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Production of AA 2024 Aluminum Alloy Ribbons by Melt Spinning Process

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ABSTRACT In this study, rapidly solidified AA2024 aluminum ribbons were produced with laboratory scale melt spinning device by using different wheel speeds. The alloy was melted with induction furnace under high vacuum atmosphere. The influence of the wheel speed on the dimensions and cooling rates of produced ribbons was examined. The produced ribbons had 20–80 µm thickness, 1–4 mm width, and 10–60 mm length. Increasing wheel speed from 28 to 43 m/s resulted in decreasing ribbon thickness from 79 µm to 24 µm. Microhardness measurements were also performed and it was noted that the hardness values changed with wheel speed (35–39 $HV_{0.01}$).

Keywords: AA2024 Aluminum Alloy, Rapid Solidification, Melt Spinning

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1. INTRODUCTION

Rapid solidification is a commonly used method and frequently used to manufacture superior metals and alloys either by rapid quenching or by sub-cooling [1]. In general, this technique can be defined as the fast extraction of thermal energy of metals or alloys from liquid state to solid state at room temperature. The metal in the liquid state is very short in contact with the cold surface, causing instant supercooling to occur in the liquid metal over 100°C during the solidification [2].

Rapid solidification can be achieved by carrying out one of the below criteria;

1. Realization of excessive cooling before solidification,
2. Achieve a high speed in the line of solidification,
3. Achieve a high cooling rate on the sidelines of solidification.

The initial condition requires supercooling or over-cooling of molten metal or alloy to the temperature that the latent heat is estranged completely from the solidifying mass, before being delivered to ambient environment. The next condition to impose rapid solidification is to move solidifying metal or alloy with very high speed during solidification drawing a thin specimen. Finally, high cooling rate is the most popular method used in rapid solidification methods. The main difference among these three techniques is that the rapid cooling is included in all stages in third method, but rapid cooling takes place just in the line of solidification in first two methods. High cooling rates allows influential conduction of thermal energy in all stages of solidification process. The main parameter to achieve high cooling rate is to reduce at least one size of solidifying metal or alloy and exposing the alloys to high heat subtraction rates [2].

There are several various rapid solidification techniques for production of superior metals. The most widespread technique is the melt spinning method. This method is nowadays standard in industrial applications for producing different dimensions of ribbons. Rapid solidification of the liquid metal in the form of ribbon is achieved by using a metal disk rotating at high speed and having high thermal conductivity in this method [3, 4]. There are many production parameters that affect the

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physical and mechanical properties of the produced ribbons such as wheel speed, liquid metal temperature, distance between nozzle and wheel surface, ejecting gas pressure and nozzle geometry [5, 6]. Among these variants, wheel speed is the most important factor [7].

The mechanical properties of aluminum and its alloys depend on purity of adding alloying elements. It is necessary to change the microstructure of the alloy to enhance the properties [8, 9]. Aluminum based intermetallic systems have important features such as; high melting point, low density, optimum chemical resistance [10]. For example, in Al-Cu alloy systems mechanical properties such as strength, hardness, fatigue and creep resistances mainly depend on copper addition [11]. AA2024 aluminum alloys are used in different areas which require high temperature, high strength, low density, low weight, fair workability, fair corrosion resistance, ductility, fatigue resistance, machinability and heat-treatability [9, 12, 13].

While various studies in literature dedicated to Al based alloys, the microstructural developments and microhardness of undercooled AA2024 alloys have not been explored. Al-Cu alloys found variety of applications in aircraft, aerospace, electronics and automotive industries. The goal of the current study is to examine the effect of the wheel speed on the undercooled ribbons' shape and to determine the effects of rapid solidification and cooling rate on the microstructural, mechanical (hardness) properties.

2. EXPERIMENTAL

The material used in this study is AA2024 aluminum alloy with the nominal composition given in Table 1. The experimental works have been carried out at laboratory scale single roller melt spinning device working in vacuum condition as shown in Figure 1. In order to study the effect of the wheel speed on dimension, microstructure and microhardness of the ribbons, a number of experiments have been performed, in which wheel speed was changed while other parameters were kept constant.

Each run was started with melting of AA2024 aluminum alloy ingot in boron nitride crucible having rectangular slit shape. The slit shape nozzle with the size of 7x0.8 mm was used. Four different wheel speeds 28, 34, 39 and 43 m.s^{-1} were employed to study the effect of wheel speed on the size of ribbons. Gap distance from the tip of the nozzle to the wheel surface was set to 1 mm. High purity argon gas (99.999%) was used to eject the molten metal on the wheel and the ejection pressure of the gas was kept 75 kPa during all experiments. Ribbons were produced with constant melt temperature of 1023 K and a pyrometer (thermometer) located near the crucible was used to monitor the melt temperature. The chamber of the melt spinning apparatus has been evacuated before each run. When the melt temperature reached the expected temperature, molten metal was ejected by applying a pressurized gas through the slit nozzle on the rotating copper wheel as the ribbon shape.

