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EVOLUTION OF THE MECHANICAL, ELECTRICAL AND THERMAL PROPERTIES OF AL-MN-XCU ALLOYS BY THE VERTICAL BRIDGMAN METHOD

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ABSTRACT

Aluminum alloy is used in many areas of industry due to its superior physical and mechanical properties. The discovery of new properties increases the applications of these alloys day by day. In this work, the effect of Cu content (0.5, 1.5 and 5 wt.%) and growth velocity on the microhardness, ultimate tensile strength, electrical resistivity, enthalpy and specific heat properties of the directionally solidified Al–Mn eutectic alloy have been investigated. Al-1.9Mn-xCu (x=0.5, 1.5, 5 wt.%) samples were prepared from pure metals under the vacuum and these alloys were directionally solidified under constant temperature gradient (7.1 K/mm) and four different growth rates (8.3, 41.6, 166.3 and 978 μm/s) in a vertical Bridgman–type growth apparatus. Measurements of microhardness, ultimate tensile strength and electrical resistivity of the samples were carried out and then expressed as functions of growth velocity and Cu content. Additionally, the enthalpy of fusion and specific heat capacity for the same alloys were determined by a differential scanning calorimeter from the heating curves. It has been found that the values of microhardness, ultimate tensile strength and electrical resistivity increase with increasing values of growth velocity and Cu content.

Keywords: Aluminum alloys, Solidification, Mechanical properties, Electrical resistivity, Thermal properties

1. INTRODUCTION

In the Al 3XXX alloy, the main alloying element is Mn, whose chemical composition is in the range of 1.0-1.9 wt. %. Manganese is known to improve deformation uniformity in aluminum alloys (Lyman, 1961). Although aluminum alloys have good ductility, the strength of these alloys is low compared to other structural alloys. This low strength limits the practical use of aluminum alloys. Many aluminum alloys have been developed to increase the strength of these alloys. However, it needs to be changed in other properties to increase strength. High strength aluminum alloys such as Al 7050, Al 7075 and Al 2024 are widely used in many applications due to their good combination of high strength and good machinability.

It has been reported that the addition of Mn in commercial aluminum alloys can form fine distribution. These distributions strongly affect strength, fracture toughness, recrystallization characteristics and grain structures. Many investigations have shown that the addition of manganese to the aluminum alloys very significantly enhances strength without loss of ductility (Garrett and Knott, 1978, Santner, 1978, Westengen, Auran and Reiso, 1981, Westengen, Reiso and Auran, 1980, Park and Nam, 1995, Lee, Park and Nam, 1999, Nam and Lee, 2000) On the other hand, copper has a great use in aluminum alloys and is the main alloying part of aluminum. These alloys are widely used in the aircraft industry and are corrosion resistant as they are heat treatable alloys. This alloy also has a wide range of applications including machine frames and parts, especially in pistons and cylinders (Al-Sabur, 2021).

It is well known that the physical properties (mechanical, electrical, thermal etc.) of metallic materials are affected by their morphology. The microstructure evolution during solidification depends on the composition; melting conditions, growth velocity, casting process and the applied thermal treatment. In the previous work, the effects of Cu composition and growth velocity on the microstructure of Al–Mn–xCu (x=0.5, 1.5, 5 wt.%) ternary alloys were investigated (Büyük et al., 2021). The aim of this work is to experimentally investigate the effect of Cu content and growth velocity (V) on the Vickers microhardness (HV), ultimate tensile strength (UTS), electrical resistivity (ρ), enthalpy of fusion (ΔH) and specific heat capacity (C_P) of the directionally solidified Al-1.9Mn-xCu (x=0.5, 1.5, 5 wt.%) alloys.

