Article

Effect and applications of convergent collision of metal jets with extremely high velocity

Ryuichi Tomoshige*, Akio Kira*, Masahiro Fujita*, Kazuyuki Hokamoto**, Yasuhiro Ujimoto***, and Akio Kato*

New experimental apparatus was developed for getting extremely high shock pressure. The apparatus utilized convergent collision of metal jets generated between a conical concave metal block and metal flyer plate. That is, since the plate is accelerated toward the metal block by detonation of plastic explosive, metal jets with high velocity are launched from points where the flyer plate collided with the metal block. As the collision points are on a concentric circle of surface of the conical concave metal block, metal jets are launched toward center portion, resulting in the converging collision of the metal jets. From relation among flying velocity of the plate, travelling velocity of the collision point, and deformative inclined angle of the flyer plate in accordance with the detonation of explosive, some of calculated results were derived for estimation for generation limit of the jetting. If launching velocity of the metal jets attains at an order of 10000 m s^{-1}, a head-on collision of the jets will generate relative velocity of about 20000 m s^{-1}. Therefore, the high velocity collision may lead to generation of extremely high shock pressure, for example, an order of TPa.

1. Introduction

Explosively shock pressure has been utilized in a field of material science. For example, powder compaction and explosively cladding techniques are typical instances for it[1-3]. Especially, the explosive cladding, which can join different kinds of materials, has some unique properties, i.e. formation of wavy interface, and jetting at interface during joining. It is also well known that the jetting plays an important role on formation of strong joining strength of the interface. Namely, jetting phenomenon has effects of cleaning of interface, and melting of material surface, and so on.

Now, since shock pressure depends on particle velocity, high particle velocity leads to high shock pressure. One has ever been successful in getting high pressure of the order of GPa. However, it is required complex equipment to get the high pressure, e.g. two-stage light gas gun.[4] Though it is not easy to get such a high pressure, it is very important to research properties of various materials. Consequently, we required developing a system to get easily high pressure by using simpler equipment.

Here, it may be effective to utilize the explosively cladding system for getting the high pressure, since the system generates the metal jetting with high particle velocity in most of cases as mentioned above.

In this paper, a novel concept will be proposed to develop a generation system for obtaining extremely high shock pressure by utilizing a double-layered metal cladding system in accordance with the jetting. In addition, an

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*Sojo University, Kumamoto-shi 860-0082, JAPAN
Tel: +81-(0)96-326-3111 Fax: +81-(0)96-326-3000
E-mail: tomosige@chem.sojo-u.ac.jp
**Kumamoto University, Kumamoto-shi 860-8555, JAPAN
Tel: +81-(0)96-342-3740 Fax: +81-(0)96-342-3729
E-mail: hokamoto@mech.kumamoto-u.ac.jp
***Asahi KASEI Corporation, Oita-shi 870-0392, Japan
Tel: +81-(0)97-592-2340 Fax: +81-(0)97-592-9603
E-mail: a8112690@ut.asahi-kasei.co.jp

experimental instance will be indicated.

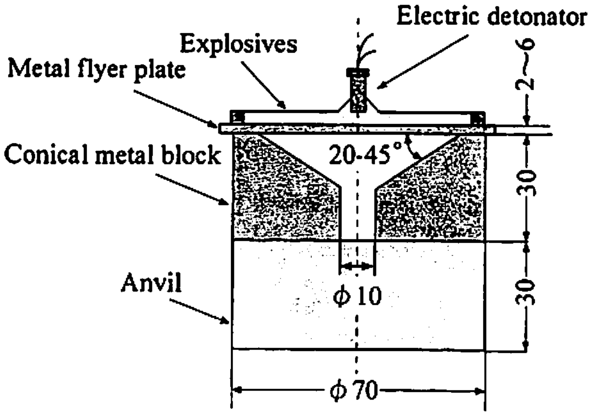


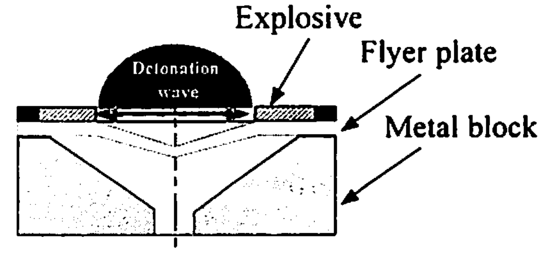
Fig. 1 Schematic illustration of the extremely high-pressure generation apparatus.