The microstructure and surface properties of produced ribbons were examined with a scanning electron microscope of Zeiss EVO MA model. The hardness measurements of the ribbons were performed with a NOVA 130/240 (INNOVATEST, Maastricht the Netherlands) model digital microhardness tester at room temperature. Vickers pyramidal indenter with 0.01 kg and 5 seconds of holding time were employed.

Table 1. Chemical composition of AA2024 (ASTM B209-14)

Elements	% weight
Cu	3.8-4.9
Mg	1.2-1.8
Mn	0.3-0.9
Fe	0.5
Si	0.5
Zn	0.25
Ti	0.15
Cr	0.10
Al	Balance

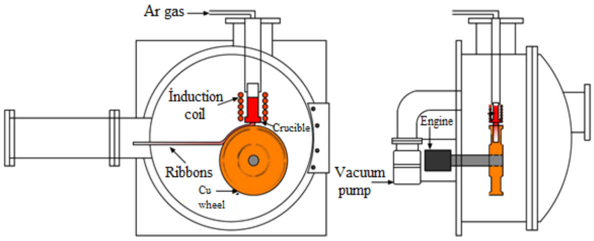

Fig. 1. Schematic diagram of melt spinning system

3. RESULTS

Figure 2 shows macro image of the melt spun AA2024 aluminum alloy ribbons produced with wheel speeds of 28, 34, 39 and 43 m.s^{-1}. As it can be seen from the figure, discontinuous ribbons with the sizes of 20–78 µm in thickness, 1–4 mm in width, and 10–60 mm in length were produced. It is also seen from

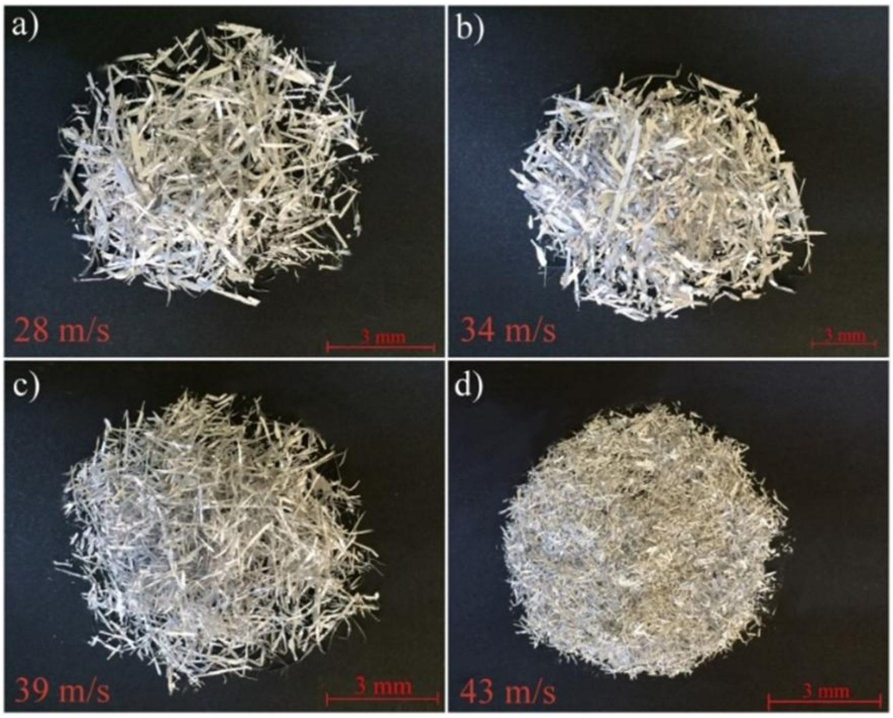

Fig. 2. Macrograph of discontinuous ribbons produced with different wheel speeds. Wheel speeds: a) 28 m/s, b) 34 m/s, c) 39 m/s and d) 43 m/s

the figure that the sizes of the ribbons decreased with increasing wheel speed. Among the size parameters, the ribbon thickness is the most important factor that effects the cooling rate and microstructure of the ribbons. From this perspective, the effect of wheel speed on the thickness was studied in a detailed manner. Figure 3 demonstrates the variation of thickness parameter of melt-spun ribbons as a function of the wheel speed. During these processes, as stated above, ejection pressure of 75 kPa, melt temperature of 1023 K, and nozzle-wheel distance of 1 mm were kept constant. As it can be seen from the Figure 3, the ribbon thickness decreased significantly with increasing wheel speed. For wheel speeds of 28, 34, 39 and 43 m.s^{-1}, the average ribbon thicknesses are recorded as 70 µm, 52 µm, 40 µm and 24 µm, respectively. Beyond 43 m/s wheel speed, the ribbon shape starts to convert into powder shape. This can be explained by increasing centrifugal energy given to the liquid metal to break up [10, 14]. The SEM micrographs of the produced ribbons had two different surface morphologies on the wheel side and air side are shown in Figure 4 and Figure 5, respectively. The wheel side surface of the ribbons is relatively smooth and has air pockets due to existence of poor heat transfer between the wheel and melted alloy [15]. The air side of the ribbons has rough surface with metal flow lines parallel to melt flow direction.

