Flow measurement around the edges and curved outer surface of a rotating disk

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Abstract
An experimental study is performed to investigate the flow structures near the edges of rotating disks with different edge shapes. By changing the rotational speed, the Reynolds number is changed from 277 to 356. It is found that the fluid motion near the sharp edge differs depending on whether a rotating shaft is at the disk surface. A flow developing on the flat side of the disk surface changes its direction toward the curved outer surface on the shaft side, and the flow goes straight outward, leaving the disk on the flat side. The existence of the supporting shaft increases the radial velocity of the flow while decreasing the azimuthal velocity. The effects of the edge shape of the disk on the flow fields are also investigated by changing the shape of the disk edges. Rounded and chamfered edges have no noticeable effect on the azimuthal velocity on the curved outer surface, whereas changing the edge shape enhanced the velocity in the disk-thickness direction. In the FFT analyses of the azimuthal velocity measured at the edge of the curved outer surface when the disk edge is rounded, an increase in power across a range of frequencies is observed. Only in the chamfered edge disk case, a peak in the spectrum of the velocity that corresponds to a wavenumber which appears in the transitional boundary layers is observed.

Keywords: Rotating disk edge, Spin casting, Experiment, Flow visualization

1. Introduction

The quenching technique is widely used in the industry. In particular, the single-roll quenching method has often been used to produce amorphous alloy ribbons because it could produce a few hundred millimeter long ribbons (Liebermann and Graham, 1976; Suzuki et al., 1981). This method is straightforward: molten metal is poured onto the curved surface of a metallic disk, which turns into a thin amorphous ribbon when it is cooled down, as shown in Fig. 1(a). The quality of a generated ribbon is judged by its thickness and the smoothness of its surface. Takayama and Oi (1979) reported that the rotational speed of the disk and the ejection pressure of the molten metals affect the ribbon thickness. Fiedler et al. (1984) derived a formula for the ribbon thickness as a function of the rotation speed, ejection pressure, nozzle width, and dropping distance of molten metal. Air pockets and undesired wavy patterns are sometimes formed, which decreases the surface smoothness of the ribbon. Bizen and Sunagawa (2001) demonstrated that the air pockets could be generated by the expansion of the gas between the rotating disk and the molten metals. Carpenter and Steen (1992) observed three patterns of the ribbon surface textures depending on several parameters, namely disk speed, the gap between the disk and nozzle, nozzle width, and ejection pressure of molten metal. To improve the quality of amorphous ribbons, some studies tried to control the surrounding gas environment where the ribbon is solidified. Pavuna (1981) succeeded in obtaining a uniform thickness and smooth surface condition of the ribbons using helium gas as the atmospheric gas and reported that the ribbon width could be controlled by a flow volume of the helium gas. Fujikura et al. (1995) found a method to stably obtain smooth surface ribbons by supplying a small amount of helium gas at a location just before the molten metals touch the rotating disk. They also pointed out that there is an optimum flow volume of the helium gas. Yagi et al.
(1988) obtained wide ribbons with a less wavy surface and few air pockets by reducing the pressure around the rotating disk. These studies indicate that the gas between the disk and molten metal is the key to the ribbon quality.

The flow structures on the flat surface of an infinite rotating disk in a still fluid are often explained in terms of flow instabilities (Lingwood 1995; Itoh 1996; Lee et al. 2017). The surrounding fluid is sucked toward the disk surface and driven outward by centrifugal force. A boundary layer on the disk surface changes from a laminar state to a turbulent state. The transition and turbulent regions thus lie in the outer region of the rotating disk (Itoh et al. 1994; Appelquist et al. 2018; Lee et al., 2018). The flow near the disk edge was also investigated. Imayama et al. (2013) discussed the effect of the edge condition on the flow instability of the rotating disk flow. Pier (2013) reported that the edge is a strong source of the fluctuation. Flow structures on the curved circumferential surface at the end of the disk and near the disk edge, however, are not yet well understood because the flow there is complicated because of the interaction between the flow developing on the flat disk surface and the flow along the curved outer surface, as shown in Fig. 1(b).

This study focuses on the motion of the fluid around the disk edge. The flow structures developing at the curved outer surface and the edge of a rotating disk are measured in detail by a single-type hot wire anemometer and observed by a smoke-wire visualization technique. Furthermore, the effects of the rotating shaft and edge shape on the flow structures are examined.