2. MATERIALS AND METHODS

2.1 Sample Preparation

Al-1.9Mn-xCu (x=0.5, 1.5, 5 wt.%) alloys have been prepared under vacuum atmosphere by using 99.90 % purity metals. After allowing time for melt homogenization, the molten alloy was poured into the hot filling furnace. The molten alloy was directionally solidified from bottom to top to ensure that the crucible was completely full. Then, each sample was positioned in a Bridgman type furnace in a graphite cylinder. In this technique, the samples were heated to about 100 K above the melting temperature. After stabilizing the thermal conditions in the furnace, the samples were grown by pulling it downwards at different growth conditions under an argon atmosphere. The samples were solidified under steady-state conditions at a constant temperature gradient and wide range of growth velocities (8.3–978 μm/s) in the Bridgman-type growth apparatus described elsewhere. After 10–12 cm steady-state growth, the samples were quenched by rapidly pulling them down into the water reservoir. The temperature of water in the reservoir was kept at 283 K by using a heating/refrigerating circulating bath. The sample temperature was controlled with an accuracy of ±0.1 K using a temperature controller. In order to see the effect of growth velocity and Cu content on mechanical and electrical properties, directional solidification experiments were made at four different growth velocities (8.3, 41.6, 166.3 and 978 μm/s) for each Al–Mn–xCu alloy.

2.2 Measurement of Temperature Gradient and Growth Velocity

The temperatures in the samples were measured by three K-type thermocouples. All the thermocouples were connected to the measurement unit consisting of data-logger and computer. The cooling curves were recorded with a data-logger via computer during the solidification process (details are given in Reference Büyük et al., 2021) When the second thermocouple was at the solid/liquid interface, the temperature difference (ΔT) between the first and second thermocouples was read from data-logger record. The temperature gradient in liquid at the solid-liquid interface (G =ΔT/ΔX) for each sample was calculated from three cooling curves using the measured value of ΔT and the value of ΔX.

2.3. Microstructure Characterization

The quenched samples were removed from the graphite crucible and cut into lengths of typically 8 mm. The longitudinal and transverse sections of the ground samples were then cold mounted with epoxy-resin. The longitudinal and transverse sections were ground flat with (180, 500, 1000, 2500 and 4000) grit SiC paper, and then polished with (6, 3, 1, 0.25, and 0.05) μm diamond paste. After polishing, the samples were etched (95 ml distilled water + 5 ml HF from 5 to 8 s). The microstructures of the samples were revealed and photographed by the SEM (LEO model).

Especially, cell-dendritic transition was detected for low growth velocity (41.6 μm/s) for alloys containing 0.5 and 1.5Cu. The microstructure of Al-Mn-xCu alloys consists of Al-rich cellular and dendrites. With increasing growth velocity, the microstructure is completely converted to a dendritic form. Details were given in the previous work (Büyük et al., 2021)

2.4. Measurements of Microhardness, Ultimate Tensile Strength and Electrical Resistivity

Vickers microhardness values of the samples were measured by using a DuraScan digital hardness test device. In this work 100 g load was applied to the sample for 10 seconds. After taking about 20 measurements from the longitudinal and transverse sections of each sample, the average value of these measurements were taken. The tensile tests were performed at a strain rate of 10^{-3} s^{-1} with a Shimadzu AG-XD universal testing machine. Cylindrical tensile specimens with a diameter of 4 mm and gauge length of 50 mm were machined from the directionally solidified samples prepared at different growth velocities. Electrical resistivity of the directionally solidified samples was measured by the D.C. four-point probe method at temperatures ranging from room temperature to 590 K.

2.5. Measurements of Enthalpy and Specific Heat Capacity

The thermal properties (enthalpy of fusion and the specific heat capacity) of the Al–Mn-xCu samples were measured by DSC thermal analysis. The instrument measures the difference between heat flows from the sample and reference (empty crucible) sides of a sensor as a function of temperature. The specific heat capacity measurements were performed following the standard ASTM E-1269-05. The Al-Mn-xCu cast alloys were heated with a heating velocity of 10 K/min from 293 K to 1200 K. The values of the enthalpy of fusion and the specific heat capacity were also calculated from the curves of the heat flow.