2. Experimental apparatus

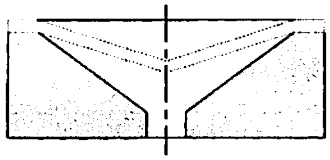
Figure 1 shows a schematic illustration of the extremely high-pressure generation apparatus. The apparatus consists of a 2 to 6 mm-thick metal square plate as a flyer plate, a metal concavely conical block, metal anvil and an explosive charge with an electric detonator. The metal plate, which aluminum was used in this study, was put on the conical titanium block that had conical angle of 20 to 45 degrees. SEP plastic explosive charge provided from Asahi Kasei Corporation, Tokyo, Japan, was used, and was put directly on the flyer plate after shaping into a disc shape. The explosive has detonation velocity of about 6900 m s^{-1}. A No.6 electric detonator (according to Japan Industrial Standard: JIS) was settled at center point of the explosive charge.

3. Explanation for generation of metal jet

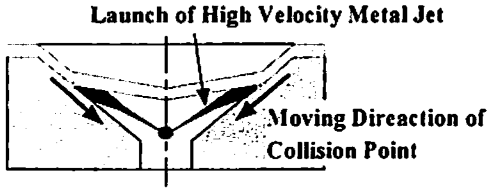
When the explosive is detonated, detonation waves spread axi-symmetrically, as shown in Figure 2(a). After that, since the flyer plate is subject to an action of detonation pressure, the plate is accelerated rapidly and is projected with high velocity. Therefore, the flyer plate begins to make a certain angle depending on reaching time of the detonation wave to the plate. After the detonation wave reaches periphery of the flyer plate (Fig. 2(b)), the plate initiates gradually to collide with the conical block. The collision, naturally, will occur first from peripheral portion of the block to which the plate located at the nearest. As time passes, the collision circle moves toward a center axis on the conical block as shown in Fig.2(c). Because the two kinds of metals, which are aluminum and titanium, collide in high velocity with an appropriately inclined angle, the jetting with high velocity initiates to generate from all of the points on the collision circle. Consequently, the metal jet, which may be an aggregate of metal particles with significantly high velocity, travels toward the center axis of the block, resulting in convergent collision of the metal jet. In this case, since the jet causes a head-on collision, it is expected that relative velocity reaches significantly high particle velocity, which will correspond simply to twice as much as the jet velocity. Thus, it will be effective to utilize the metal jet with higher velocity for getting higher shock pressure.



(a) Initial detonation of explosive.



(b) State after the detonation completed.



(c) Generation of metal jet.

Fig. 2 Scheme of generation process of high velocity jet.

4. Theoretical consideration on generation of extremely high shock pressure

4.1 Estimation of flying velocity of jets

When the plate flies by undergoing the detonation pressure, it forms a deformative inclined angle, β as illustrated in Figure 3. The angle depends on a

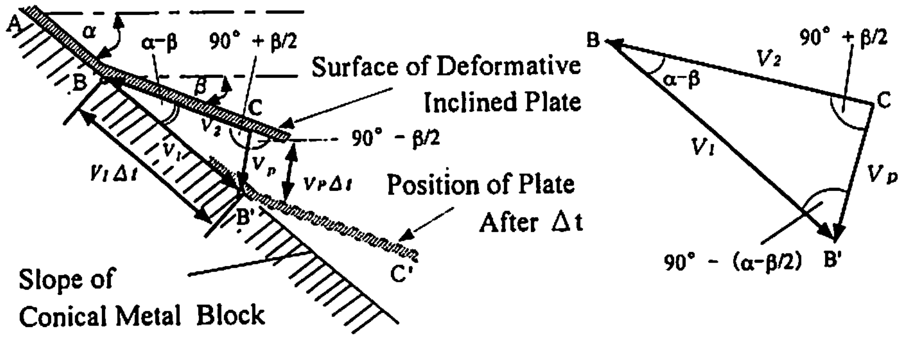


Fig. 3 Scheme of deformation behavior of flyer plate.