2. Experimental Setup and Procedures

Figure 2 shows schematic views of experimental setups and their pictures. The dimensions of the rotating disk used in this experiment were similar to a disk which is practically used to produce thin ribbons. The disk is made of aluminum alloy, 50 mm in width and 300 mm in diameter and was mounted by one or two supporting shafts made of stainless steel with a diameter of 25 mm. Figure 2(a) shows a two-sides supported disk, and Fig. 2(b) shows a disk with a cantilever-type support. The disks were polished, and their arithmetic average roughness was 1.6 \( \mu \)m. The maximum roundness error was 0.02 mm. One of the shafts was connected to a V-belt driving system and a geared motor. The rotating speed was measured using a rotary encoder. The disk was located at least 100 mm away from the frame, which supported the disk. Two primary coordinates were used in this study. The first one was for the flat surface of the disk. The origin of the first coordinate system \( O \) was set at the disk center, as shown in Fig. 2(c), where \( r, \theta \), and \( z \) axes were the radial, the azimuthal, and the height from the flat surface, respectively. The second coordinate was for the curved surface of the disk. Its origin \( O' \) was at the center of the disk thickness, as shown in Fig. 2(c). The \( l_r \) and \( l_z \)-axes represented the distance from the outer curved surface and the location in the thickness direction, respectively. The velocity components in the azimuthal and radial directions at the flat disk surface were denoted by \( u_\theta \) and \( u_r \). The velocity components in the disk-thickness directions in the curved disk surface was denoted by \( u_z \). Figure 3 shows the shapes of the disk edge, namely sharpened,
chamfered, and rounded edges. The sharpened edge is the ordinary type used in single-roll quenching. The chamfered edge disk had the corner cut by 9 mm at the angle of 45 degrees to the two surfaces, and the rounded edge disk had filleted edges whose radii were 9 mm.

![Diagram of disk arrangements and experimental setups](https://via.placeholder.com/150)

(a) Schematic view of the both-sides supported disk
(b) Schematic view of the cantilever supported disk
(c) Defined coordinates

**Fig. 2** (a) Schematic view of two-sides supported disk and disk with a cantilever-type support (b) Pictures of experimental setups for the two supporting methods (c) Two coordinates used. The unit is mm.

![Diagram of edge shapes](https://via.placeholder.com/150)

(a) Sharpened (b) Chamfered (c) Rounded

**Fig. 3** Details of edge shape

Velocity measurements were conducted using a single-type hot wire probe with a sensor of 5 μm in diameter and approximately 1 mm in length. The fourth-order Butterworth low-pass filter with a cut-off frequency of 2.5 kHz was employed to eliminate the aliasing errors. The filtered signals were converted to digital data at a sampling rate of 5 kHz with a 16-bit resolution. The hotwire anemometer was fixed at a three-dimensional traverse mechanism with a spatial accuracy of 0.01 mm. The probe location was calibrated by a digital camera with a resolution of approximately 0.1 mm. Calibration of the hotwire was performed using a blow-out type wind tunnel, and the output was fitted by a cubic function. Two velocity components, \( u_r \) and \( u_\theta \), were obtained by doing the measurement twice in the flat surface. The authors also obtained the velocity components, \( u_z \) and \( u_\phi \) in the curved surface, setting the hotwire probe at the angles of ±45 degrees against the direction of the disk rotation, and the velocity components were calculated such as done by Sato et al. (2011). Flow near the outer edge of the disk was visualized using a smoke-wire method, and \( r - z \) cross-sectional images were obtained. The wire was placed at the flat surface side 20 mm inward from the disk edge and 1 mm away from the disk surface (\( l_r = -20 \) mm, \( z = \pm 26 \) mm). The wire was 300 mm long made of three threads twisted together. One thread was a tungsten wire of 0.15 mm in diameter, and the other two were tungsten wires of 0.04 mm in diameter. The wires
were coated with propylene glycol and heated to generate smoke. The smoke was illuminated by a slide projector with an effective luminous flux of 5,000 lm, and images were taken by a digital camera at 400 fps. Each picture had an average of 60 images taken in 0.15 sec.