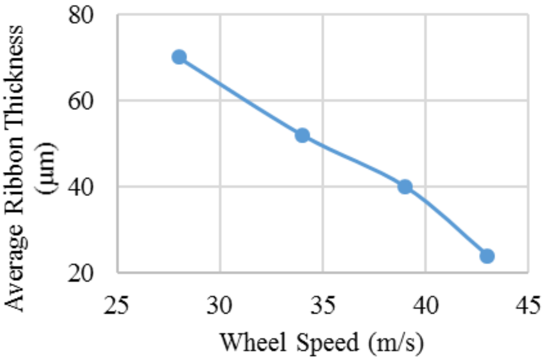

Fig. 3. The variation of the ribbon thickness with wheel speed

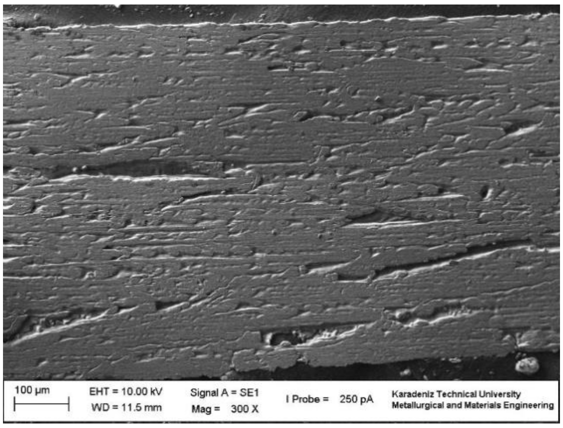

Fig. 4. SEM micrographs of wheel side surface of produced ribbons (at wheel speed of 28 m/s)

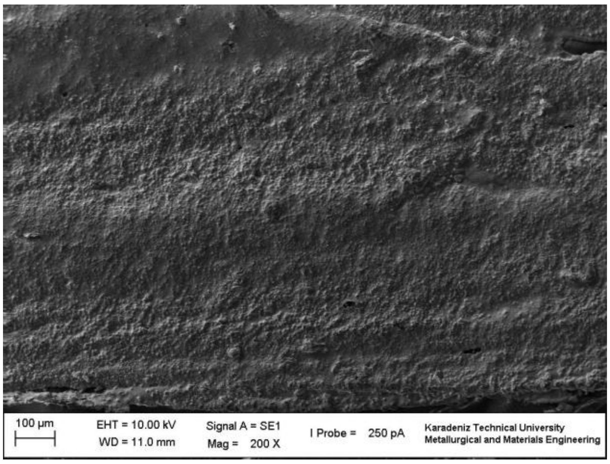

Fig. 5. SEM micrographs of air side surface of produced ribbons (at wheel speed of 28 m/s)

Figure 6 and Figure 7 show the SEM images of the microstructure for melt spun ribbons produced with 28 and 39 m/s wheel speeds, respectively. As it can be seen from the figures, the microstructures of the ribbons were characterized by fine-grained structure. The average grain size decreased with increasing wheel speed. The average grain sizes were measured as 15 µm and 12 µm for ribbons produced at wheel speeds of 28 m/s and 39 m/s, respectively.

Cooling rates and dendrite arm spacing depending on wheel speed for AA2024 were calculated. Some empirical equations were suggested by different authors to estimate the cooling rate of aluminum-copper alloys. Sarreal and Abbaschian [16] indicated cooling rates of the Al-4.9Cu alloy by Equation 1. The calculation of the cooling rates in this study was based on Equation 1;

$$DAS = 46.6 \times \varepsilon^{-0.29} \tag{1}$$

where, DAS represents the dendrite arm spacing or average grain size in µm, and ε stands for the cooling rate in K/s.

The variation of average grain size and cooling rate values depending on ribbon thickness is evaluated. Cooling rate becomes 49.83 K/s while average grain size is about 15 µm for 28 m/s wheel speed and it is 107.58 K/s for average grain size of 12 µm at 39 m/s wheel speed.

The key goal of this paper was to work the fabrication of undercooled Al–Cu alloy ribbons by using melt-spinning method and determine relationships between wheel speed and microhardness of AA2024 alloy. Hardness test is applied to determine the mechanical properties of rapid solidified ribbons. One of these tests, the Vickers hardness (Hv) is the ratio of the load applied to the brale to the surface area of the indentation. The hardness value is calculated using the Vickers formula [11, 17].