ratio of flying velocity of the plate, V_P, to the detonation velocity of the explosive, V_D. By the way, Cowan et al.[5] considered that a velocity vector of the plate corresponds to the direction of bisector of angle formed between before and after the plate deformed. Then, they derived the deformative inclined angle as follows,

$$\beta = 2\sin^{-1}\left(\frac{V_P}{2V_D}\right) \qquad (1)$$

Now, let us consider a situation that the plate with a velocity, V_P, collides with a surface of the concave metal block as shown in Fig. 3. We assume that the plate, which is expressed by a segment ABC at a given time, moves to segment AB'C' in accordance with a collision of the plate toward the surface of the metal block after Δt, and that the direction of the velocity vector of the plate hardly changes. Here, V_1 and V_2 are a travelling velocity of the collision point, B, and a relative velocity of V_P to V_1, respectively. In addition, $V_P\Delta t$ and $V_1\Delta t$ correspond to a flying distance of the plate, and a travelling distance of the collision point during Δt, respectively. Since the vectors, V_P, V_1 and V_2, form a triangle, the following equation is obtained according to the law of sine.

$$\frac{V_P}{\sin(\alpha-\beta)} = \frac{V_1}{\sin\left(90^\circ+\frac{\beta}{2}\right)} = \frac{V_2}{\sin\left(90^\circ-\left(\alpha-\frac{\beta}{2}\right)\right)} \qquad (2)$$

From an addition theorem of trigonometrical function,

$$V_1 = \frac{\cos\frac{\beta}{2}}{\sin(\alpha-\beta)}V_P, \qquad V_2 = \frac{\cos\left(\alpha-\frac{\beta}{2}\right)}{\sin(\alpha-\beta)}V_P \qquad (3)$$

According to Cowan's theory, jet velocity, V_J, is obtained by sum of V_1 and V_2. Thus, V_J is derived from following equation,

$$Vj = V_1 + V_2 = \frac{1}{\sin(\alpha-\beta)}\left\{\cos\frac{\beta}{2}+\cos\left(\alpha-\frac{\beta}{2}\right)\right\}V_p \qquad (4)$$

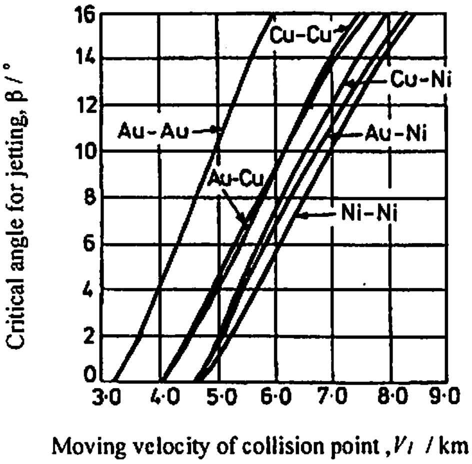


Fig. 4 Critical angle for calculated jetting and collision velocity

By the way, launch of the jets does not occur always under any condition. The collision angle, α−β, must be more than a lower limit angle for the occurrence of the jetting when V_1 is relatively high. Here, Cowan et al. performed some experiments by using parallel set-up combining various metal plates. The calculated values on the basis of the experimental results are shown in Figure 4[5], which illustrates as a relation between critical angles for generation of the jet and the travelling velocity of collision point. This figure means that, for example, if the travelling velocity of collision point is 6000 m s^{-1} in case of copper-copper combination, the angle, β, must be more than 9.5 degree to occur the jetting. Thus, the jetting will occur on the left-hand side of the calculated curves in Fig.4. Moreover, lower limit of the collision angle for a given V_1 (m s^{-1}), which was estimated from the experimental data in Fig.4, is derived in the case of using copper–copper combination as follows,

Table 1 Calculated values of velocity of metal jet at a condition of V_p = 1000 [ms^{-1}] and β = 8.192 [degree] .