3. Results and Discussion
3.1. Flow structures on the curved outer surface at the end of a rotating disk

To discuss the averaged structure of the flow around the edge for an ordinary disk with a sharpened edge, the velocity distributions near the disk edge and at the curved surface were measured. Figure 4 shows the time-averaged azimuthal velocity distribution on the curved outer surface for (a) the two-sides supported disk and (b) the disk with cantilever-type support. The labels "A" and "B" indicate the sides with and without the rotating shaft. The azimuthal velocities are non-dimensionalized by the disk surface velocity at the disk edge $U_e$. In the figure, the disk surface moves from the far side to the near side. The disk edges were at $z = \pm 25$ mm. The vertical axis $l_z$ represents the vertical distance from the curved outer surface, as shown in Fig. 2. The disk rotation speed was kept constant at $N = 493$ rpm, where the azimuthal velocity at the edge of the disk $U_e$ was $7.74$ m/s, and the Reynolds number at the edge based on the disk radius, $Re_e = R \sqrt{\omega/\nu}$, was $277$, where $R$ indicates the radial location, $\omega$ is the angular velocity and $\nu$ denotes the dynamic viscosity. The flow field strongly depended on the supporting method. For the two-sides supported disk shown in Fig. 4(a), the velocity distribution is symmetric with respect to $z = 0$ mm. A high-velocity region spreads in the radial direction at the center of the disk, $z = 0$ mm. Near the disk surface, high-velocity regions appear at the mid-span of the disk thickness and the edges, indicating that the boundary layer formed on the curved surface is thick in these regions. On the other hand, for the cantilever supported disk shown in Fig. 4(b), the velocity distribution is asymmetric. A high-speed region spreading in the radial direction is observed near the disk edge of side B, which is the non-supporting shaft side. As for the area near the disk surface, the thickening of the boundary layer can only be observed at the disk edges on both sides and not at the mid-span of the disk thickness.

![Fig. 4 Azimuthal velocity $u_\theta$ distribution in a curved-out surface measured by a hotwire anemometer. A is the supporting shaft side, and B is the no shaft side. The Reynolds number based on edge velocity and radius of the disk is 273. The disk rotates from the far side to near.](image)

Figure 5 shows the averaged luminance distributions for 0.15 sec obtained from the smoke visualization. The smoke was introduced at both flat surfaces. The rotating direction is from the far side to the near side in the images. The smoke patterns for the two-sides in Fig. 5(a) shows that the flows turned 90 degrees at both corners traveling toward the center of the curved surface before flowing away from the surface. On the other hand, in Fig. 5(b), the smoke on side B moves straight upward without changing direction. These results show the strong influence of the rotating shaft on the flow field around the disk edges.

Figure 6 shows the radial variation of the averaged crossflow velocities normalized by the velocity of disk edge $\tilde{a}_z/U_e$ for various locations in $z$-direction. Figure 6 (a) is the disk with a cantilever-type support, while the disk in Fig. 6 (b) is supported at both sides. A, B indicate whether a rotating shaft is present or not. The color of the lines indicates the location in $z$ direction, where $z = \pm 25$ mm are the locations of the sharp edges. For the cantilever supported disk, the velocity profiles in side "A" and "B" are different. The asymmetric velocity profiles are consistent with the motion of the smoke observed in Fig. 5. On the other hand, for the both-sides supported disk, the velocity profiles are similar. Strong crossflow velocity $u_c$ can be observed near the edge on side for both disks, and the magnitude of the crossflow velocity $u_c$ was approximately 7 – 9% of the disk edge velocity $U_e$. The velocity profiles have an inflectional point at approximately
$l_e = 2 - 3$ mm near the edge ($l_e = 24$ mm). The inflectional points for both-sides supported disk was slightly closer to the disk than that for the cantilever disk. Flow with an inflectional point in the velocity profile is often unstable. Considering that the high-speed region of the azimuthal velocity component shown in Fig. 4 was found closer to the wall below 2 mm, the flow appears to be twisting and complicated at the disk edge region. Notably, a small reversed flow region can be observed near the wall and the edge on the supported side, A, of the cantilever supported disk. The reversed flow disappears around $l_e = -18$ mm, suggesting the formation of a separation bubble when the flow turns the disk edge.

### 3.2. Flow structure near edge of flat surface side of disk

Flow velocities at the flat surface side near the edge were also measured. Figure 7 shows the measurement region, where $l_e$ is the distance in the $z$ direction from the flat surface, and $l_r$ is the distance in the radial direction from the curved surface. The origin $(z, l_e) = (0, 0)$ is set at the edge of the disk. The measurement region covers an area of $0.5$ mm $\leq z \leq 2.5$ mm, and $-10$ mm $\leq l_r \leq 5$ mm. The opposite side was also measured; the direction of $l_r$ is the same but the direction of $z$ is defined in the opposite direction.