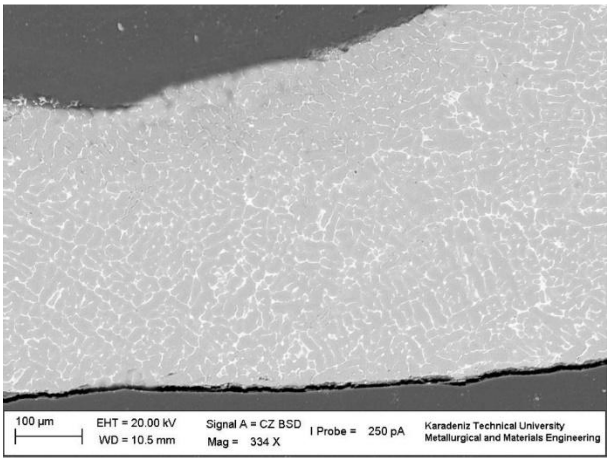

Fig. 6. Microstructure of AA2024 aluminum alloy melt spun ribbons produced with 28 m/s wheel speed

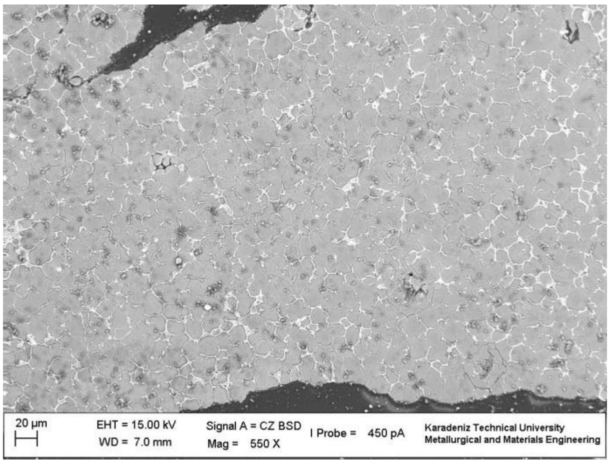

Fig. 7. Microstructure of AA2024 aluminum alloy melt spun ribbons produced with 39 m/s wheel speed

$$H_V = \frac{2P\sin(\frac{\theta}{2})}{d^2} \tag{2}$$

where P is the applied load (kg), d the mean diagonal of the indentation (mm), θ the angle between opposite faces of the diagonal brale (136°).

In this work, the mechanical properties of produced ribbons were determined by Vickers microhardness measurement. The measured microhardness values were given in Figure 8. The average values were measured as 35.13, 36.14, 38.78, and 39.40 $HV_{0.01}$, for wheel speeds of 28 m/s, 34 m/s, 39 m/s, and 43 m/s, respectively. As it can be seen from the figure, the increasing wheel speed barely enhances microhardness values [18, 19].

The grain sizes of rapidly solidified ribbons produced with higher wheel speed is smaller than that for low-speed ribbons. This increase in hardness values can be explained by the reduction of the average grain size due to increased cooling rate with increasing wheel speed [3, 20]. Minor change in microstructure results minimal effect from 35 to 39 $Hv_{0.01}$ in microhardness.

In other respects, the microhardness values of the produced ribbons at the highest wheel speed 43 m/s are slightly higher. The reason for that the microstructure of this ribbon is clearly finer than others. These results show the homogeneous distribution of the microstructure and the average grain size greatly affect the hardness of the undercooled ribbons.

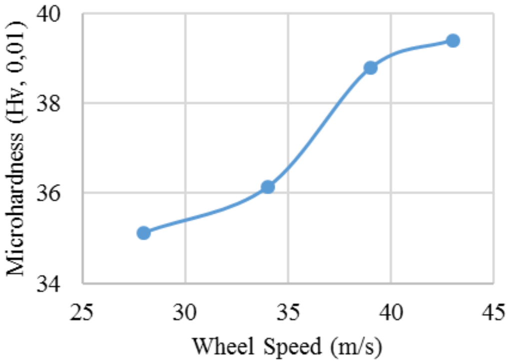

Fig. 8. The effect of wheel speed on microhardness of produced ribbons

4. CONCLUSION

The rapidly solidified AA 2024 aluminum alloy ribbons were produced with the single roller melt spinning method and the size and microstructural properties of the ribbons changed with wheel speed. The following conclusions were drawn from the present results;

- AA2024 aluminum alloy ribbons with discontinuous form were produced with melt spinning method and the sizes of the ribbons such as length, width, and thickness decreased with increasing wheel speed.
- Microstructure of the produced ribbons was characterized by equiaxed grains and the average grain sizes decreased with increasing wheel speed.
- Microhardness of the produced ribbons increased with decreasing ribbon thickness.

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