XIII International Symposium on Explosive Production of New Materials: Science, Technology, Business, and Innovations

EPNM-2016

OBSERVATION OF THE METAL JET GENERATED BY THE INCLINED COLLISION USING A POWDER GUN

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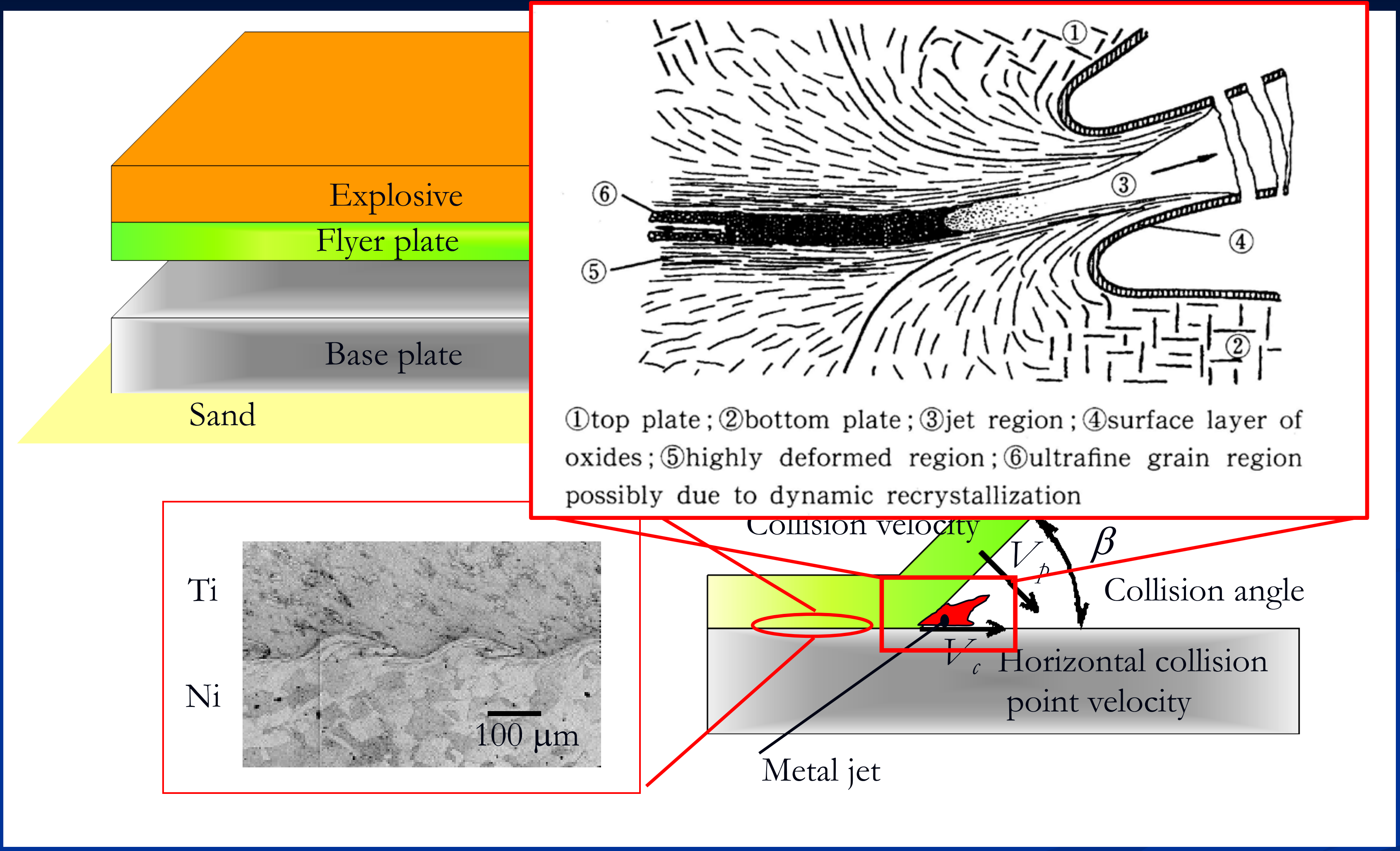
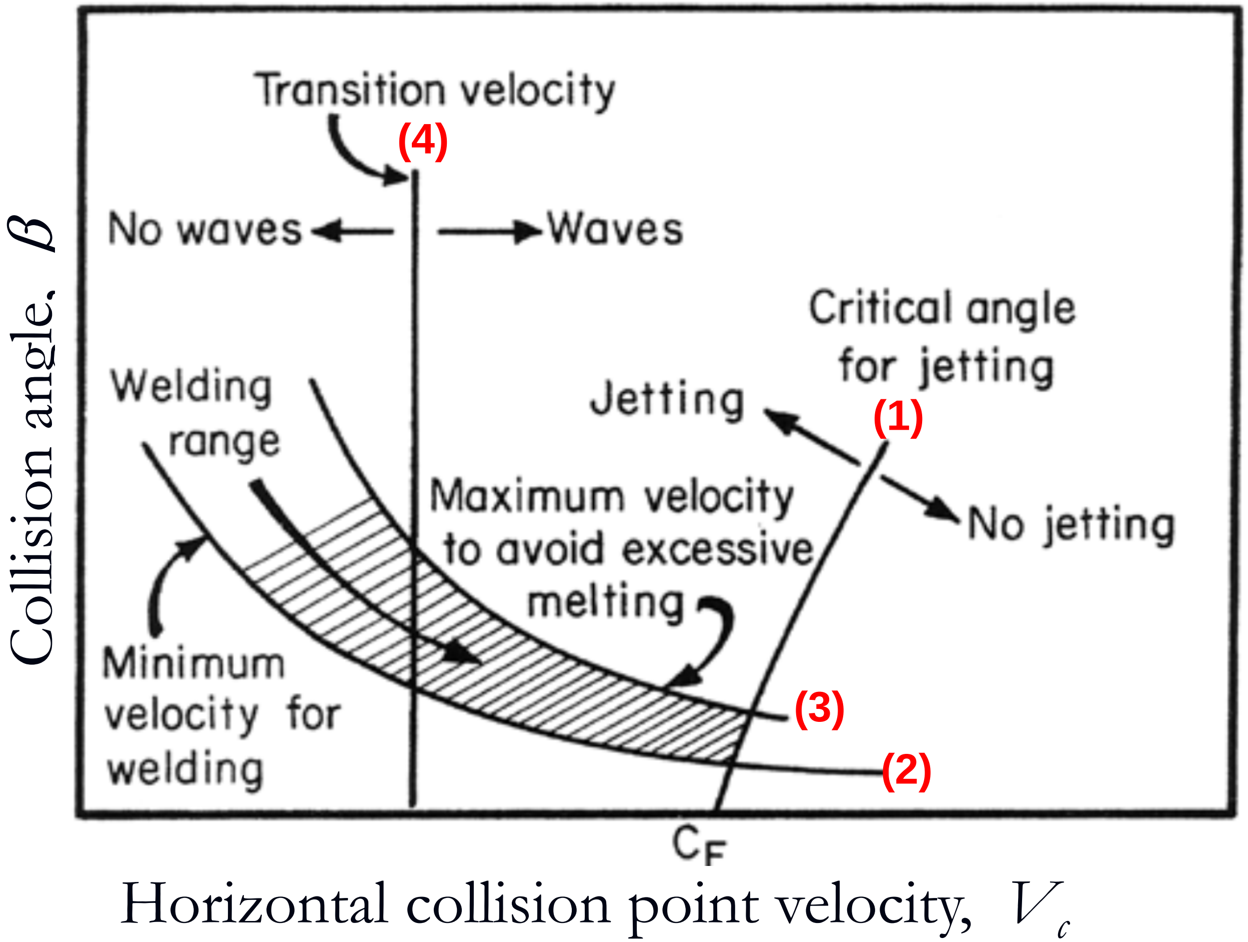
Explosive welding technique



- Thin heat affected layer (no intermetallics)
- High bonding strength

Welding window proposed by Wittman and Deribas



Boundary conditions

(1) Critical angle for jetting

(2) Lower limit:

$$\sin(\beta/2)=k_1(H_V/\rho V_c^2)^{1/2}$$

(3) Upper limit:

$$\sin(\beta/2)=k_3/(t^{0.25}\cdot V_c^{1.25})$$

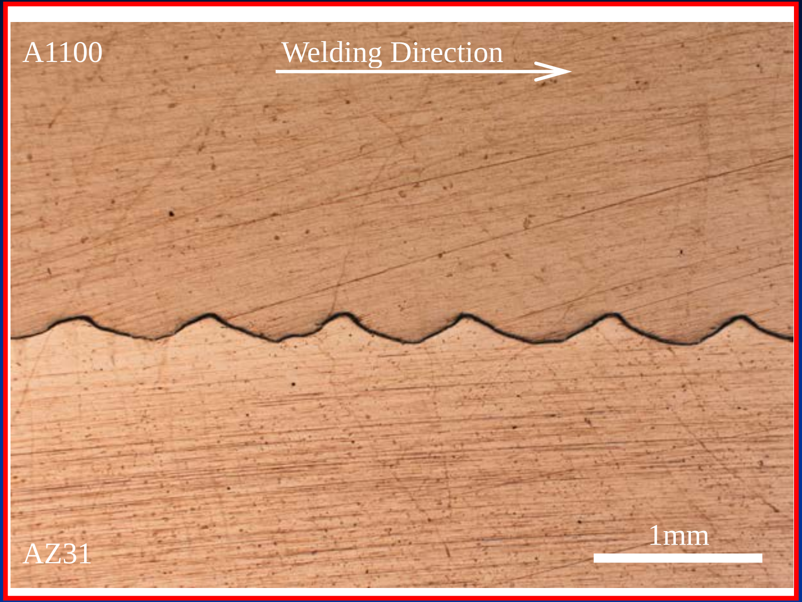
(4) Transition velocity:

$$Re=(\rho_F+\rho_B)\, V_c^2\,/(2(H_{VF}+H_{VB}))$$

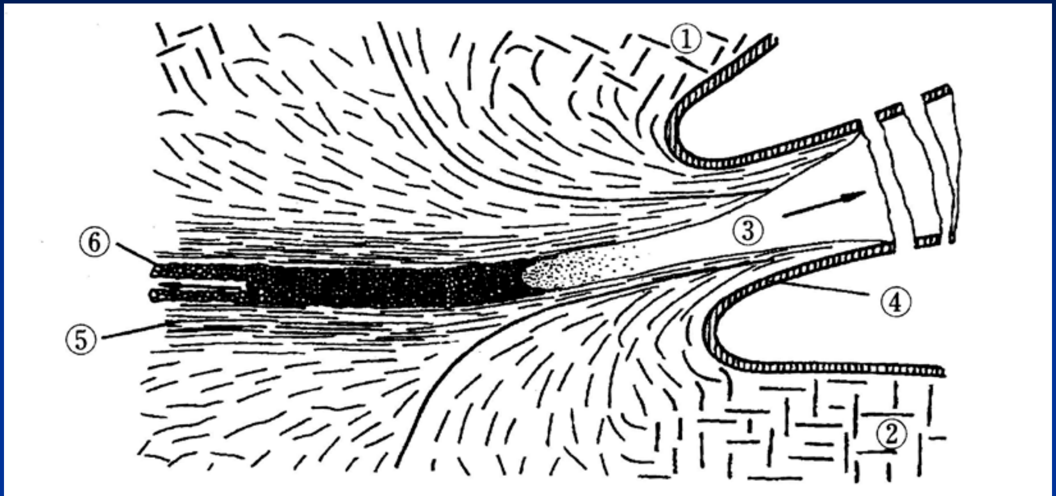
Relation of the collision point velocity V_c, collision velocity Vp, and collision angle β

$$V_p = 2V_c \sin\left(\frac{\beta}{2}\right)$$

Ref. Explosive welding of metals and its application, B. Crossland

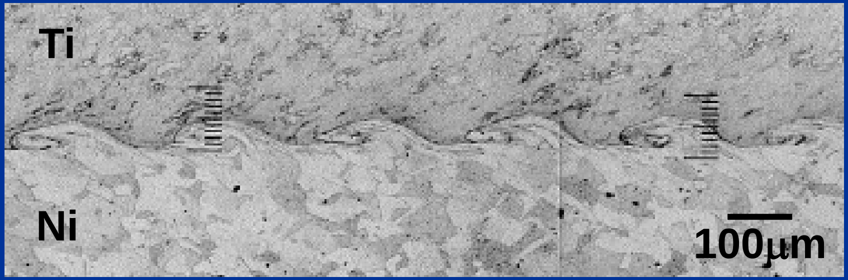


Wavy interface of aluminum alloy / magnesium alloy



①top plate ; ②bottom plate ; ③jet region ; ④surface layer of oxides ; ⑤highly deformed region ; ⑥ultrafine grain region possibly due to dynamic recrystallization

Schematic of the metal jet generation



Wavy interface of titanium / nickel

Metal jet

Metal jet is known well as the one of the important parameters to achieve the good welding in the explosive welding technique.

This phenomena have been researched by many researchers.

