Journal of Alloys and Compounds 472 (2009) 507–511

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jallcom

Dissimilar material welding of rapidly solidified foil and stainless steel plate using underwater explosive welding technique

Kazuyuki Hokamoto[a,*], Kazuhiro Nakata[b], Akihisa Mori[a], Shota Tsuda[c], Takuya Tsumura[b], Akihisa Inoue[d]

[a] Shock Wave and Condensed Matter Research Center, Kumamoto University, 2-39-1 Kurokami, Kumamoto 860-8555, Japan
[b] Joining and Welding Research Institute, Osaka University, Ibaraki, Osaka 567-0047, Japan
[c] Graduate School of Science and Technology, Kumamoto University, Japan
[d] Tohoku University, Sendai 980-8577, Japan

ARTICLE INFO

Article history:
Received 29 February 2008
Received in revised form 30 April 2008
Accepted 2 May 2008
Available online 17 June 2008

Keywords:
Amorphous materials
Composite materials
Metallic glasses

ABSTRACT

Rapidly solidified amorphous and metallic glass thin foils clad on a stainless steel base plate is attempted by employing underwater shock wave assembly. The conditions of the explosive welding are numerically analyzed and discussed based on the earlier welding limits. The thin foils successfully welded along the length of 50 mm show clear waves typically found in explosively welded interface. The interfacial microstructure characterized through optical and scanning electron microscopes shows evidence of excessive melting generated due to the trapping of metal jet in limited area.

1. Introduction

Some of the authors have developed a method of explosive welding using underwater shock wave. The theoretical aspects and practical considerations of underwater explosive welding of thin plates of large areas have been reported earlier by some of the authors [1–3]. Using this technique, the welding of difficult to weld materials such as a thin metal plate on a zirconia ceramic [4] and the welding of amorphous plates on a steel base plate [5] have been demonstrated. The present study is undertaken with the objective of joining non-equilibrium films with a base metal useful for practical applications. The method of joining such combinations is yet to be developed. Due to the extremely short processing time, explosive welding is considered as the most desirable method among the other joining techniques.

The present investigation deals with the underwater shock wave for the welding of non-equilibrium thin foils like metallic glass using varied-thickness explosive assembly, capable of applying uniform pressure through the welding area [3]. The welding of relatively thick metallic glass (2.5-mm thick) has been reported [6] but the welding of thin metallic glass film has not been reported yet. Some investigations have been made for the welding of amorphous and other films on a substrate metal plate by just modifying the conventional explosive welding technique, in which the thin plate was bonded with flyer or base plate. Nevertheless, cracks were developed in the thin welded plate [7,8]. In this study, the calculated welding conditions were numerically simulated using a commercial code AUTODYN-2D and compared with the critical conditions required for welding. Microstructural characterization studies were conducted at the welding interface in order to clarify the mechanism of the welding process.

2. Experimental

The assembly used for the present investigation is illustrated in Fig. 1. The horizontal collision point velocity V_c, which is controlled by setting high explosive pack at a certain angle, must be substantially lesser than the sonic velocity of the welding plates. This raises the concern of non-uniform pressure along the horizontal direction when a fixed-thickness explosive is employed in underwater explosive welding technique. Hence, the varied-thickness explosive [3], so as to obtain a uniform pressure with longitudinal direction, was employed. The value V_c was estimated as 3820 m/s [4] for SEP explosive (detonation velocity, V_d = 7 km/s, density = 1300 kg/m^3) produced by Asahi-Kasei Chemicals Corp. [1–3] when the inclination angle of the explosive α was set at 20°. The thickness of the explosive was changed from 3 to 10 mm along the length of 148 mm. The pressurizing condition, the details of the basic setup and the theoretical bases are described elsewhere [3]. A Ni-based amorphous film ($(Ni_{0.6}Nb_{0.4})_{65}Zr_{30}Co_5$: 38-μm thick) or a Ni-based metallic glass film ($Ni_{53}Nb_{20}Ti_{10}Zr_8Co_6Cu_3$: 28-μm thick) using a plastic adhesive agent with an aluminum cover plate 0.1-mm thick is illustrated in Fig. 1. The role of the cover plate is important to control the collision velocity towards vertical direction V_p moderate for welding and it also releases the momentum reflected from bottom.

* Corresponding author.
E-mail address: hokamoto@mech.kumamoto-u.ac.jp (K. Hokamoto).