3. RESULTS AND DISCUSSION

3.1. The Effect of Growth Velocity and Cu Content on Microhardness and Ultimate Tensile Strength

In this work, The Al-Mn-xCu samples were solidified at different growth velocities ranging from 8.3 μm/s to 978 μm/s. The microhardness measurements were made on transverse sections at about 30 different randomly selected regions and the results are given in Fig. 1. As shown in Fig. 1, an increase in the growth velocity leads to an increase in the microhardness. From the experimental results, the relationship between microhardness and growth velocity can be written as; $HV=k_1(V)^a$ where k_1 is the constant and a is the exponent of the growth velocity V.

It is found that the increasing growth velocity from 8.3 μm/s to 978 μm/s leads to an increase of microhardness values from 392.60 MPa to 653.70 MPa depending on the Cu content. The exponent values a are found to be 0.02, 0.03, and 0.11 for the 0.5Cu, 1.5Cu and 5Cu alloys, respectively. The exponent values a is in a good agreement with the reported values ranging from 0.03 to 0.08 reported of Kaya et al. (Kaya et al., 2003), Guo et al. (Guo et al., 2004), Lapin and Marecek (Lapin and Marecek, 2006), Perdrix et al. (Perdrix et al., 1999) for ternary and multicomponent alloys prepared under similar solidification condition.

Fig. 1 also shows that the HV values increase with the increasing Cu composition. At the growth velocity of 8.3 μm/s, the values of HV are measured to be 470.3 MPa, 511.1 MPa, and 392.6 MPa for 0.5Cu, 1.5Cu and 5Cu alloys, respectively. The non-proportional variation in the microhardness value with the increase of Cu composition is thought to be due to the cell-dendritic transition at low velocity. On the other hand, at the growth velocity of 978 μm/s, the microhardness values increase from 521.1 MPa to 653.7 MPa with the increasing Cu content from 0.5 to 5 wt.%.

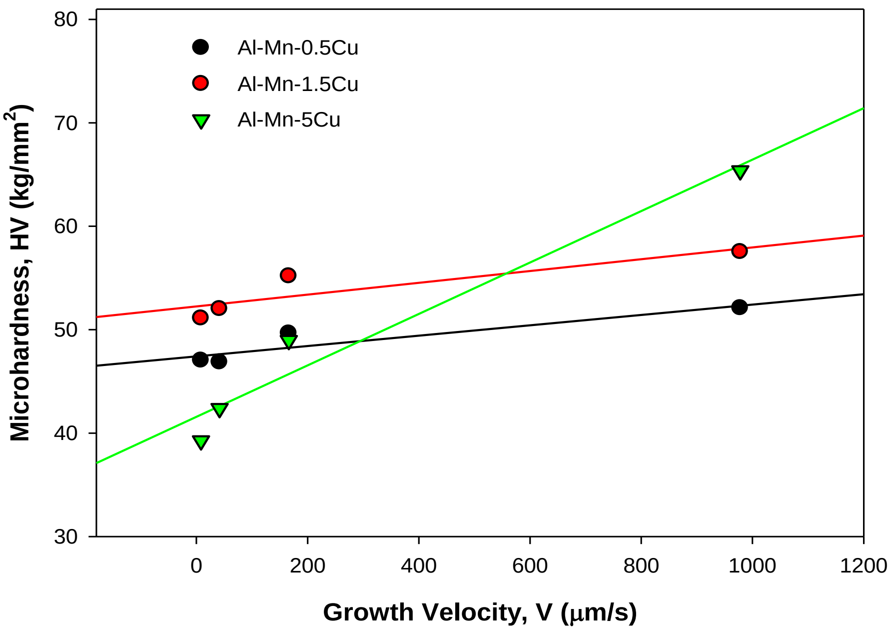

Fig. 1 Variation of HV versus V for different Cu contents

The effect of growth velocity and Cu content on the ultimate tensile strength (UTS) of Al-Mn-xCu alloys is presented in Fig. 2. While maximum value of UTS=263.56 MPa is measured for the Al-Mn-5Cu alloy at 978 μm/s, the minimum value of 108.99 MPa is measured for Al-Mn-0.5Cu at 8.3 μm/s.