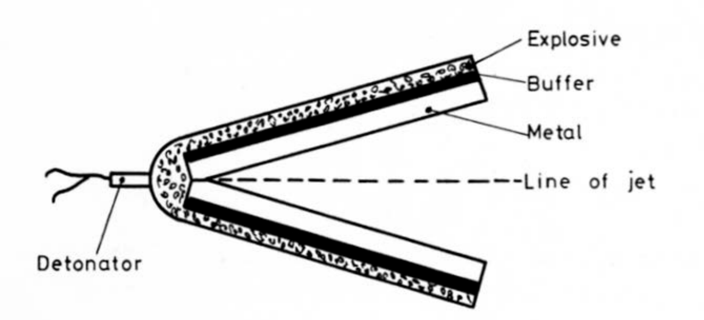
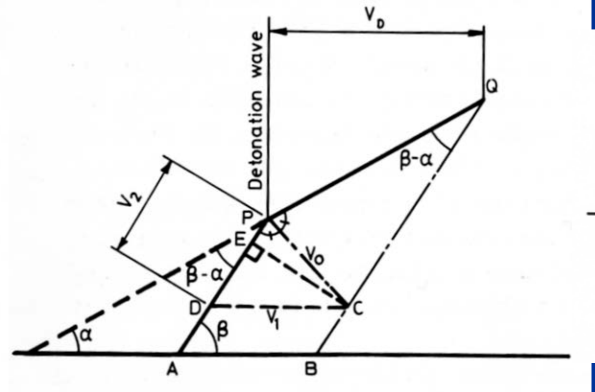
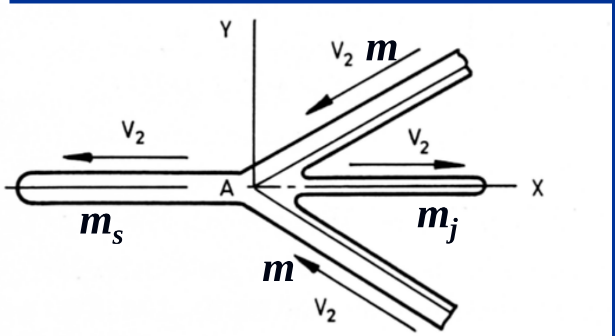


FIG. 2.5 Symmetrical oblique impact welding (11)





Velocity of jet

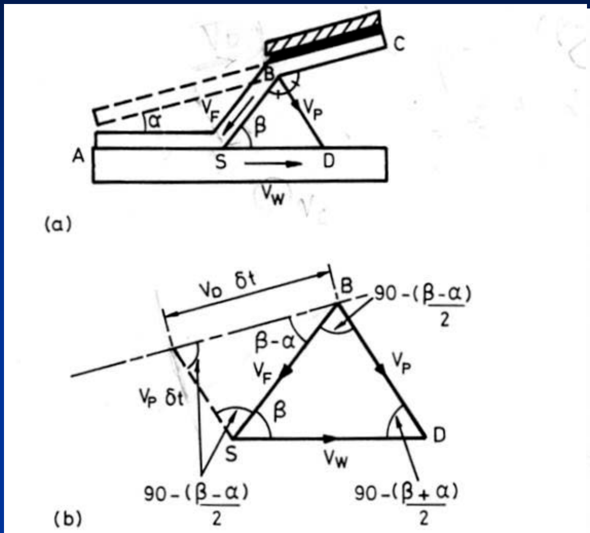
$$V_j = V_1 + V_2 = V_0 \left[\frac{\cos\frac{1}{2}(\beta-\alpha)}{\sin\beta} + \frac{\cos\frac{1}{2}(\beta-\alpha)}{\tan\beta} + \sin\frac{1}{2}(\beta-\alpha) \right]$$

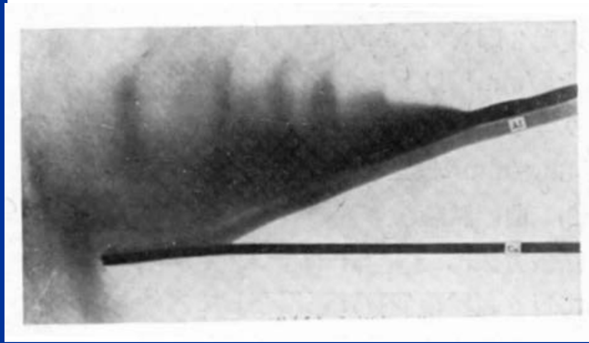
Mass of jet

$$m_j = m(1-\cos\beta)$$

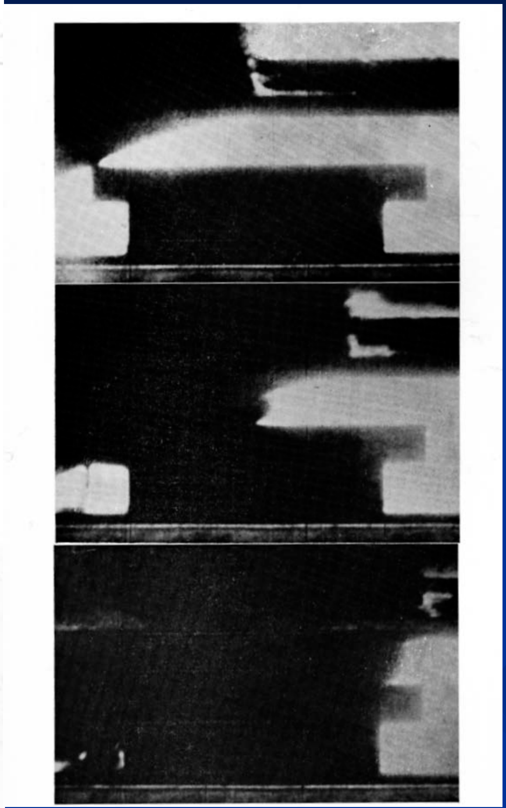
Ref: B.Crossland; Explosive Welding of Metals and its Application, Oxford University Press (1982).
Y. Ishii, Metal to Kayaku (in Japanese), No.4, (1969).

Observation of metal jet reported

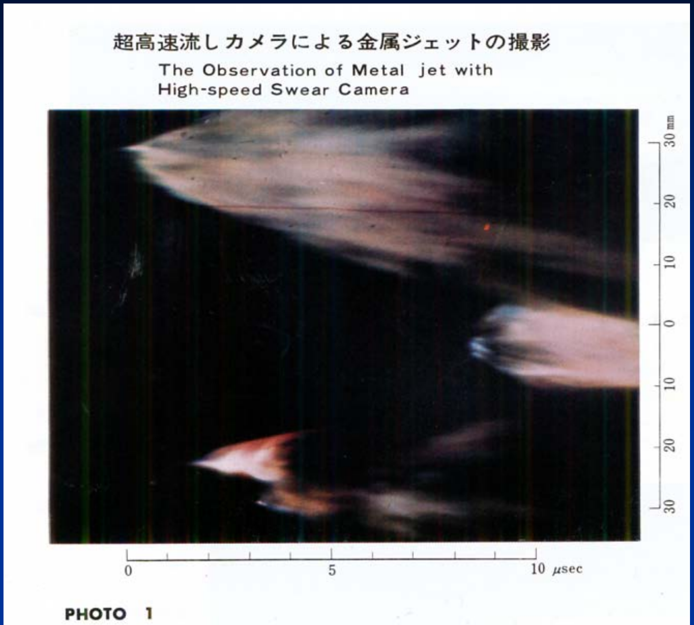


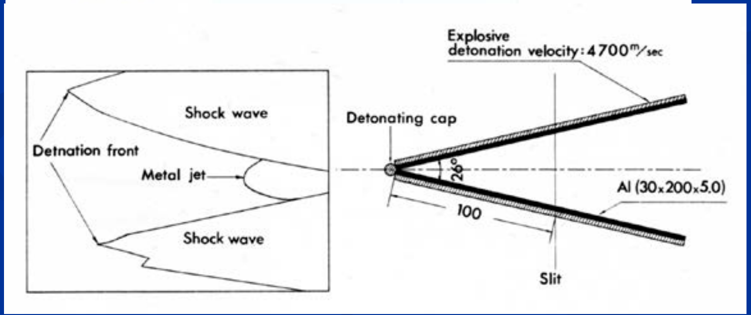


Behavior of metal in explosive welding using X-ray flash light



Metal jet generation





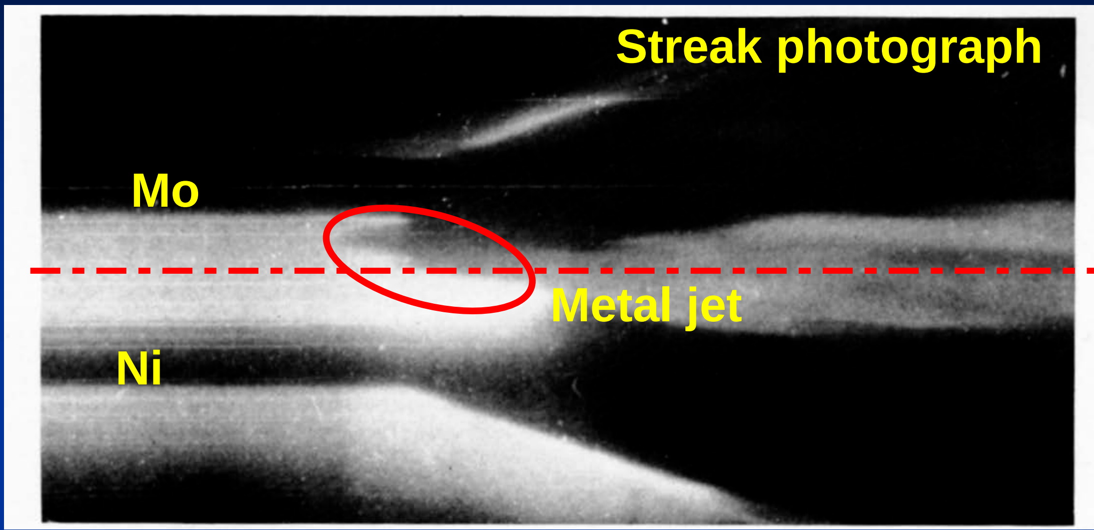
Observation of Metal jet with High-speed Streak Camera

Al/Al（Similar metal welding）

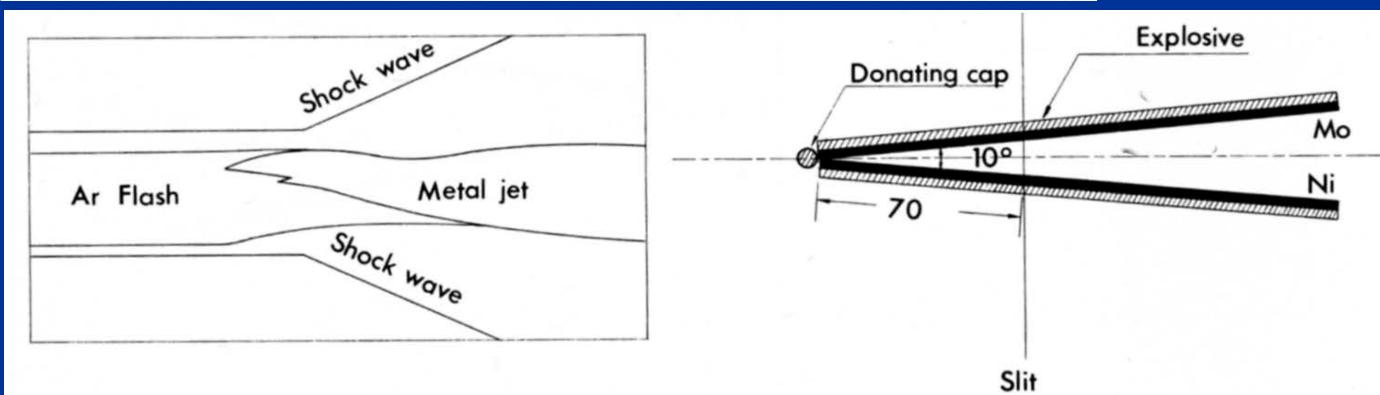
Ref: Metal to Kayaku (in Japanese) No.4, (1969).

Ref: Y. Ishii, T. Onzawa: The Observation of Metal jet with High-speed Swear Camera, Metal to Kayaku, No.7, (1970).

Behavior of a metal jet



These figures show the behavior of a metal jet in the dissimilar welding.
Prof. Ishii reported that a metal jet in the dissimilar metal combination was propagated toward the heavy metal.