0925-8388/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jallcom.2008.05.002

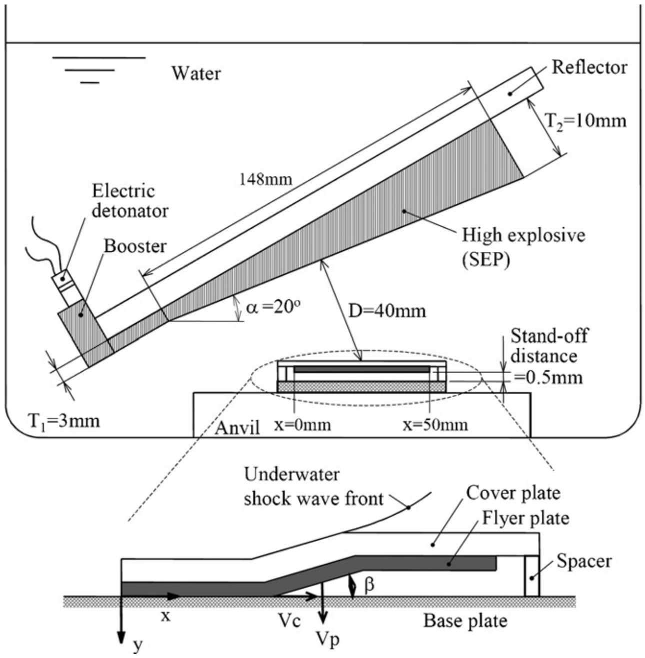

Fig. 1. Experimental setup employed for underwater explosive welding.

The bonded two plates were set above a 304 stainless steel plate (1.0-mm thick) with a fixed stand-off distance at 0.5 mm using spacers placed at the edges. The air gap between the flyer and base plates was sealed against water. The welded samples were cut at the center along the longitudinal direction and microstructure was characterized. The metallic glass and amorphous films, which have high strength and corrosion resistance, are being developed for fuel cell separator and hydrogen-permeable membrane, respectively. The method to join such film onto a base metal for potential applications is under development.

3. Numerical simulation

Two-dimensional numerical simulation using AUTODYN-2D was made for the assembly shown in Fig. 1. Basic data required for the numerical analysis has been reported elsewhere [3]. As mentioned in the previous paper [3] the profile of underwater shock wave was numerically simulated and then the collision conditions (plate velocity V_p and angle β) were calculated. Fig. 2 shows the pressure contour obtained through numerical simulation. Fig. 3 shows the pressure distribution with horizontal position x. The results revealed quite uniform pressurizing condition with different position x. The plate velocity in vertical direction for different horizontal positions x is suggested in Fig. 4 and no difference with the horizontal positions x was found, as evident from Figs. 3 and 4. For the stand off y = 0.5 mm, the vertical velocity was about 1300 m/s which is high enough to satisfy the minimum energetic condition to achieve the welding and the details are discussed in the next section. The velocity is higher than the conventional explosive welding, which lies in the order of several hundred meters per second [9], but is moderate for the welding of hard component by rapid solidification. The collision angle β, the other important parameter in discussing the welding condition, is almost proportional to the plate velocity V_p [9], and the calculated value of β was about 20° for the present case and is discussed later.

In comparison with the former investigations using modified conventional technique [7,8], the present method is possible to control the pressurizing condition precisely because of the use of high explosive which shows quite steady detonation behavior [10]. For conventional explosive welding, ANFO-based explosive is normally used, which shows relatively low detonation velocity and is unstable depending upon the size, humidity and other factors [11].

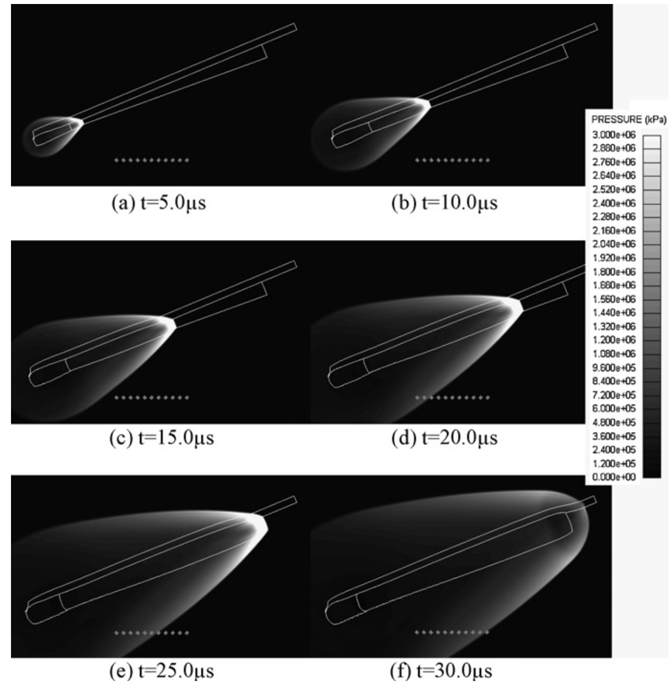

Fig. 2. Underwater pressure contour obtained through AUTODYN-2D code.