It can be seen from Fig. 2 that an increase in the V and Cu composition leads to an increase in the ultimate tensile strength. From experimental results, the dependence of UTS on V can be expressed as; $UTS = k_2(V)^b$ where k_2 is the constant and b is the exponent of the growth velocity.

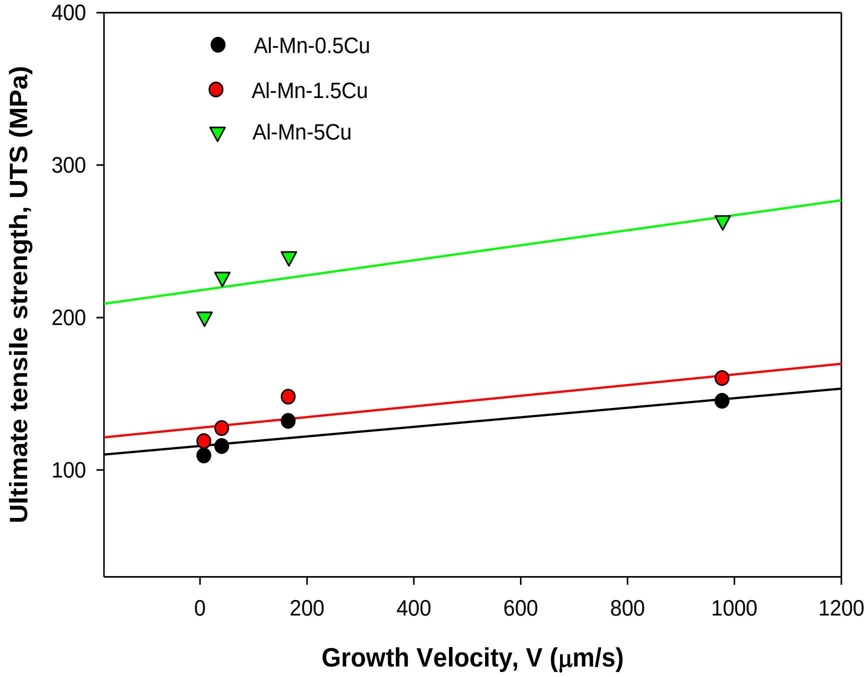

Fig. 2 Variation of the UTS with the V for different Cu contents

The values of HV and UTS increase with the increasing growth velocity and Cu content. Especially, the Al-1.9Mn-5Cu alloy has the highest values of HV and UTS. It was found that the increasing V from 8.3 μm/s to 978.0 μm/s leads to an increase of the maximum ultimate tensile strength values from 108.99 MPa to 263.56 MPa for the Al-Mn alloy with the addition of 5Cu. Homogeneous distribution of copper particles formed along the dendritic regions improves the microhardness and ultimate tensile strength of the matrix. The exponent values b is found to be 0.03, 0.04, and 0.05 for 0.5Cu, 1.5Cu and 5Cu alloys, respectively. The exponent values b is in a good agreement with the values ranging from 0.04 to 0.09 reported by Çadırlı et al. (Çadırlı et al., 2015), Kaya et al. (Kaya et al., 2003, Büyük et al. (Büyük et al., 2020) for Al-based alloys, Guo et al. (Guo et al., 2004), Lapin and Marecek (Lapin and Marecek 2006) for NiAl based-alloys. But, this exponent value is lower than the values of 0.14 and 0.15 reported by Lapin et al. (Lapin, Ondrus and Nazmy, 2002) and Fan et al. (Fan et al., 2010) for TiAl-based alloys, respectively. Fig. 2 also shows the values of UTS as a function of Cu content. The highest UTS value is obtained for the Al–1.94Mn-5Cu alloy. The UTS values increase from 144.85 MPa to 263.56 MPa, approximately by 82 %. Consequently, the microhardness and ultimate tensile strength of the alloys increase with the increasing V and Cu content.