Figure 8 shows the profiles of the non-dimensional azimuthal velocity $u_0/U_e$ together with that of the von Karman flow, which is a self-similar solution of laminar flow on an infinite rotating disk, shown by a black dotted curve. The measurement location was $l_e = 10$ mm. The broken curve with the crosses represents the velocity profile on the side without the rotating shaft. The velocity profiles on the shaft side are shown as the curves with other symbols. The velocities in the flat side are slightly lower than the von Karman theoretical profile with a discrepancy of within 10%. On the other hand, $u_0/U_e$ on the shaft side agrees well with the theoretical profile, indicating that the flow is still in the laminar state even when the rotating shaft exists.

Figure 9 shows the non-dimensional radial velocity $u_r/U_e$ and azimuthal velocity $u_0/U_e$ at 0.5 mm away from the wall on the shaft side together with the velocity on the flat side. The distance of 0.5 mm is where the radial velocity component of the von Karman flow becomes maximum. The azimuthal velocity $u_0/U_e$ on the shaft side is faster than that on the flat side. On the other hand, the radial velocity $u_r/U_e$ on the shaft side becomes slower than that on the flat side. It can be concluded that the rotating shaft enhances the azimuthal velocity of $u_0$ while decreasing the radial velocity of $u_r$. Due to this effect, the slow flow can go around the corner, as observed in Fig. 5.

### 3.3. Effect of edge shape

This section discusses the effect of the edge shape on the flow field along the curved disk surface and its dependence on the rotational speed. Figure 10 shows the smoke visualizations of flows around the disks with chamfered and rounded edges. The disks are all supported at both sides. The smoke was supplied from the flat surface side of the rotating disk, and what appears white is a smoke-concentrated area. The rotating direction is from the far side to the near side of the image. Similar to the sharper edge case, the smoke travels along the edges and changes its direction towards the center of the disk. The flow patterns are also observed in the distributions of the time-averaged azimuthal velocities $u_0$ shown in Fig. 11. Here, $U_e$ is the velocity of the end of the rotating disk, 7.74 m/s, and it non-dimensionalizes the azimuthal velocities $u_0$. The Reynolds number at the edge, $Re_e = R \sqrt{\omega / y}$, is 277. The chamfered and rounded parts are from 16 mm to 25 mm and $-16$ mm to $-25$ mm in Fig. 11. For both cases, the velocity profiles are symmetric regarding the $z$-directional center of the curved surface. As well as the sharpened edge case in Fig. 4(a), the high-speed region appears around the center of the disk in both edge cases. The center part is slightly faster than in other regions, even in the area away from the surface.
Fig. 6 $r$-direction profiles of $z$-direction velocities $u_z$ measured at curved outer surface of rotating disk. Disks are:
(a) Cantilever-type support, and (b) with both-sides supported disk. Velocities are normalized by disk edge velocity $U_e$. The side labeled with “A” has a supporting shaft, and the side with “B” has no supporting shaft.

Fig. 7 Measurement region around flat surface side of edge
Fig. 8 Profiles of the non-dimensional azimuthal velocity $u_\theta$ together with the laminar solutions of the von Karman flow (dotted curve) for both sides of the supported disk and cantilever supported disk.

Fig. 9 Velocity distribution along the radial direction at height of 0.5 mm for disks with/without supporting shaft. (a) Azimuthal velocity $u_\theta$, (b) Radial velocity $u_r$. The dotted lines are the theoretical values.

Fig. 10 Smoke visualization of flows around disks with (a) chamfered and (b) rounded edges. Colors represent the averaged luminance for 0.15 sec. Wall rotates from far side to near.
Figure 12 compares the distributions of the velocity in the $z$ direction $u_z$ near the edges for disks with different edge shapes changing the rotating speed. The velocity is normalized by the disk edge velocity $U_e$. Regardless of the edge shapes, high $u_z/U_e$ regions can be observed near the wall region around the edge, especially for the chamfered and rounded edge disks. The result shows that edge processing is useful to prevent the flow separation at the corner. The value of $u_z$ becomes the highest in the chamfered disk case. Compared with the sharpened edge disk, the rounded and chamfered edge disks show higher crossflow velocities. It can be found that the dimensionless crossflow velocity $u_z/U_e$ increases as the rotational speed increases. Moreover, the high-velocity region expands in the $z$ direction.