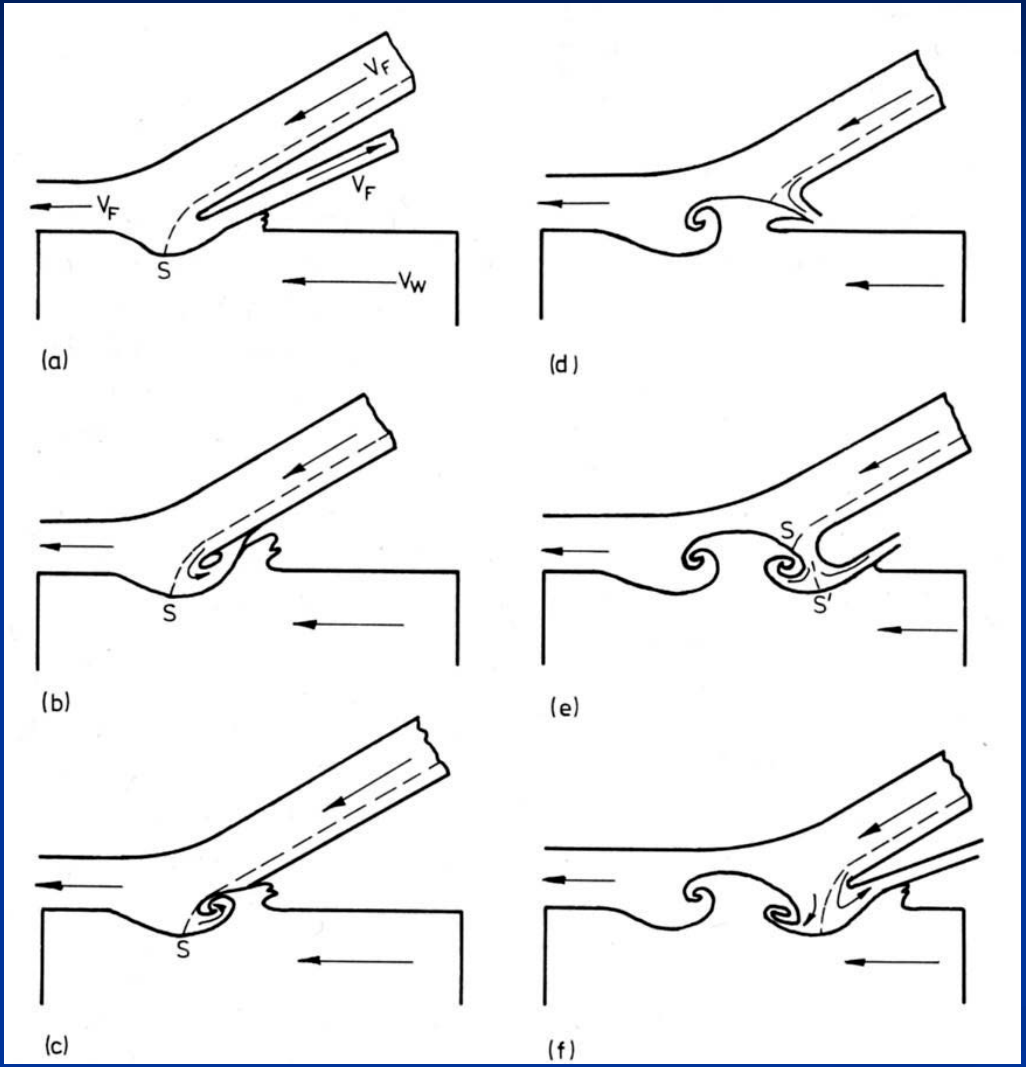


Mo/Ni（Dissimilar）

Metal jet was propagated toward the heavy material (Mo:density10280 kg/m^3)

Ref: Y. Ishii, T. Onzawa: The Observation of Metal jet with High-speed Swear Camera, Metal to Kayaku, No.7, (1970).

Wavy interface generation



- Bahrani's theory

(a) A hump is formed ahead of the point of impact by a metal jet.

(b) This hump deflects the jet upwards into the flyer plate.

(c) The hump blocks off the jet completely.

(d) When the hump blocks off the jet the stagnation point moves from the trough to the crest of the wave

(e)-(f) A hump is formed continuously ahead of the point of impact.

Ref: B.Crossland; Explosive Welding of Metals and its Application, Oxford University Press (1982).

Wavy interface generation

Interfacial waves in explosive welding is similar to the Kármán vortex street

(researched by Cowan et al, Kowalick et al, etc.)

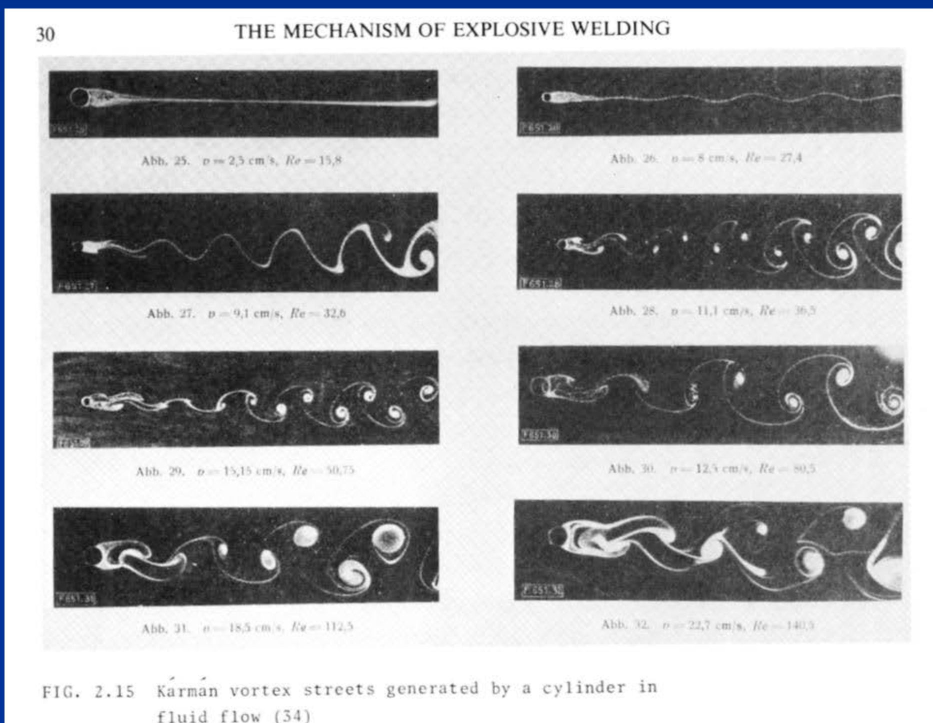

30 THE MECHANISM OF EXPLOSIVE WELDING

Abb. 25. $v = 2{,}5$ cm/s, $Re = 15{,}8$

Abb. 26. $v = 8$ cm/s, $Re = 27{,}4$

Abb. 27. $v = 9{,}1$ cm/s, $Re = 32{,}6$

Abb. 28. $v = 11{,}1$ cm/s, $Re = 36{,}5$

Abb. 29. $v = 15{,}15$ cm/s, $Re = 50{,}75$

Abb. 30. $v = 12{,}5$ cm/s, $Re = 80{,}5$

Abb. 31. $v = 18{,}5$ cm/s, $Re = 112{,}5$

Abb. 32. $v = 22{,}7$ cm/s, $Re = 140{,}5$

FIG. 2.15 Kármán vortex streets generated by a cylinder in fluid flow (34)

Kármán vortex streets generated by a cylinder in fluid flow

Kármán vortex street：

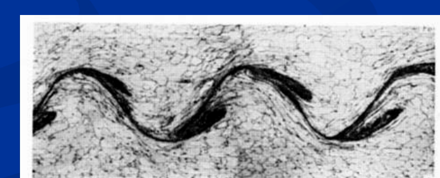
A repeating pattern of swirling vortices caused by the unsteady separation of flow of a fluid around blunt bodies.

⬇

blunt body = point of impact

fluid = flyer plate and/or base plate

Kármán vortex = Interfacial waves

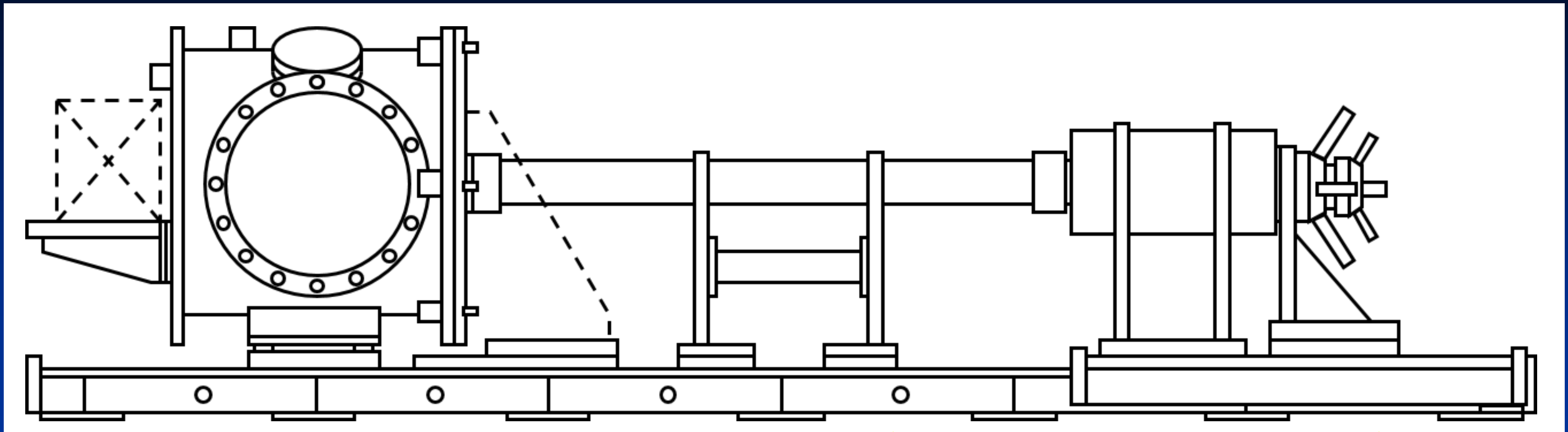


Ref: B.Crossland; Explosive Welding of Metals and its Application, Oxford University Press (1982), p.30.

Many researchers have investigated for the formation of interfacial waves and the generation of a metal jet.
These phenomena are important to achieve the good welding in Explosive welding.

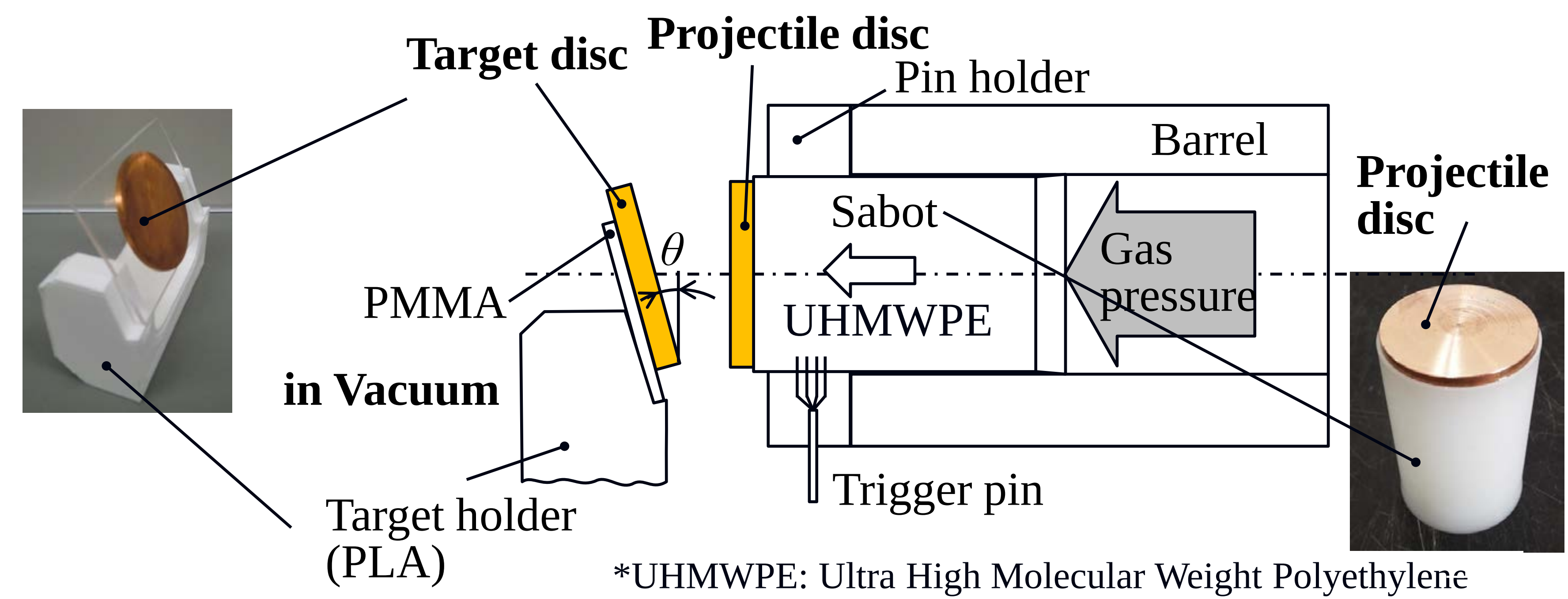
However, in explosive welding method, it is difficult to observe the welding process, such as the behavior of metal jet and collision of metals, by the optical observation system.
Because the detonation gas is spread over, and then, the shape of metal plate or the metal jet are not clear.