3.2. Electrical Properties

The electrical resistivity of the alloys is affected by microstructure, plastic deformation, heat treatment, temperature and chemical composition (Smits, 1958). The growth velocity and temperature dependence of electrical resistivity for Al-Mn-xCu alloys were measured by the four-point probe method. Details are given in Ref. (Böyük, 2012). A sourcemeter (Keithley 2400) and a multimeter (Keithley 2700) were used to provide current, and the potential drop. Platinum wires with a diameter of 0.5 mm were used as current and potential probes. The voltage drop was detected, and electrical resistivity and conductivity were determined using a standard conversion method. Figure 3 shows the variation of electrical resistivity versus growth velocity and Cu content. Dependence of electrical resistivity on growth velocity can be represented as; $\rho = k_3(V)^c$ where k_3 is the constant and c is the exponent of the growth velocity.

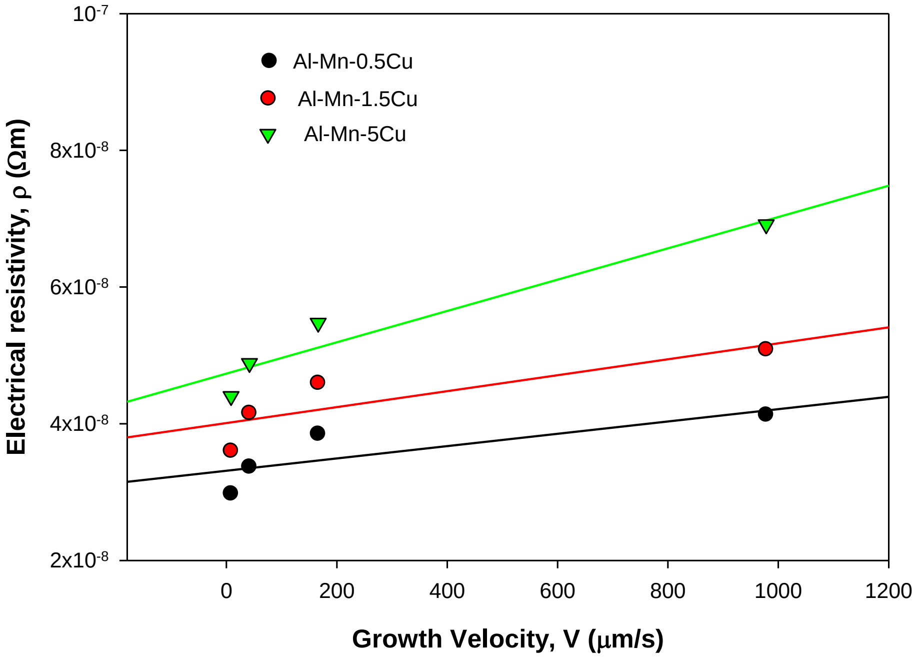

Fig. 3 Variation of the ρ with the V for different Cu contents

As seen from Fig. 3, the values of ρ increase with the increasing V values. It is found that the increase growth velocity from 8.3 μm/s to 978 μm/s leads to an increase of electrical resistivity from $2.97x10^{-8}$ Ωm to $4.13x10^{-8}$ Ωm for 0.5 Cu, from $3.60x10^{-8}$ Ωm to $5.08x10^{-8}$ Ωm for 1.5 Cu, and from $4.40x10^{-8}$ Ωm to $6.91x10^{-8}$ Ωm for 5Cu alloys. The exponent values are found to be 0.07, 0.07 and 0.09 for 0.5Cu, 1.5Cu, and 5Cu alloys, respectively. These exponent values are in good agreement with the values ranging from 0.07 to 0.09 reported by Böyük (Böyük, 2012) for Al-Si-Ni eutectic, Çadırlı et al. (Çadırlı et al., 2015), and Kaya et al. (Kaya et al., 2012, Kaya et al., 2013) for Al-Ni alloys. As shown in Fig. 3, the ρ increases with the increasing Cu content. At the growth velocity of 8.3 μm/s, the experimental values of ρ are measured to be $(2.97, 3.60 \text{ and } 4.40)x10^{-8}$ Ωm for the 0.5Cu, 1.5Cu, and 5Cu alloys, respectively, at room temperature.

