An Experimental Study on an Underexpanded Annular Impinging Jet*

Wataru MASUDA**, Takao NAKAMURA**,
Masaru KOBAYASHI** and Hideaki SAITO***

An underexpanded annular impinging jet is studied experimentally and it is shown that the aerodynamic characteristics of the impinging jet depend significantly on the distance H between the nozzle exit plane and the impinged flat plate. The annular impinging jet diverges in the downstream direction provided H is smaller than a critical value H_c . The feature of the jet changes significantly at $H = H_c$. The stream lines issuing from the inner edge of the annular nozzle join at a point upstream of the impinged plate. However, a vortex ring may appear on the plate even for $H > H_c$ depending on the magnitude of loss in the stagnation pressure at the jet axis.

Key Words: Supersonic Flow, Jet, Annular Jet, Nozzle, Shock Wave, Laser Cutting

1. Introduction

Most material cutting techniques with a focused laser beam utilize a gas jet to remove molten and/or vaporized material from the kerf. The gas can be inert to protect the workpiece from oxidation or contamination. Alternatively, an active gas may be used to assist the process with an exothermic reaction.

In conventional gas-assisted laser cutting, a circular tipped nozzle, as shown in Fig. 1(a), is mounted coaxial with the focussing beam. Recently, laser cutting of thick metals has attracted considerable interest. The thicker the workpiece, the higher the laser power needed and a laser beam of larger diameter is usually used. Moreover, in order to eject the material from deep kerf, it is desirable to use a gas jet whose momentum flux is very large. Therefore, the

reservoir pressure must be relatively high. However, in the conventional configuration, as shown in Fig. 1(a), it is very difficult for a large lens to support high pressure. Moreover, very high power laser beams cannot be focused with a lens, since the power density imposes too-high thermal distortion in the lens. Therefore, mirror focussing must be utilized for very high power lasers. For laser cutting with mirror focussing, one of the most simple methods of provid-

Fig. 1 Gas-assisted laser cutting

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** Department of Mechanical Engineering, Nagaoka University of Technology, 1603-1 Kamitomioka, Nagaoka 940-21, Japan

*** Second Research Center, Japan Defence Agency, 2-2 -1 Nakameguro, Meguro-ku, Tokyo 153, Japan

ing the assisting jet may be the use of a coaxial annular nozzle, as shown in Fig. 1(b). However, no published reports relevant to supersonic annular impinging jets have been found and it is not known whether the annular jet is suitable for laser cutting.

In the present investigation, the aerodynamic characteristics of an underexpanded annular impinging jet are studied experimentally. The measurements include the surface pressure of an impinged flat plate, the pressure at the center of the nozzle exit plane and flow visualization.

2. Experimental

Figure 2 shows the annular nozzle used in the present investigation. The annular nozzle is a converging one with a constant exit section with a length of $h=3.4$ mm. The diameters of the outer edge D and inner edge d are 5 mm and 3 mm, respectively. Air at room temperature is used as the working gas. For a reservoir pressure of $P_0=5 \times 10^5 P_a$, the Reynolds number based on the sonic conditions and D is 3.9×10^5 . A pressure tap of 0.5 mm in diameter is located at the center of the nozzle exit plane to measure the pressure P_n , as shown Fig. 2. The solid plate which simulates the workpiece is a square of 120×120 mm², as shown in Fig. 3. The square probe with

Fig. 2 Annular nozzle contour

Fig. 3 Schematic diagram of the experimental apparatus

a pressure tap of 0.2 mm at the center can be scanned transversely to the jet axis within an error of 0.02 mm using pulse motors which are controlled by a personal computer. The distance H between the nozzle exit plane and the square probe can be arranged manually. The surface pressure P_j , the pressure at the center of the nozzle exit plane P_n and the reservoir pressure P_0 are measured within the error of 1 % by pressure transducers, whose signals are digitalized and processed by the personal computer. The atmospheric pressure P_a is measured by a mercurial manometer. The visualization of the jet is performed by the schlieren method. Surface flow visualization is also carried out by painting the black solid surface with a mixture of heavy paraffin and zinc oxide. The direction of the flow in the boundary layer near the surface is also visualized by the injection of the mixture.

3. Results

Figure 4 shows the dependence of P_n and the surface pressure at the jet axis P_{jc} on H which is obtained under the conditions of $P_0/P_a=5$. Fieret et al.⁽¹⁾ demonstrated a strong correlation between P_{jc} and the maximum laser cutting speed. They showed that higher P_{jc} is necessary to attain higher cutting speed. As shown in Fig. 4, both P_{jc} and P_n almost agree with each other and decrease as H/D increases provided that H/D is smaller than a certain value $H_c/D=1.8$. However, at $H/D=H_c/D$, P_{jc} is raised and P_n is lowered abruptly. This discontinuity is accompanied by a noticeable change in the acoustic emission of the interaction of the jet with the plate. Such abrupt reduction in P_n has also been reported by Maki et al.⁽²⁾, although their experiments concerned a low-speed annular impinging jet. For $H/D > H_c/D$, P_n/P_a is almost constant and independent of H/D . On the other hand, P_{jc} varies periodically with H/D due to the variation of the shock structure in the jet.