Inclined collision using single-stage powder gun



Single-stage powder gun（Kumamoto Univ.）

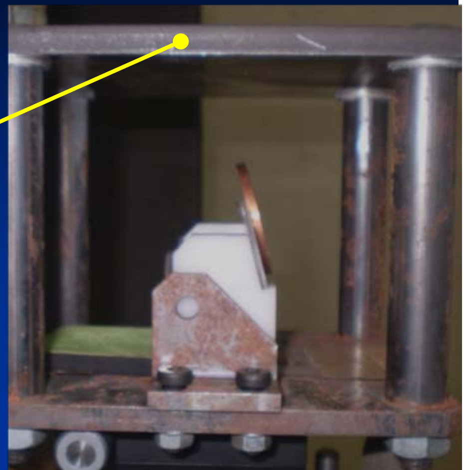
As the generated gas exists only behind the projectile, the collisional process can be observed clearly

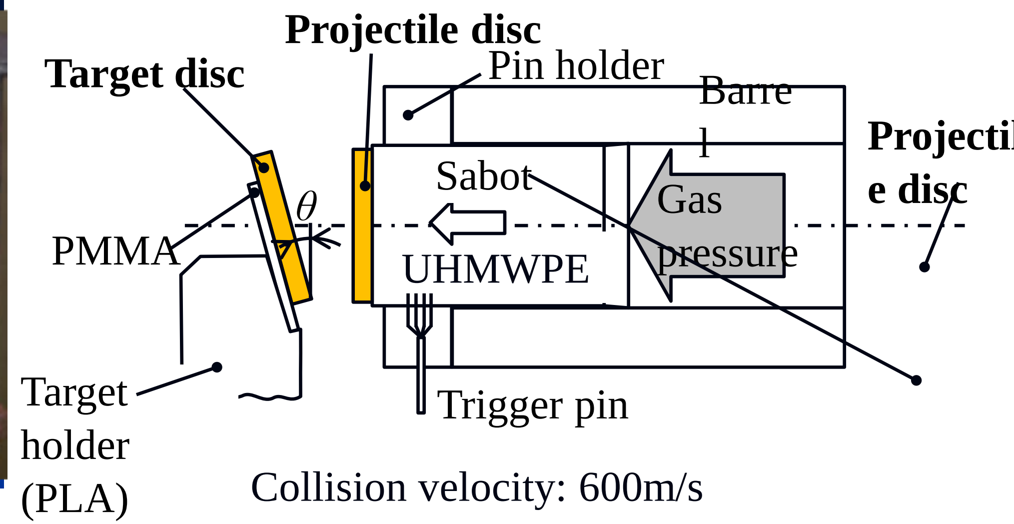


*UHMWPE: Ultra High Molecular Weight Polyethylene

Optical observation system

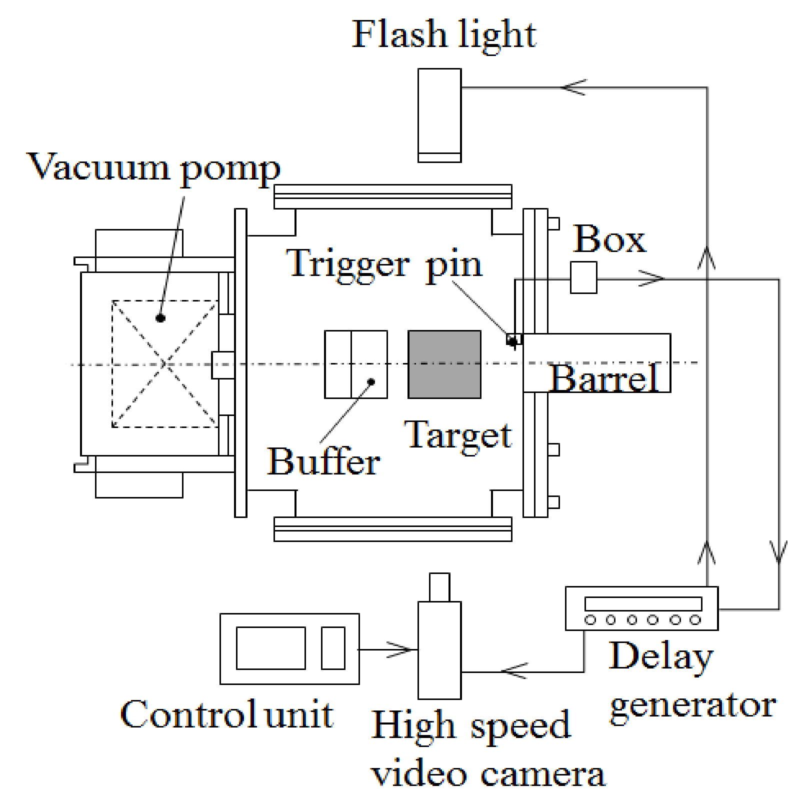
Protection plate for a metal jet





Collision velocity: 600m/s

Collision angle (Inclined angle of target disc)
: θ = 20 degrees



High-speed video camera, HPV-1
(Shimadzu Inc.)

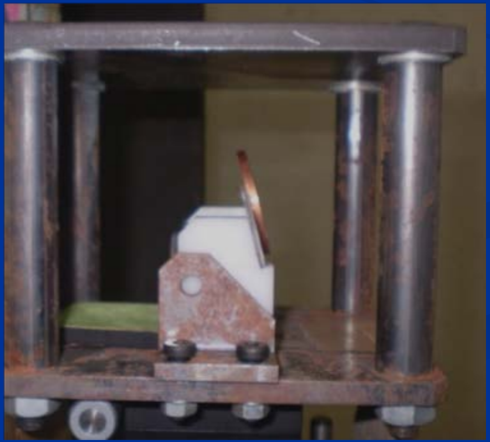
Phenomena (metal jet, interface wave) can be observed same as the explosive welding technique, by high-speed inclined collision using a powder gun.

【Objective】

1. **Optical observation of metal jet generation for the similar/dissimilar metals experimentally.**
2. **Observation of metal jet generation and the behavior of metals by numerical analysis.**

Experimental conditions

No.	Metals	Inclined angle [deg.]	Collision velocity obtained from the experiments [m/s]
Cu/Cu	Copper / Copper (Diameter: 38 mm) (Thickness: 3 mm)	20	610 (experimental results)
Mg/Cu	Magnesium alloy (AZ31) / Copper (Diameter: 38 mm) (Thickness: 15.5 / 3 mm)	20	580 (experimental results)



Target velocity: 600 m/s

Numerical condition

ANSYS AUTODYN 2-dimensional analysis

Solver : SPH

(Smoothed-particle hydrodynamics)

Material: Cu/Cu, AZ31(Mg) / Cu

diameter: 38 mm, thickness : 3 mm

inclined angle of target disc: 20°

collision velocity, V_p : 600m/s

particle size

(like as the mesh size in Lagrangian)

Cu/Cu: 0.05mm, Mg/Cu: 0.04mm

Material parameters used

Mie-Grüneisen formed shock equation of state

$$P = \frac{\rho_0 C^2 \eta}{(1 - s\eta)^2}\left(1 - \frac{\Gamma \eta}{2}\right)$$

P : pressure, ρ_0 : density, C : sound velocity
s : material parameter, Γ : Grüneisen coefficient
$\eta = 1 - \rho_0 / \rho$

Shock E.O.S.	ρ_0 [kg/m³]	Γ	C [m/s]	s	T_{ref} [K]	c_p [J/kgK]
Cu	8960	1.99	3940	1.489	300	383
Mg（AZ31）	1755	1.43	4516	1.256	300	100

Johnson-Cook Strength model

$$Y = \left[A + B\varepsilon_p^n\right]\left[1 + C\ln\varepsilon_p^*\right]\left[1 - T_H^m\right]$$

J-C	G [Gpa]	A [Mpa]	B [MPa]	C	n	m	T_{melt} [K]
Cu	46	90	292	0.025	0.31	1.09	1356
Mg(AZ31)	165	224	380	0.012	0.761	1.554	878

ε_p : effective plastic strain, ε_p^* : normalized effective plastic strain rate
T_H : homologous temperature = $(T - T_{room}) / (T_{melt} - T_{room})$
A = Initial yield stress, B = Hardening constant, C = Strain rate constant
n = Hardening exponent, m = Thermal softening exponent

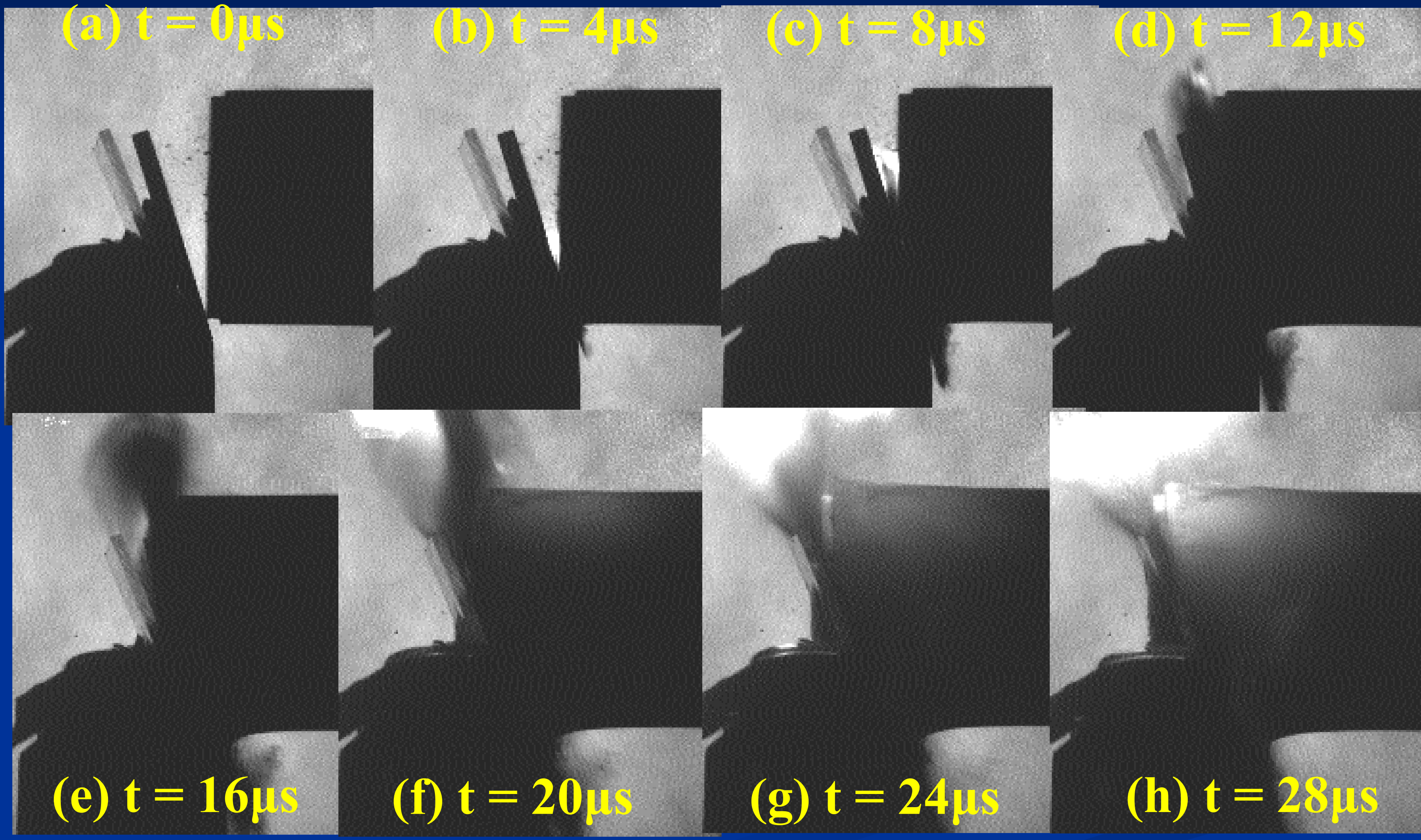
Experimental results

（ Cu/Cu, V_p＝610m/s, β＝20° ）

Interval per frames: 4μs

Experimental results

(Cu/Cu, V_p＝610m/s, β＝20°)



Collision point velocity : 1756 m/s calculated by $V_p = 2V_c \sin(\beta/2)$
Velocity of the front of the metal jet: 3000～3184 m/s