α [°]	V_1 [m/s]	V_2 [m/s]	m_j [mass%]	m_s [mass%]	V_j [m/s]	V_s [m/s]
15	8414.2					
20	4874.3	4699.7	0.0106	0.989	9574.1	174.57
25	3449.4	3230.6	0.0214	0.979	6680.0	218.79
30	2684.9	2421.4	0.0358	0.964	5106.3	263.58
35	2211.6	1902.5	0.0537	0.946	4114.1	309.13
40	1892.4	1536.8	0.0751	0.925	3429.2	355.63
45	1664.8	1261.5	0.0997	0.900	2926.3	403.31

Table 2 Calculated values of velocity of metal jet at a condition of V_p = 1500 [ms^{-1}] and β = 12.30 [degree] .

α [°]	V_1 [m/s]	V_2 [m/s]	m_j [mass%]	m_s [mass%]	V_j [m/s]	V_s [m/s]
15	13659.5					
20	11130.8					
25	6783.7					
30	4905.3	4512.4	0.0237	0.976	9417.7	392.91
35	3864.6	3404.5	0.0387	0.961	7269.1	460.06
40	3208.3	2679.9	0.0573	0.943	5888.3	528.39
45	2760.6	2162.3	0.0792	0.921	4922.9	598.22

Table 3 Calculated values of velocity of metal jet at a condition of V_p = 2000 [ms^{-1}] and β = 16.43

α [°]	V_1 [m/s]	V_2 [m/s]	m_j [mass%]	m_s [mass%]	V_j [m/s]	V_s [m/s]
15						
20	31789.7					
25	13283.5					
30	8436.5					
35	6215.7	5606.3	0.0260	0.974	11822.0	609.40
40	4950.3	4251.5	0.0417	0.958	9201.9	698.77
45	4139.2	3349.4	0.0609	0.939	7488.5	789.79

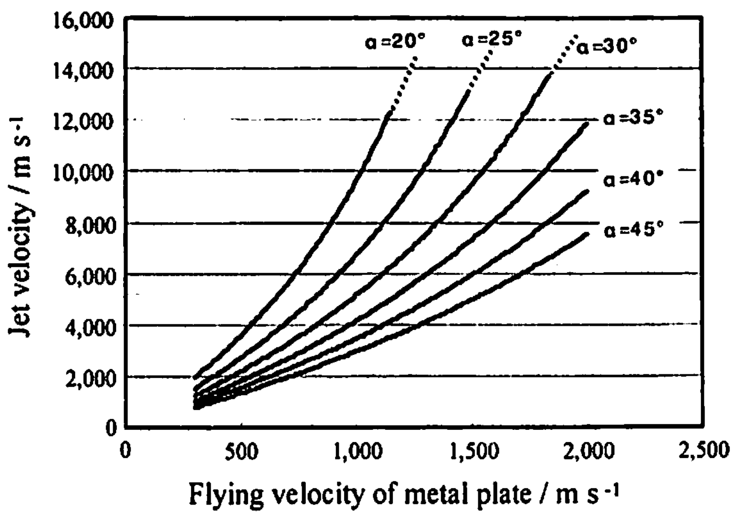


Fig. 5 Calculated jet velocity as a function of the flying velocity.

$$\alpha-\beta=\frac{14}{3000}(V_1-4000)\ \text{(degree)} \qquad (5)$$

where $\alpha > \beta$. Here, some values of V_j calculated from equation (5) are listed in Tables 1 to 3. The calculation was performed for V_P=1000 m s^{-1}, 1500 m s^{-1} and 2000 m s^{-1}. In the tables, Vs means a velocity of slug of the flyer plate. Some curves for the calculated jet velocity are also shown in Figure 5. These results suggest that an optimum conical angle exists. For instance, because it is speculated that maximum of the flying velocity of plate will be around 2000 m s^{-1}, it is expected that the fastest jet velocity of around 12000 m s^{-1} is obtained at the conical angle, α, of around 30 to 35 degree in this calculation condition.