Figure 5 shows the schlieren photographs of the

Fig. 4 Dependence of P_{jc}/P_n and P_n/P_a on H/D measured at condition $P_0/P_a=5$

Fig. 5 Schlieren photographs taken at condition $P_0/P_a=5$

supersonic annular impinging jets for $P_0/P_a=5$. Figures 5(a) and 5(b) show that the annular jet diverges in the downstream direction, provided that H/D is smaller than H_c/D . It is thought that there is a slowly recirculating region near the jet axis which extends from the nozzle exit plane to the impinged plate, since P_n and P_{jc} closely agree with each other, as shown in Fig. 4. Figure 5(c) shows that the feature of the annular impinging jet changes drastically at $H/D=H_c/D=1.8$. On leaving the nozzle, the jet boundary must immediately adjust to the atmospheric pressure. The jet expands suddenly at the nozzle exit and then is compressed rapidly by oblique shock waves forming a sharp neck. Just above the solid surface, a shock wave which is upwardly convex and spans the jet can be clearly observed. Therefore, it is apparent that the stream lines issuing from the inner edge of the annular nozzle join at a point upstream of the convex shock wave. The abrupt rise in P_{jc} at $H/D=H_c/D$ (shown in Fig. 4) is due to the confluence of the stream lines where the stagnation pressure is considerably high. For H/D greater than H_c/D , the flow structure upstream of the convex shock wave is independent of H/D . As seen from Fig. 5(g) which is taken at $H/D=\infty$, the flow pattern downstream of the first neck undergoes cyclic changes. The expansion alternates with the compression forming necks. Figures 5(d) and 5(f) show that the convex shock wave is located near a neck in the cases $H/D=2.8$ and 4. Since the Mach number is relatively low at the

Fig. 6 Distributions of the surface pressure P_j measured at condition $P_0/P_a=5$

necks, the reduction in stagnation pressure due to the convex shock wave is not very large. Therefore, it is seen from Fig. 4 that P_{jc} is relatively high at $H/D=2.8$ and 4. On the other hand, the convex shock wave is located at the expanded region of the jet in the case $H/D=3.6$, as shown in Fig. 5(e). It is seen from Fig. 4 that the convex shock wave at the expanded region of the jet leads to the considerable reduction in P_{jc} .

Profiles of the surface pressure P_j measured at $P_0/P_a=5$ are shown in Fig. 6, where r is the radius with the jet axis at $r=0$. The most notable feature of the profiles for $H/D < H_c/D$ is that the pressure near the nozzle axis is almost constant and rises to a maximum at r/D somewhat less than unity. These

profiles suggest the presence of a large recirculating region around the jet axis. The location of the maximum pressure moves abruptly toward the nozzle axis at $H/D = H_c/D = 1.8$. It should be noted, however, that P_{jc} is not the maximum pressure. The sunken distribution of P_j suggests the presence of a vortex ring or stagnation bubble on the solid surface, although the stream lines issuing from the inner edge of the annular nozzle join at a point upstream of the convex shock wave. Some studies⁽³⁾⁻⁽⁵⁾ demonstrated the existence of a vortex ring even in circular impinging jets with $d = 0$. The sunken pressure distribution near the center disappears at $H/D = 2.8$ and 4 , where the Mach number of the convex shock wave is low and the loss in the stagnation pressure at the jet axis is not very large. However, the sunken distribution clearly appears at $H/D = 3.6$, where the Mach number of the convex shock wave is relatively high.

The surface flow pattern, obtained at conditions $P_0/P_a = 5$ and $H/D = 2.1$ by painting the black solid surface with a mixture of heavy paraffin and zinc oxide, is shown in Fig. 7. A circular deposit at the central stagnation point and several annular deposits of the paint can be observed. The profiles of P_j are shown in Fig. 8 where the paint deposits are represented along the r/D coordinate. The paint deposits near the central stagnation point since the wall shear stress is not very high. The shear stress is also reduced in the presence of an adverse pressure gradient. Therefore, the annular deposit corresponds to the pressure minimum. However, the presence of recirculation near the center cannot be confirmed from Fig. 7. The paint is then injected through an orifice to visualize the flow in the boundary layer near the solid surface. The flow direction on the solid surface is determined by the direction of the paint spreading. The flow visualization using paint injection clearly shows that there is a reverse flow near the

Fig. 7 Surface flow pattern

central stagnation point, provided that maximum pressure is present outside of the center. It is obvious that the gas accumulation at the central stagnation is detrimental to the laser's cutting ability.