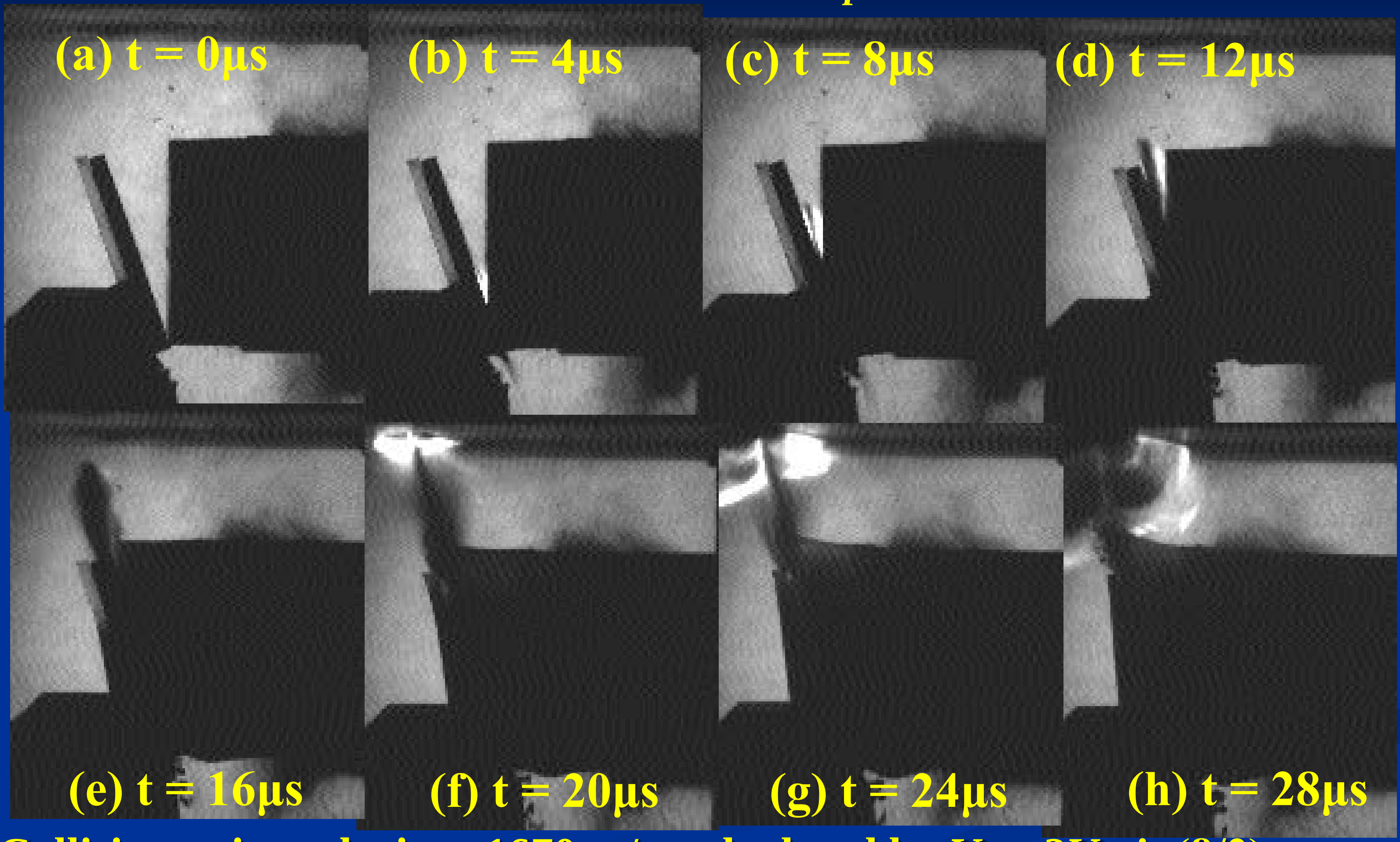
Experimental results

（ Mg/Cu, V_p＝580m/s, β＝20° ）

Interval per frames: 2μs

Experimental results

(Mg/Cu, V_p＝580m/s, α＝20°)

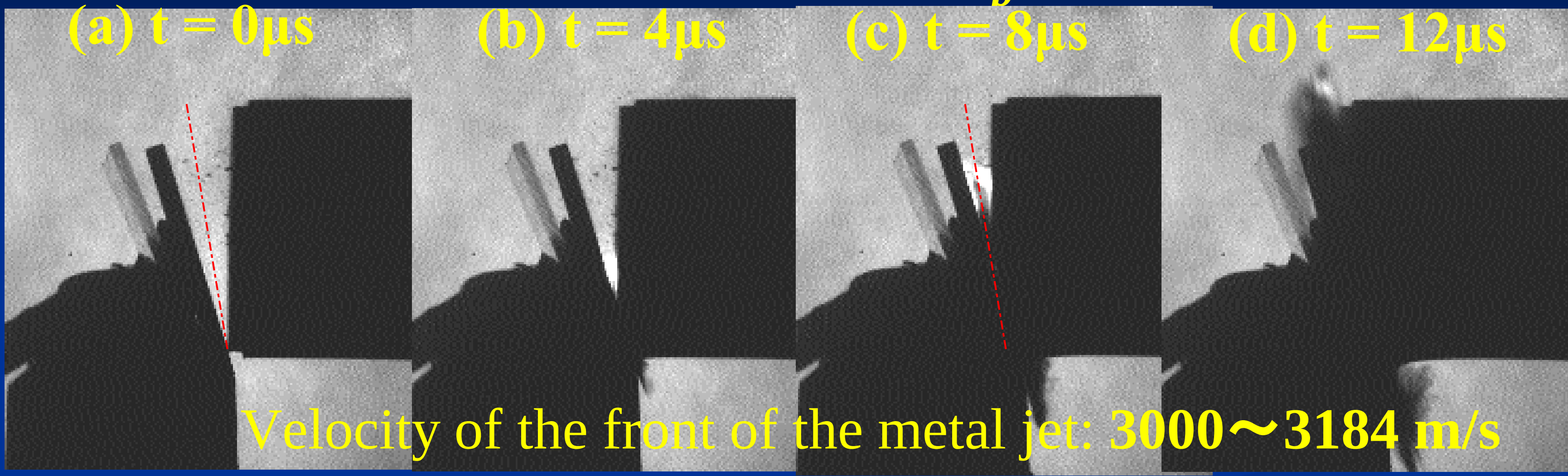


Collision point velocity : 1670 m/s calculated by $V_p = 2V_c \sin(\beta/2)$

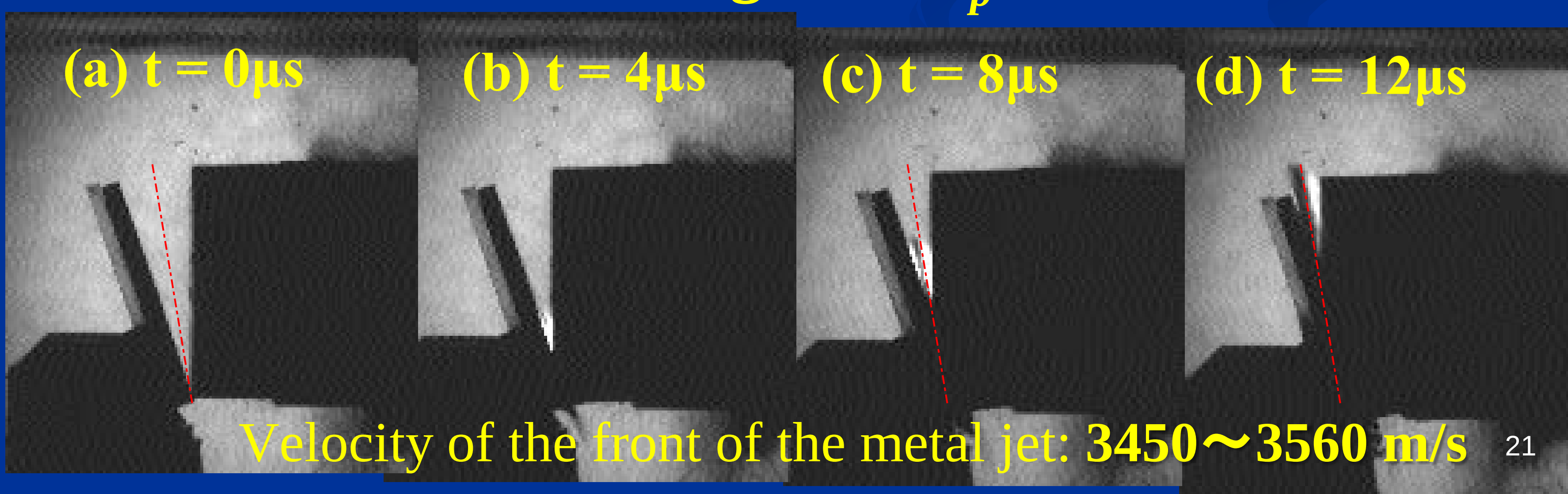
Velocity of the front of the metal jet: 3450～3560 m/s