The values of electrical resistivity in the temperature interval 290-590 K were determined and the data are plotted in Fig. 4. The ρ values increase linearly with the increasing T values for each alloy and increase with the increasing Cu content. The similar trend is supported by the previous results of Boekelheide et al. (Boekelheide et al., 2009) and Çadırlı et al. (Çadırlı et al., 2017). The electrical resistivity was determined to increase from $2.97x10^{-8}$ Ωm to $14.06x10^{-8}$ Ωm with the increasing temperature from 290 to 590 K.

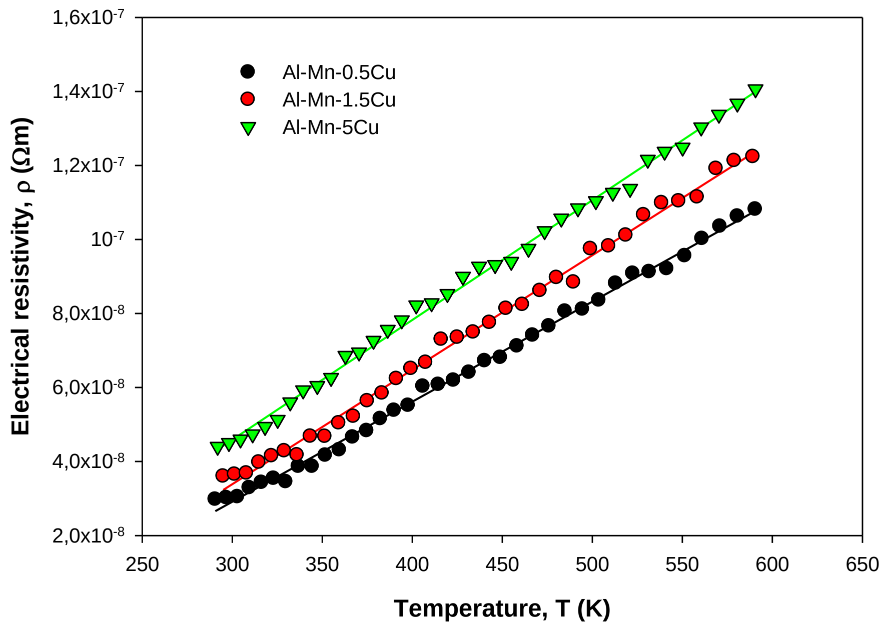

Fig. 4 Variation of the ρ with the T for different Cu contents

3.3 Thermal Properties

The Al–Mn–xCu alloys were heated with a heating velocity of 10 K/min from room temperature to 1000 K by using a Perkin Elmer Diamond model DSC. The corresponding heat flow versus temperature curves are shown in Fig. 5. The melting temperatures were detected to be 944.2 K, 937.1 K and 928.6 K for the 0.5Cu, 1.5Cu and 5Cu alloys, respectively. The values of the enthalpy of fusion were calculated to be 182.6 J/g, 154.7 J/g, and 166.7 J/g for the 0.5Cu, 1.5Cu and 5Cu alloys, respectively. The values of the specific heat capacity were also calculated to be 0.272 J/gK, 0.232 J/gK and 0.254 J/gK for the 0.5Cu, 1.5Cu and 5Cu alloys, respectively. As shown in Fig. 5 and results from the calculated results, the melting temperature of Al-1.9Mn-xCu alloys increase, but ΔH and Cp values decrease with the increasing Cu content.

The recommended values of the ΔH for pure Al, Mn and Cu are 396.9 J/g, 240.3 J/g and 231.1 J/g, respectively (Hultgren et al., 1973, Cagran, Wilthan and Pottlacher, 2006). The values of ΔH (182.6, 154.7 and 166.7 J/g) in this work are smaller than the ΔH values of the pure Al, Mn and Cu. The specific heat capacity values for pure Al, Mn and Cu are 0.879 J/g K, 0.48 J/g K, and 0.384 J/g K at the melting temperature, respectively (Hultgren et al., 1973, Carvill, 1993). Similarly, the calculated specific heat capacity values (0.272, 0.232 and 0.254 J/gK) in this work are much smaller than the Cp values of 0.879, 0.48 and 0.386 J/g K for the pure Al, Mn and Cu respectively.