The dependence of H_c/D on P_0/P_a is shown in Fig. 9. It is seen that H_c/D increases with P_0/P_a , is maximized at $P_0/P_a = 4$, and then decreases gradually.

Figure 10 shows the dependence of P_{jc}/P_a and P_n/P_a on H/D which is obtained under the conditions of $P_0/P_a = 3$. The abrupt increase in P_{jc} and abrupt

Fig. 8 Distribution of the surface pressure and paint deposits

Fig. 9 Dependence of H_c/D on P_0/P_a

Fig. 10 Dependence of P_{jc}/P_a and P_n/P_a on H/D measured at condition $P_0/P_a = 9$

Fig. 11 Schlieren photographs taken at condition $P_0/P_a=3$

decrease in P_n at $H/D=H_c/D=1.81$ are also observed at this reservoir pressure. The schlieren photographs are shown in Fig. 11. Figures 11(b) and 11(c) distinctly show that the features of the annular impinging jet change drastically, depending on whether H/D is smaller or larger than H_c/D . However, Fig. 11(c) shows that no shock wave spanning the jet can be observed clearly above the solid surface, although oblique shock waves can be observed in the annular part of the jet. Therefore, no evidence of confluence can be discerned from Fig. 11(c). However, the flow structure near the nozzle exit does not depend on H/D in the region $H/D > H_c/D$. Moreover, the abrupt increase of P_{jc} at $H/D=H_c/D$ shown in Fig. 10 clearly demonstrates that the stream lines issuing from the inner edge of the annular nozzle join at a point upstream of the impinged plate. This discontinuity is also accompanied by a noticeable change in the acoustic emission. As seen from Fig. 11(d) which is taken at $H/D=\infty$, the jet undergoes cyclic changes due to the presence of oblique shock waves which span the jet. However, the period is short and the difference in the width of the expanded region and the compressed region is small compared to those shown in Fig. 5(g), since the Mach number of the jet is relatively low. As a result, the dependence of P_{jc}/P_a on H/D is weak in the region $H/D > H_c/D$ as seen from Fig. 10.

Figure 12 shows the dependence of P_{jc}/P_a and P_n/P_a on H/D which is obtained under the condition of $P_0/P_a=9$. The schlieren photographs are shown in Fig. 13. Figures 13(b) and 13(c) show that the changes in the feature of the annular impinging jet at $H/D=H_c/D=1.12$ are not very apparent at this reservoir pressure. However, Fig. 13(c) shows that a shock wave which is upwardly convex appears at the jet center. The shock wave becomes concave, shifts in the downstream direction as H/D is increased then maintains a constant location for H/D larger than 3. It is seen that

Fig. 12 Dependence of P_{jc}/P_a and P_n/P_a on H/D measured at condition $P_0/P_a=9$

the flow structure upstream of the shock wave does not depend on H/D in the region $H/D > H_c/D$. As the shock wave moves in the downstream direction, P_{jc} is reduced severely and is minimized at $H/D=3$, as shown in Fig. 12. This result shows that the Mach number in front of the shock wave increases with the shift of the shock wave. However, P_{jc} is gradually increased again beyond $H/D=3$; the reason for this might be that the flow near the jet center is mixed with the flow in the annular part of the jet which suffers no significant loss in the stagnation pressure due to the normal shock wave. Although not shown in Fig. 12, P_{jc} decreases gradually in the region $H/D > 10$.

Let us define a diameter D^* where the maximum of the surface pressure is located. The dependence of D^*/D on H/D is shown in Fig. 14. Maki et al.⁽²⁾ showed, in the experiments on low-speed annular impinging jets, that the sunken pressure distribution disappears abruptly at $H/D=H_c/D$. However, the present experiments on the compressible annular impinging jets show that the sunken distribution is preserved beyond H_c/D . For $P_0/P_a=3$, D^*/D decreases monotonically with H/D in the region $H/D > H_c/D$. For $P_0/P_a=5$, however, D^*/D varies periodically with

Fig. 13 Schlieren photographs taken at condition $P_0/P_a=9$

Fig. 14 Dependence of D^*/D on H/D

H/D and vanishes completely in the region $H/D > 5$. For $P_0/P_a=9$, H/D larger than 10 is needed for D^* to vanish.

4. Conclusions

The present experiments show that the annular impinging jet diverges in the downstream direction, provided that H/D is smaller than H_c/D . However, the features of the jet change significantly at $H/D=H_c/D$. The stream lines issuing from the inner edge of the annular nozzle join at a point upstream of the impinging plate. However, a vortex ring may appear on the solid surfaces even for H/D greater than H_c/D depending on the magnitude of the loss in the stagnation

pressure at the jet axis. It is obvious that the gas accumulation at the central stagnation is detrimental to the laser's cutting ability. However, the vortex ring disappears in the region $H/D > 4$ provided that P_0/P_a is less than 5. Therefore, it is thought that annular jets with coaxial mirror focussing with a practical F -number can be used for laser cutting.

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