Experimental results
– comparison similar/dissimilar collision –

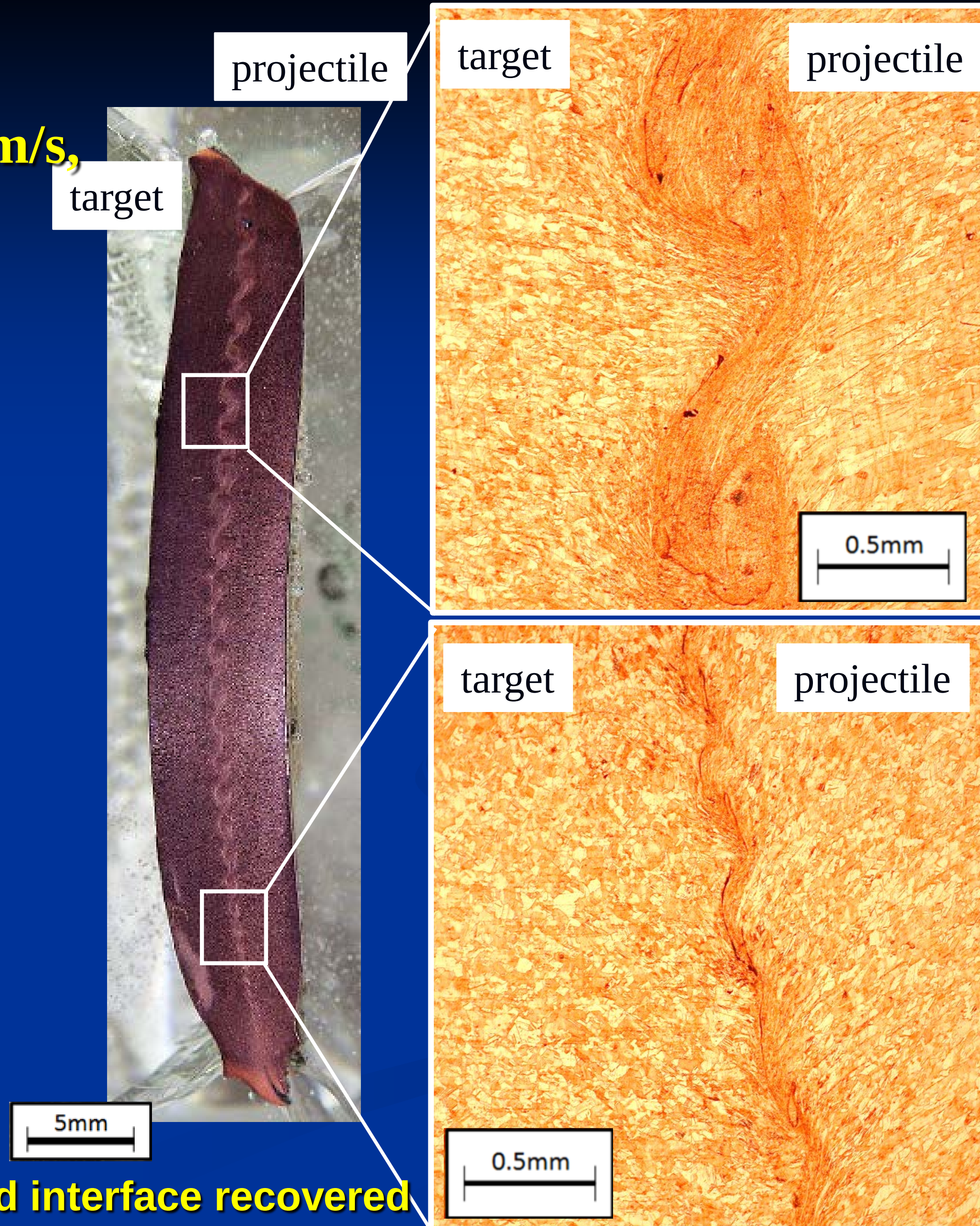
（ Cu/Cu, V_p＝610m/s, α＝20° ）



（ Mg/Cu, V_p＝580m/s, α＝20° ）



Cu/Cu,
Vp = 600m/s,
α=20°



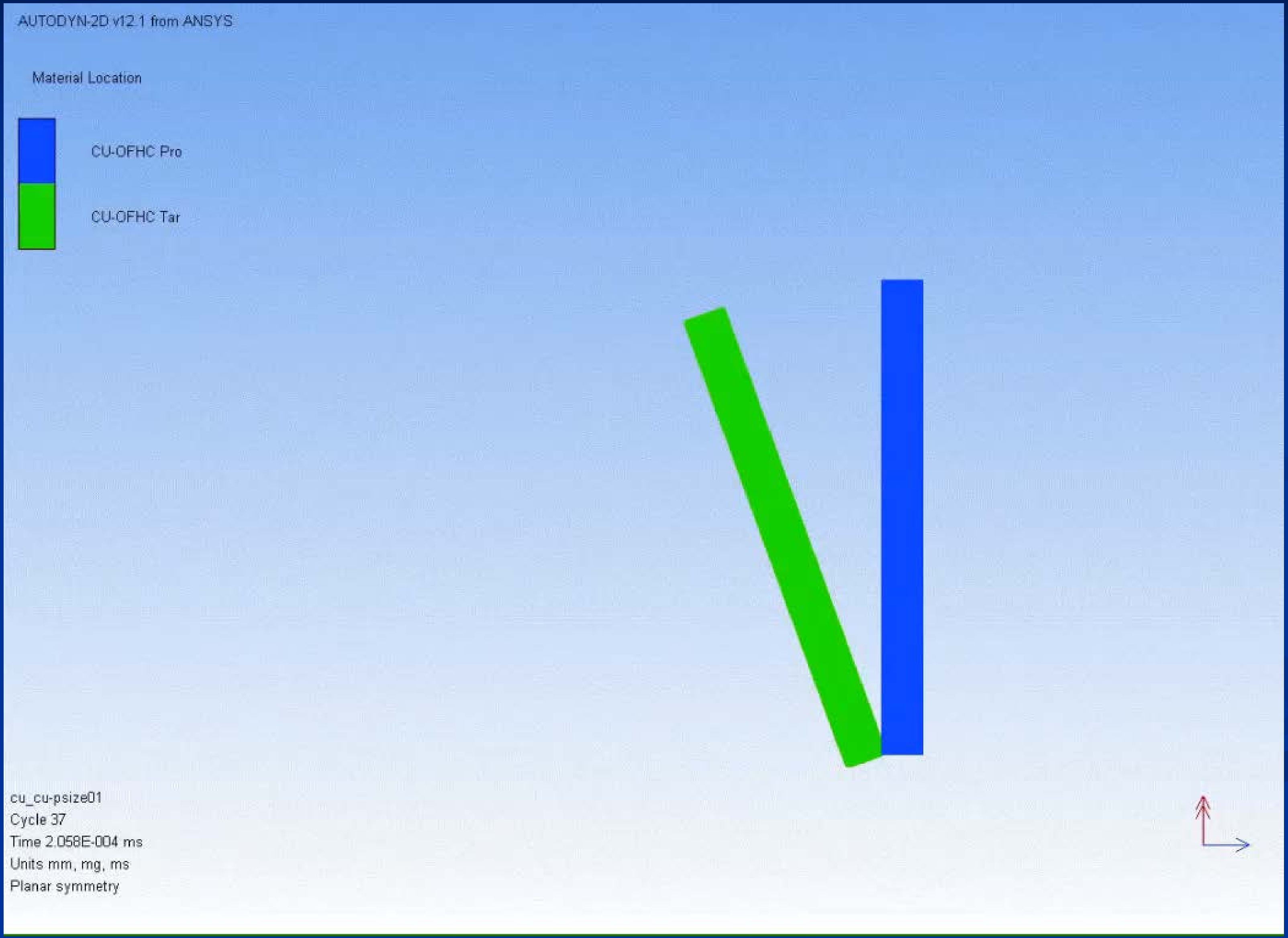
Welded interface recovered

Mg/Cu

No weld

Shock E.O.S. Particle Size 0.05mm

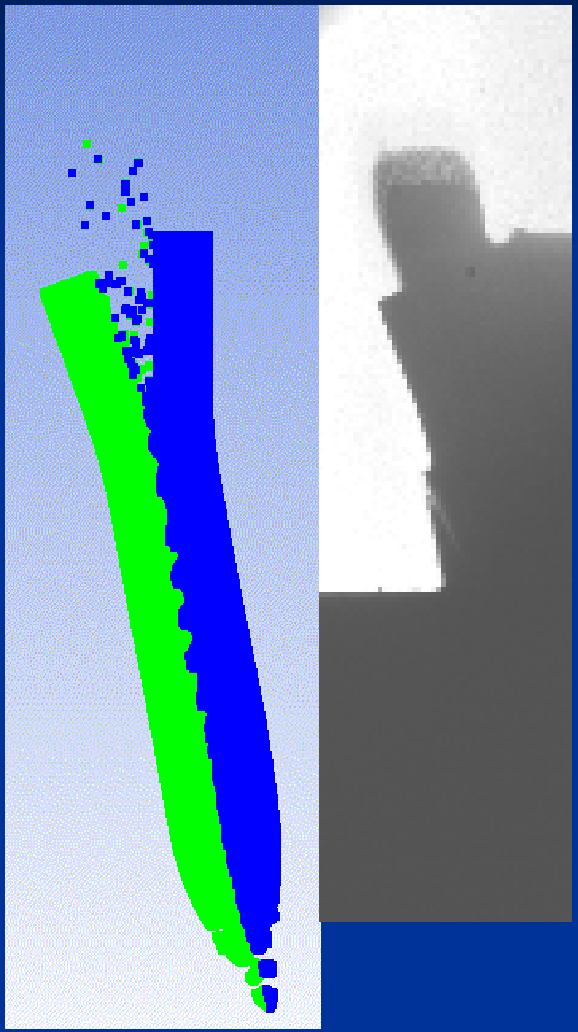
Johnson-Cook strength model

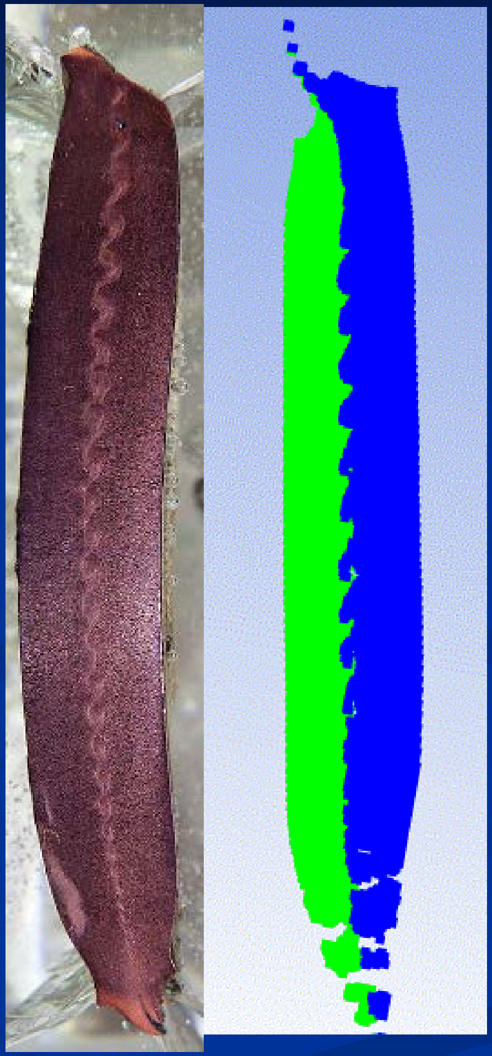


Shock
Johnson-Cook strength model

Particle Size 0.05mm

15μs

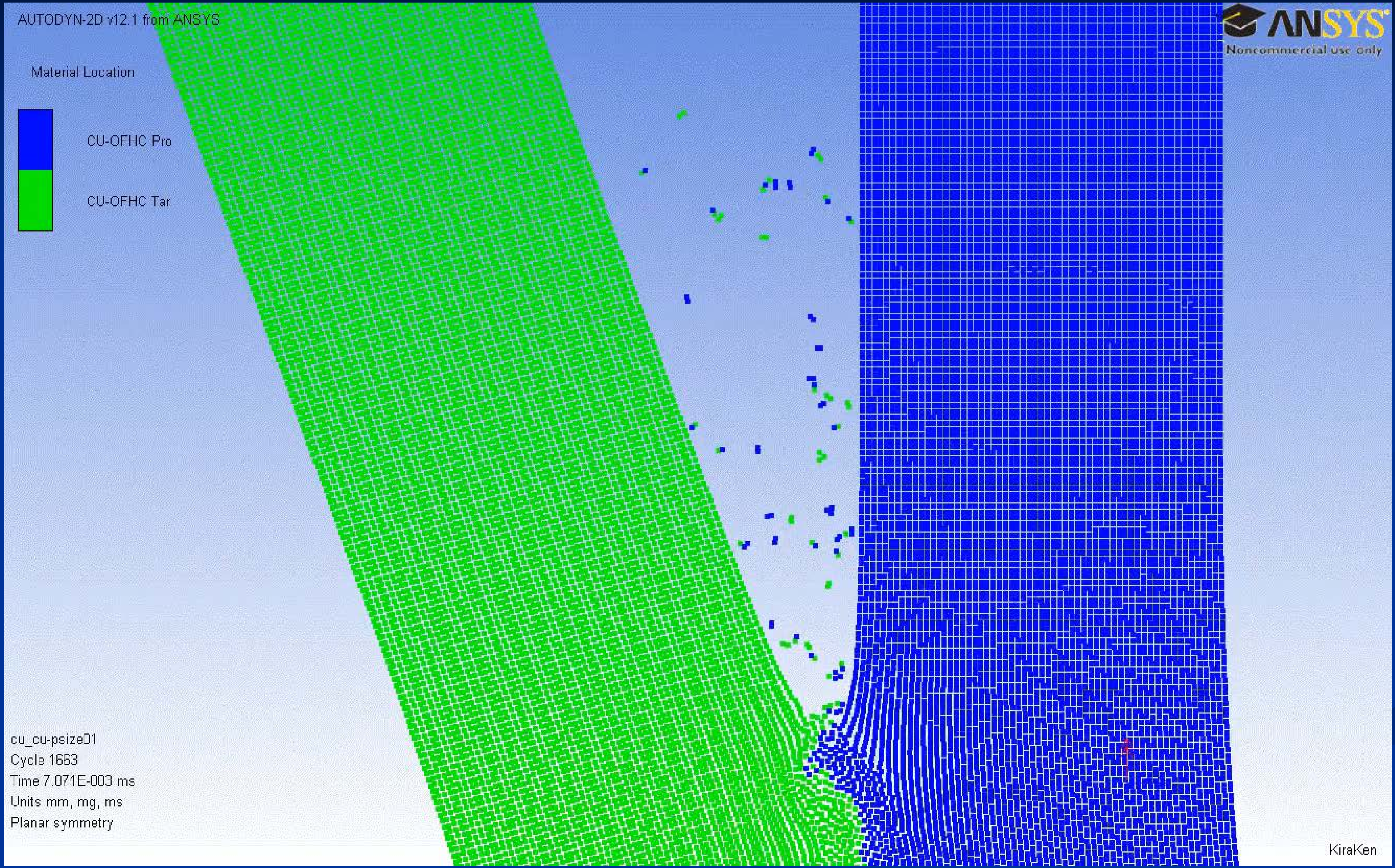




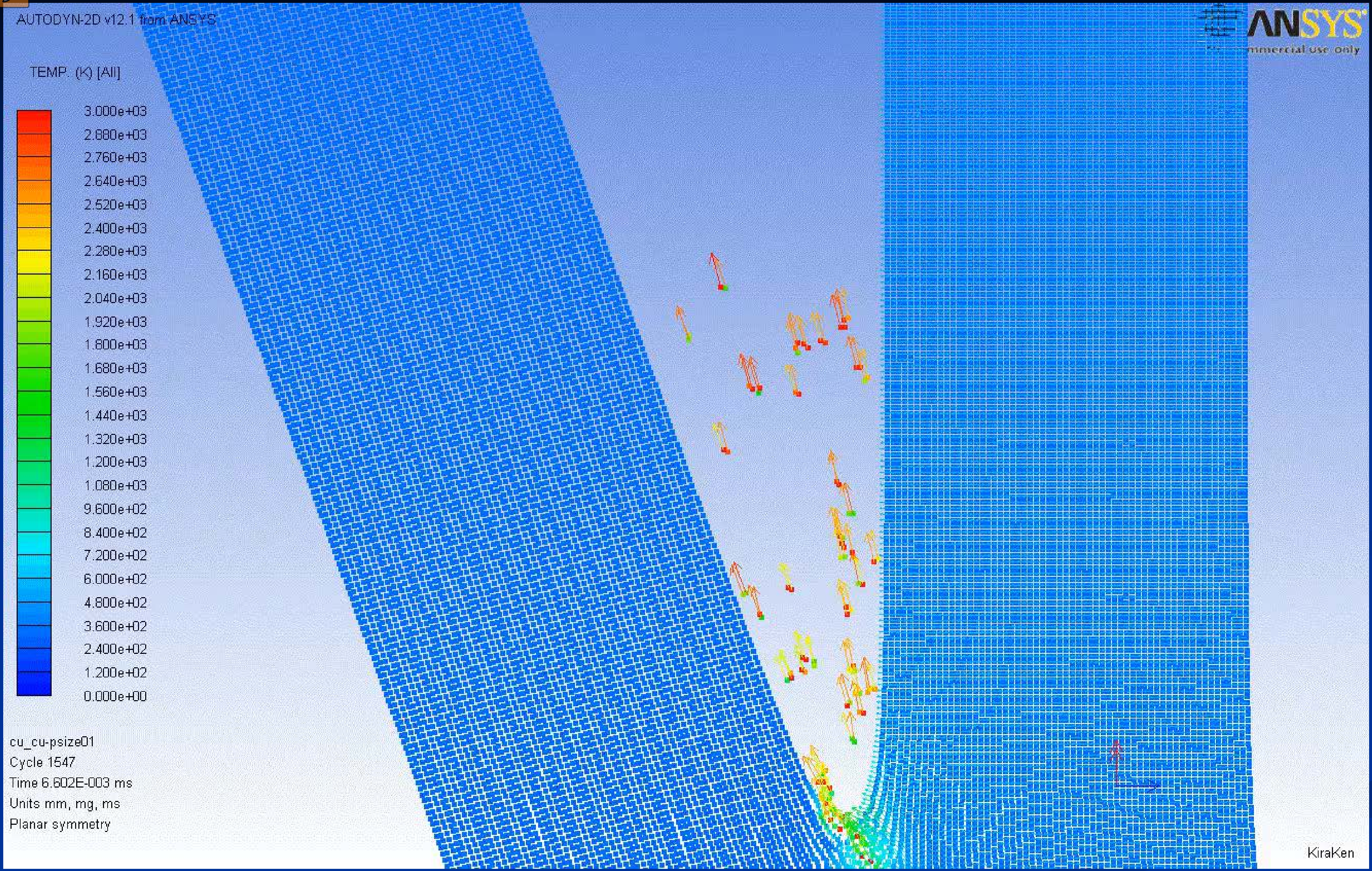
20μs

Velocity of the metal jet and the tendency of wavy interface generation are agree well with the experimental results.