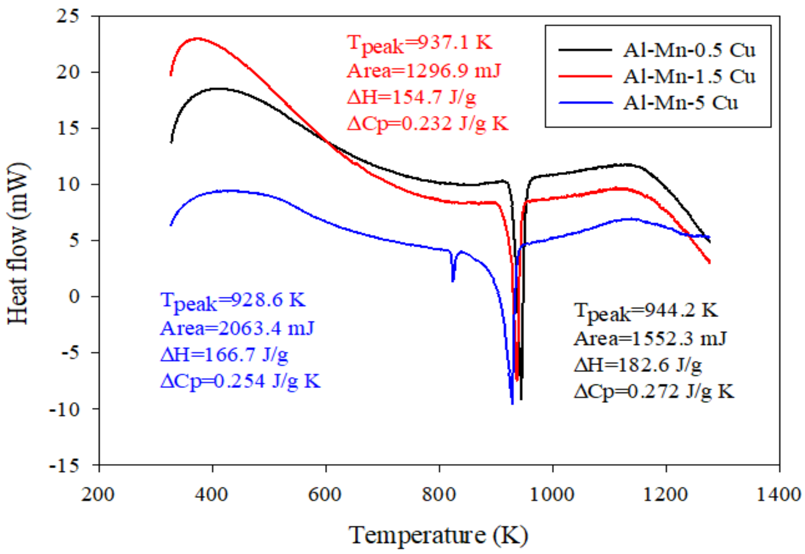

Fig. 5 Variation of the W with the T for different Cu

4. CONCLUSIONS

In this work, the effect of growth velocity and Cu content on the mechanical, electrical and thermal properties of Al–1.9Mn–xCu (x=0.5, 1.5, 5 wt.%) alloys have been investigated. The principal results can be summarized as follows:

i. The HV values increase from 392.60 MPa to 653.70 MPa with the increasing growth velocity from 8.3 to 978 μm/s. At a constant growth velocity (8.3 μm/s), the values HV varies from 470.3 MPa, 511.1 MPa, and 392.6 MPa with the increasing Cu content from 0.5 to 5 wt.%. This non-proportional variation in the microhardness value with the increase of Cu composition is thought to be due to the cell-dendritic transition at low velocity.

ii. Depending on Cu content, the increasing growth velocity V from 8.3 μm/s to 978.0 μm/s leads to an increase of UTS values from 108.99 MPa to 263.56 MPa. At a constant growth velocity (8.3 μm/s), the values UTS increase from 108.53 MPa, 119.39 MPa, and 198.86 MPa with the increasing Cu content from 0.5 to 5 wt.%.

iii. The values of ρ increase with the increasing growth velocity. It was found that the values of electrical resistivity changes with the Cu content. While the maximum ρ value of 6.91 $x10^{-8}$ Ωm is measured for Al-Mn-5Cu alloy, minimum ρ value of 2.97 $x10^{-8}$ Ωm is measured for Al-Mn-0.5Cu alloy.

iv. The values of the melting temperature, enthalpy of fusion and the specific heat capacity decrease with the increasing Cu content. The melting temperatures of the Al-1.9Mn-xCu alloys are found to be 944.2 K, 937.1 K and 928.6 K for x=0.5, 1.5 and 5 wt.%, respectively. The values of the enthalpy of fusion were calculated to be 182.6 J/g, 154.7 J/g, and 166.7 J/g for the 0.5Cu, 1.5Cu and 5Cu alloys, respectively. The values of the specific heat capacity were also calculated to be 0.272 J/gK, 0.232 J/gK and 0.254 J/gK for the 0.5Cu, 1.5Cu and 5Cu alloys, respectively.

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