Fig. 12 Mean azimuthal velocity $u_z$ near curved outer surface for various rotational speeds and edge conditions

The power spectra of the azimuthal velocity of $u_0$ on the curved surface are compared in Fig. 13. The result (a) shows the spectrum for the sharpened edge disk when the rotating speed was 493 rpm ($Re_e$ of 277). The spectrum was measured at $l_z = 24.5$ mm and $l_r = 0.5$ mm, a location close to the disk edge. Here the frequency resolution $\Delta f$ was approximately 0.3 Hz. Some peaks are found at 8.2 Hz, 16.5 Hz, and 33.0 Hz, corresponding to the disk rotation speed and their harmonics. These peaks are derived from the mechanical vibration of the disk and are not significant. On the
other hand, no peaks are found in the sharpened edge case except for the peaks from the mechanical vibration of the disk. The spectra for the chamfered edge and rounded edge disks are shown in Fig. 13. The Reynolds numbers $\text{Re}_e$ are (b) 277 and (c) 324. The spectra were obtained at $l_z = 14$ mm and $l_r = 0.5$ mm. In the rounded edge disk cases, elevations in the power spectra with many fine peaks can be observed in the frequency ranges of 100 Hz through 200 Hz in the Reynolds number $\text{Re}_e=277$ case and 200 Hz through 400 Hz in the Reynolds number $\text{Re}_e=324$ case. The many fine peaks indicated the modulation of the waveform. Frequency from one peak to the next peak was about 4.5 Hz in the $\text{Re}_e=277$ case and 6.1 Hz in the $\text{Re}_e = 324$ case. On the other hand, in the chamfered edge case, only when the Reynolds number $\text{Re}_e$ is 324, a strong single peak appeared at 335 Hz, which did not take place in the Reynolds number $\text{Re}_e=277$ case. This peak frequency of 335 Hz corresponds to 30 waves during one disk rotation. In the flat surface of a rotating disk flow, various studies reported that 28 to 32 vortices appeared inside transitional boundary layers. In their theoretical and experimental studies, Kobayashi et al. (1980) and Malik et al. (1981) reported that the critical Reynolds number was around 290. Because the wavenumber of 30 observed in our experiment is close to the wavenumber of fluctuations observed in the transitional rotating disk boundary layers, they could be related, which should be studied in the future works.

![Power spectra of azimuthal velocity fluctuation $u'_\phi$ on curved outer surface. Data acquired at $l_z = 14$ mm and $l_r = 0.5$ mm for the chamfered and rounded edge disk cases and at $l_z = 24.5$ mm and $l_r = 0.5$ mm for the sharpened edge disk.](image)
4. Conclusions

This study investigated flow structures developing around the curved outer surface of a rotating disk and the edges of the disk by flow measurement using a single hotwire anemometer and a smoke-wire visualization technique. The rotating disk used in this experiment was made of aluminum alloy with 50 mm in width and 300 mm in diameter, whose dimensions were close to disks used in the industries. The visualization and the averaged velocity distribution of the flow at the curved outer surface revealed that flow. It flowed along the flat surface of the disk and changed its direction at the disk edges to the direction along the curved outer surface at the side with a supporting shaft. On the other hand, on the side without the supporting shaft, the flow from the flat side went straight and issued outward from the edge. The shafts affected the radial velocity on the flat side of the disk, which was lower than the laminar theoretical solution, but its influence on the azimuthal velocity was small.

The effects of the edge shape of the disk on the flow fields were also investigated by changing the shape of the disk edges. The rounded and chamfered edges were found to have no noticeable effect on the azimuthal velocity, whereas changing the edge shape enhanced the crossflow velocity. In the FFT analyses of the azimuthal velocity at the edge on the curved outer surface when the disk edge was rounded, an increase in power across a range of frequencies could be observed. Only in the chamfered edge disk case, a peak in the spectrum of the velocity that corresponded to a wavenumber that appeared in transitional boundary layers was observed.

The air trapped inside the molten metal reduces the quality of the amorphous ribbon (Steen and Karcher (1997)), forming air pockets. The flow pattern around the disk, especially on the curved surface, might affect the entrainment of the air to the molten metal.

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