Wavy interface generation, Cu/Cu

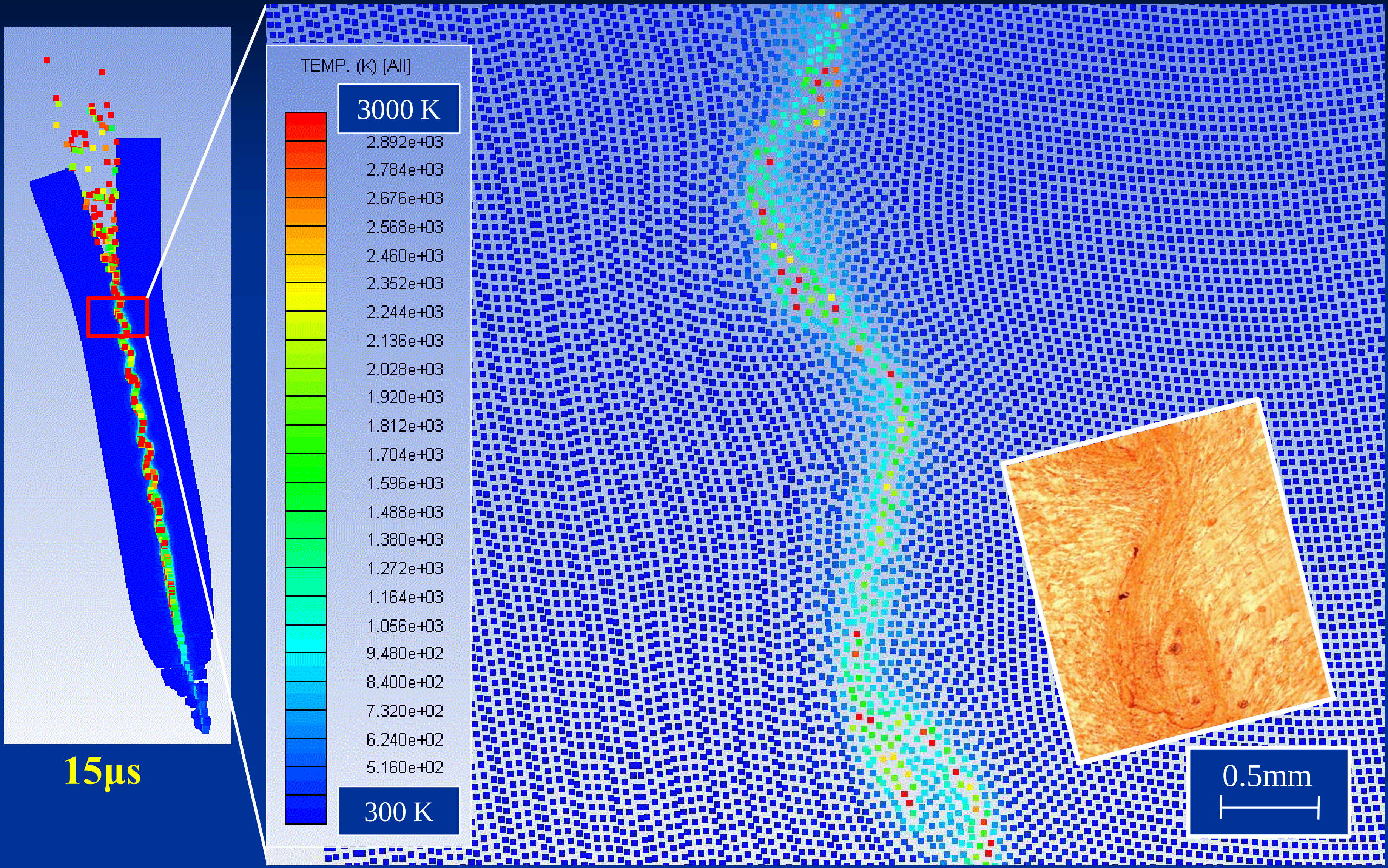


The metal jet consists of projectile and the target metal



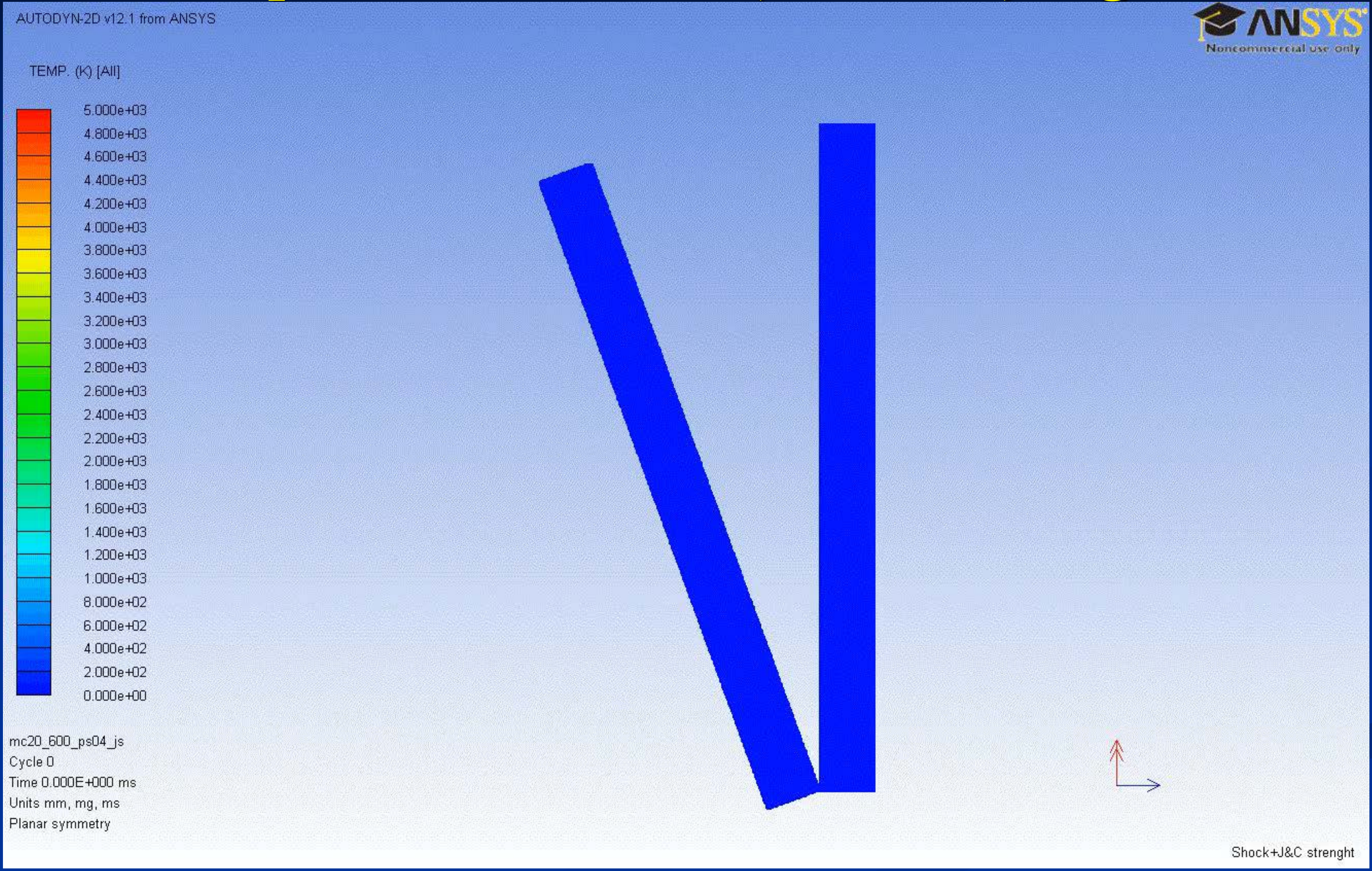
Temperature contour (0 K : blue ~ 3000 K : red) with Velocity vector (red: over 3500m/s)

Temperature contour (300 K ~ 3000 K) without Velocity vector



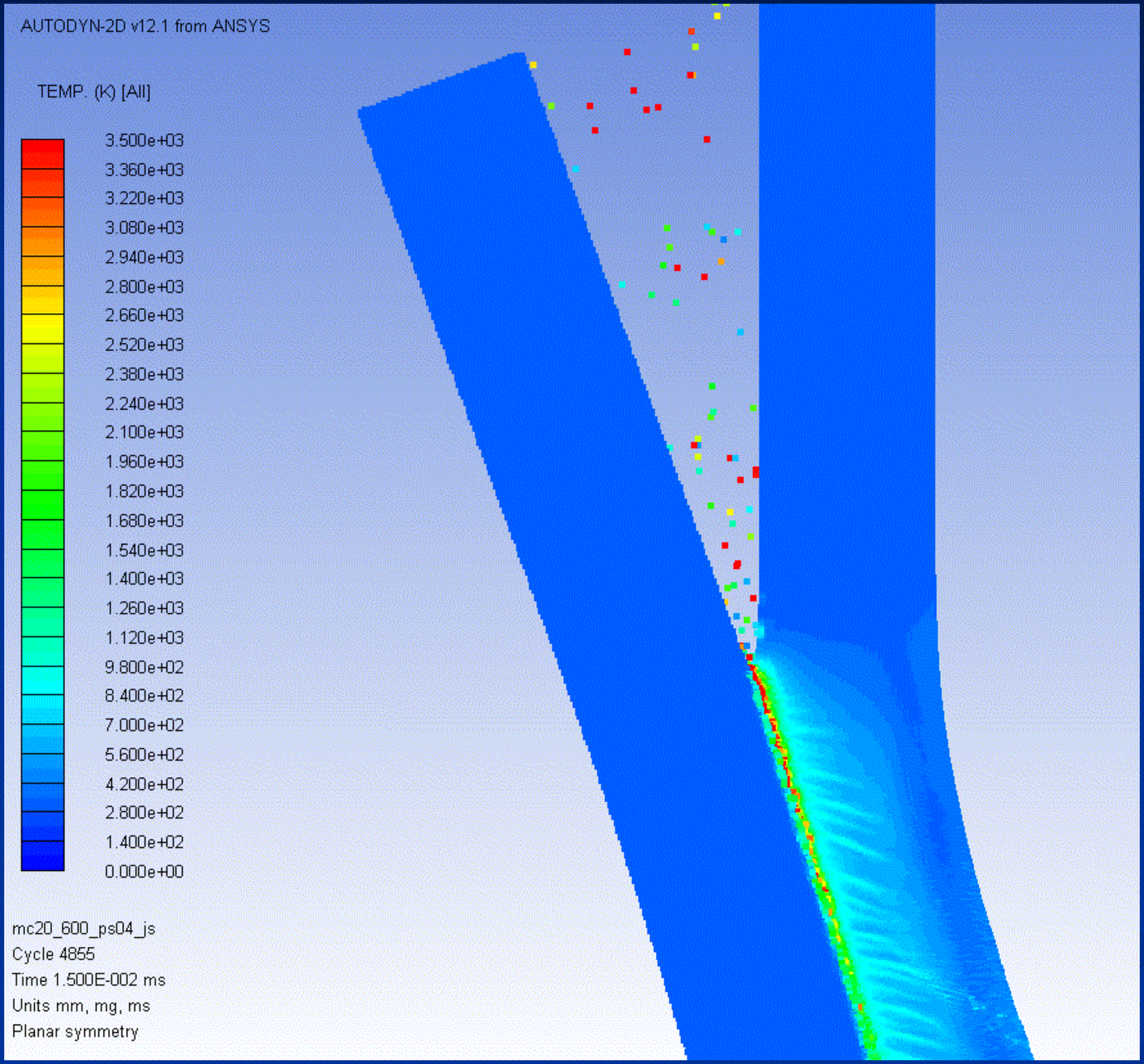
Temperature contour (300 K ~ 3000 K) without Velocity vector

