," *J. Alloys Compd.*, vol. 598, pp. 253–265, 2014.

[15] B. Hu, W.-W. Zhang, Y. Peng, Y. Du, S. Liu, and Y. Zhang, "Thermodynamic reassessment of the Al–Cr–Si system with the refined description of the Al–Cr system," *Thermochim. Acta*, vol. 561, pp. 77–90, 2013.

[16] A. Almeida and R. Vilar, "Al–Al7Cr eutectic in Al–Cr alloys synthesized by laser alloying," *Scr. Mater.*, vol. 63, no. 8, pp. 811–814, 2010.

[17] B. Grushko, B. Przepiórzyński, and D. Pavlyuchkov, "On the constitution of the high-Al region of the Al–Cr alloy system," *J. Alloys Compd.*, vol. 454, no. 1–2, pp. 214–220, 2008.