Now, it is assumed that an object M_1 with a given shock velocity, U_l, collides with another object M_2 at rest as shown in Figure 6. Relation between shock pressure, P, and applied time of shock pressure, Δt, is expressed according to the conservation law of momentum as follows,

$$\rho_l U_l \Delta t\,(u_2-u_l) = (P_l-P_2)\,\Delta t \qquad (6)$$

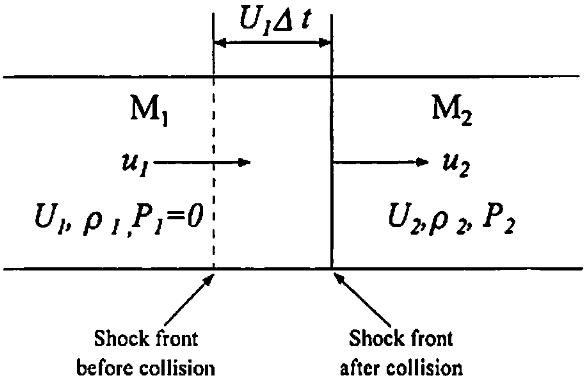


Fig. 6 Schematic illustration for explanation of conservation law of momentum.

where ρ and u are density and particle velocity, respectively. Subscripts 1 and 2 are defined for flying and shock-loaded objects, respectively. Here, since M_1 has no shock pressure before collision, P_2, is given as

$$P_2=\rho_l U_l (u_l-u_2) \qquad (7)$$

Now, let us apply Eq.(7) to a case of the experimental apparatus in this study. At first, the velocity of the metal jets (12000 m s^{-1}) is regarded as particle velocity indicated in Fig 5. We also assume that the same materials are used as M_1 and M_2, Here, when a head-on collision of the metal jets occurs at center of the metal block, u_l becomes zero. Therefore, shock pressure obtained by head-on collision of metal jets is given by

$$P_2=\rho_l U_l u_l \qquad (8)$$

Here, U_l is sum of sound velocity, c_l, and u_l. Thus, from Eq.(8), an expression for shock pressure at the head-on collision of metal jet is derived as follows,

$$P_2=\rho c_l u_l + \rho u_l^2 \qquad (9)$$

In addition, we assume that metal copper is used as object M whose density is about 8900 kg m^{-3}. As a result, it is found to be obtained extremely high shock pressure in order of TPa (10^{12} Pa) from only the second term in the right-hand side of Eq.(9) at least, though the sound velocity c_l at that time is uncertain.

4.2 Experimental results of generation of metal jets

Figure 7 shows an outer view of the experimental apparatus used in this study. Figures 8(a) and (b) show the apparatus to which shock pressure was applied and its sectional region of the metal block, respectively. The experiment was performed by using aluminum-titanium combination system as mentioned above. The sectional view was taken from center axis region of the titanium block. It was observed that some of metal jets were trapped in the neighbor of the center axis. When the interface between aluminum

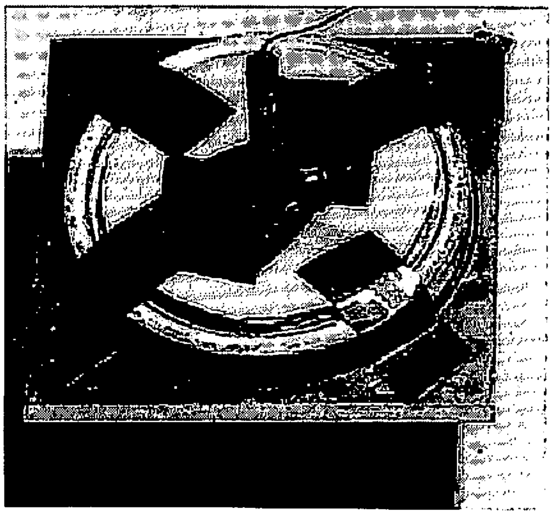


Fig. 7 Photograph of outer view of the experimental apparatus.