Temperature contour (0~5000K) Mg/Cu



Mg/Cu, Vp = 600m/s, β=20°

Particle size 0.04mm (40 μm)



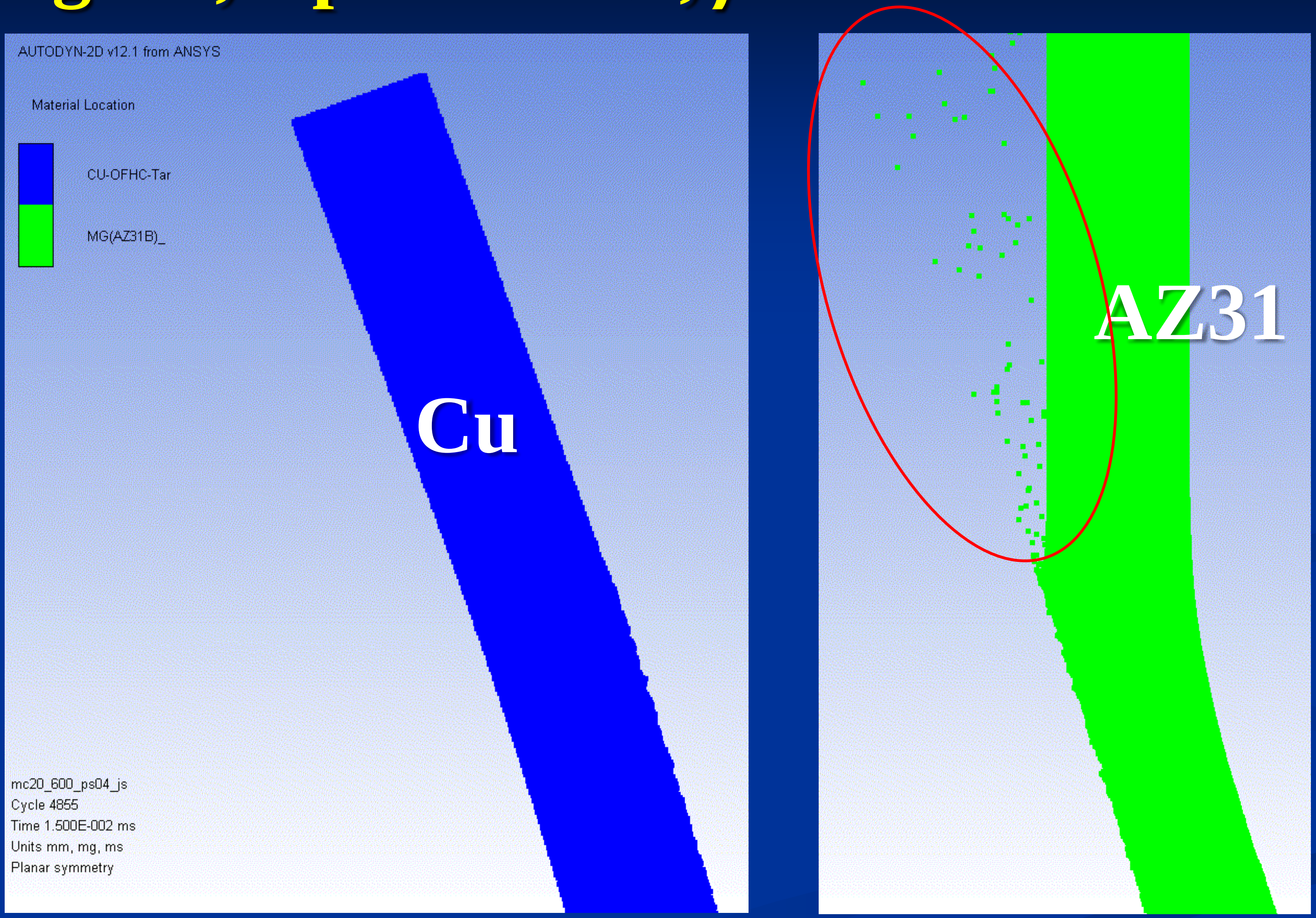
Temperature was increased at over 3500 K in the interface of metals. The heat affected area was widened compared with the case of the Cu/Cu collision.

And, temperature were increasing from the collision interface to the backside, like shear band.

Temperature contour (0 K ~ 3500 K)

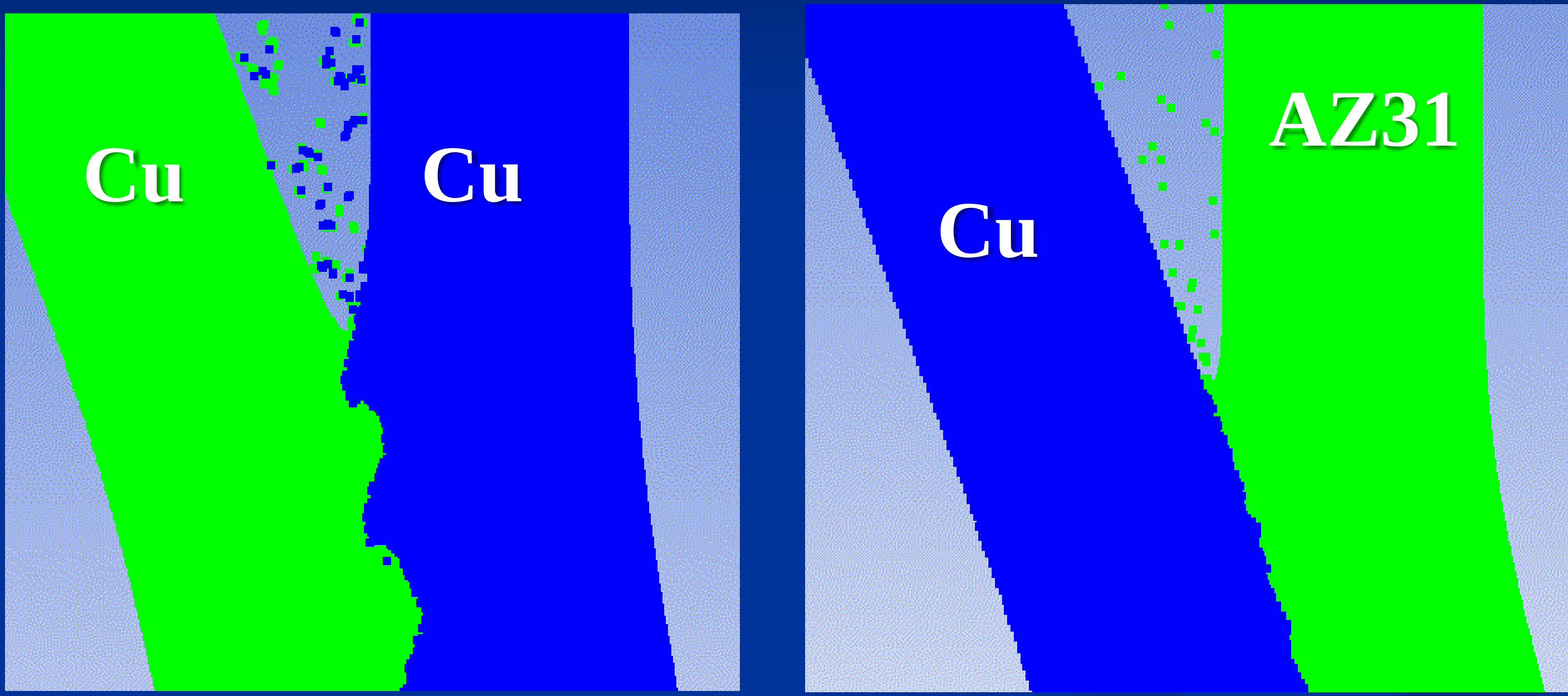
Particle size 0.04mm (40 µm)

Mg/Cu, Vp = 600m/s, β =20°

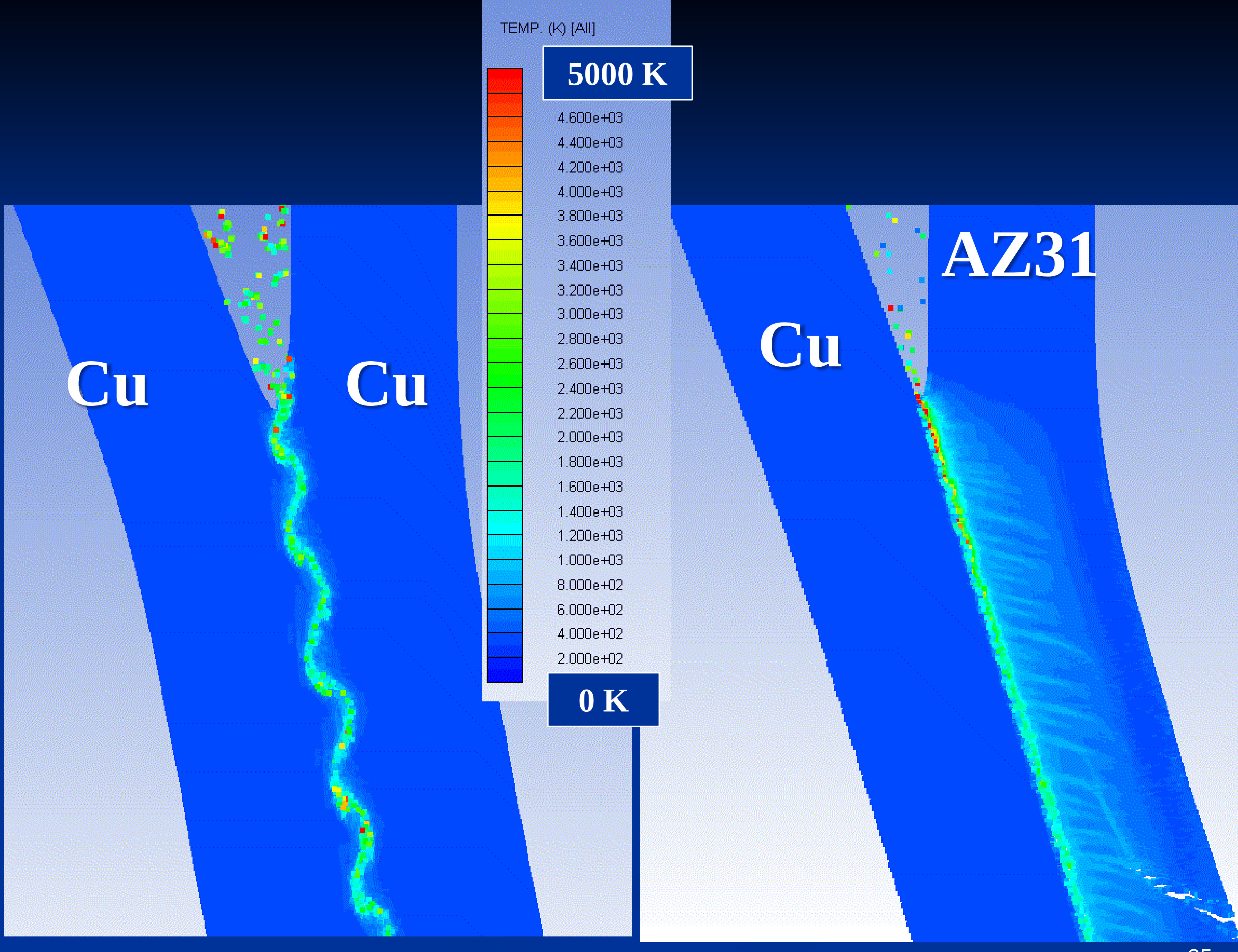


The metal jet only consists of the projectile metal, AZ31 in Mg/Cu combination.

Comparison of the collision conditions by numerical results



Vp = 600m/s, β =20°


TEMP. (K) [All]
5000 K
4.600e+03
4.400e+03
4.200e+03
4.000e+03
3.800e+03
3.600e+03
3.400e+03
3.200e+03
3.000e+03
2.800e+03
2.600e+03
2.400e+03
2.200e+03
2.000e+03
1.800e+03
1.600e+03
1.400e+03
1.200e+03
1.000e+03
8.000e+02
6.000e+02
4.000e+02
2.000e+02
0 K
Cu
Cu
Cu
AZ31

Summary

- The high speed inclined collision, as like the explosive welding process, was observed by using the single stage powder gun and high-speed video camera, for similar (Cu/Cu) and dissimilar（Mg alloy/Cu）combinations.

- Metal jet generation was observed clearly for the similar and the dissimilar combinations.

- From the numerical analysis by the ANSYS-AUTODYN, tendency of the wavy interface and the metal jet were agree well with the experimental figures.

  And, the thermal conditions of metals at high speed collision and the generation of interfacial waves, which are difficult to know from the experiments, can be obtained from the numerical results.

Thank you for your kind attention