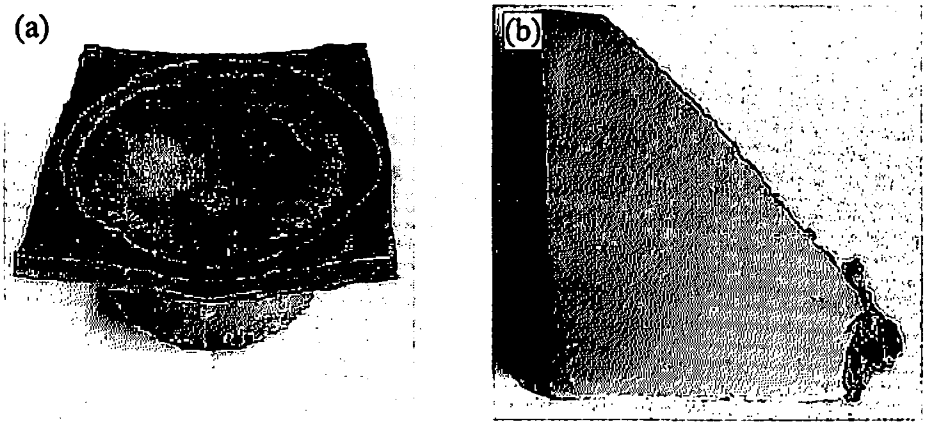


Fig. 8 Photographs of cross sectional region of the metal block after shock loading.

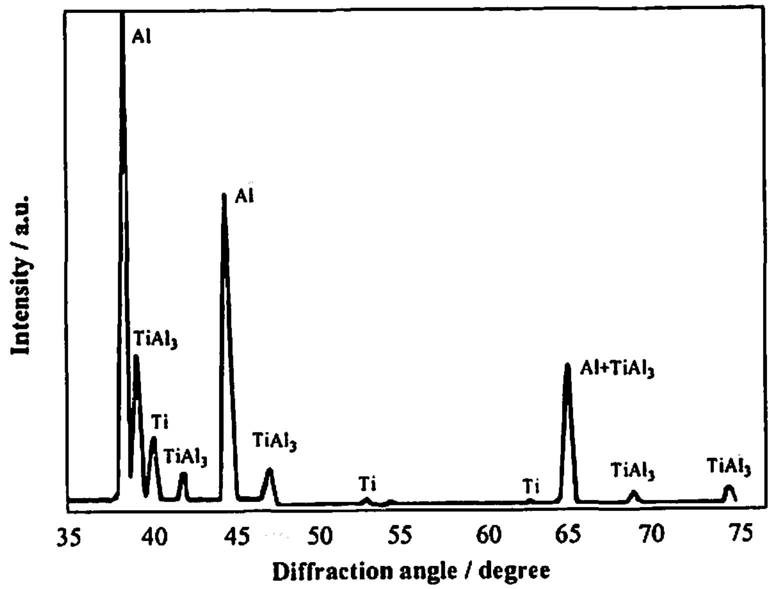


Fig. 9 X-ray diffraction pattern from interface of the specimen obtained after shock was applied.

and titanium was investigated by X-ray diffractometry (X-ray source: Cu kα, Rigaku Corporation, Tokyo, Japan), $TiAl_3$ intermetallic compound was detected accompanying with aluminum and titanium as shown in Figure 9. This means that a reaction accompanied with shearing and friction occurred, while the aluminum flyer plate collided heavily with the titanium block. In addition, a thick anvil (see Fig. 1) was fractured due to the collision of the metal jets. It was considered that the launched jets were converged on center axis, then were spouted downward along the 10 mm-center hole of titanium block. It was also speculated that the jets must have been launched as very fine molten particles because no massive metal was found after experiments. Thus, it suggested that the jets with high velocity had possibility to create extremely high shock pressure even small quantities.

5. Conclusions

In this study, apparatus for generating extremely high shock pressure was developed newly by utilizing convergent collision of metal jets. In this apparatus, it was found that the metal molten particle flow with high velocity must have been formed during collision of flyer plate with concavely conical metal block. After that, the metal jets converged at center axis of the metal block. It was suggested that the collision of the metal jets should produce extremely high shock pressure because the shock pressure depends on particle velocity of the metal jets. In this system, optimum conical angle in the metal block to get high jet velocity is present, e.g. 30 to 35 degree. If the metal jets have particle velocity of about 12000 m s^{-1}, it is expected that extremely high shock pressure of an order of TPa is obtained. In addition, this high-pressure generation system may include possibilities to produce novel alloy or high-pressure phase.

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