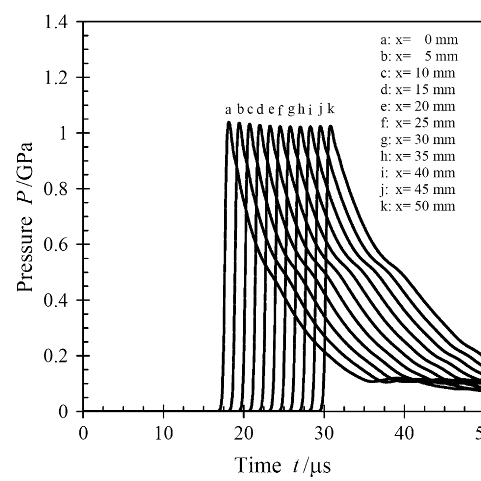

Fig. 3. Underwater pressure distribution with horizontal position x just above the cover plate.

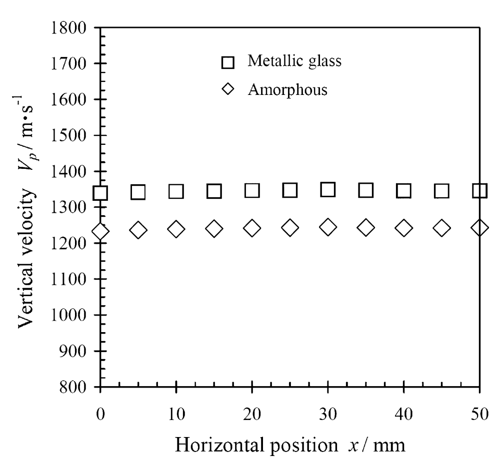

Fig. 4. Vertical velocity change toward y direction for different horizontal positions x.

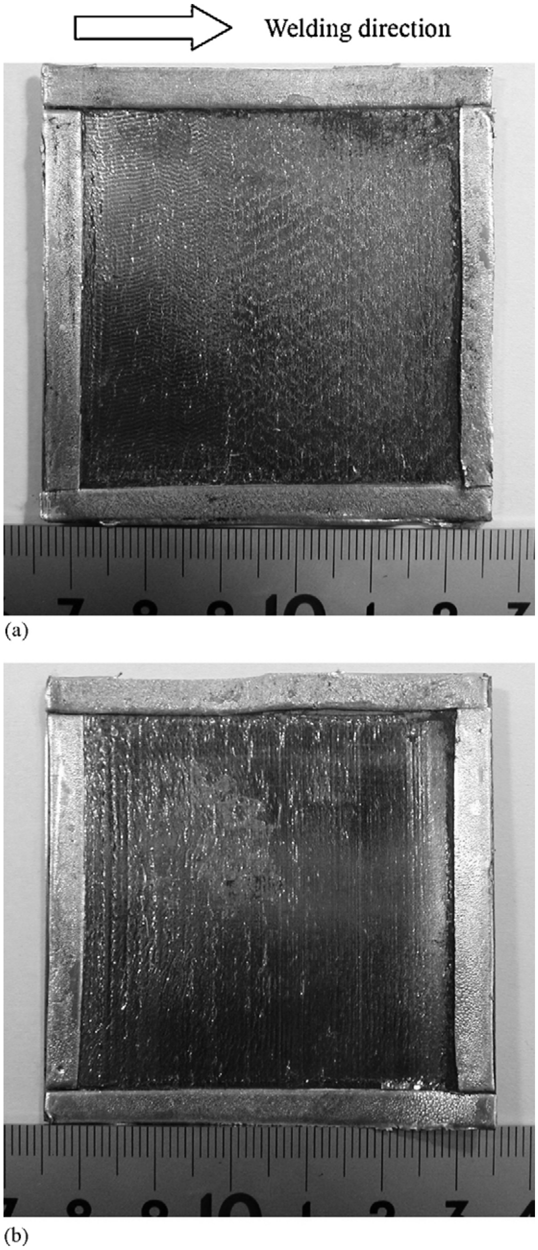

Fig. 5. Upper view of recovered samples: (a) amorphous and (b) metallic glass.

4. Results and discussion

4.1. Condition of welding

Fig. 5 features the photograph of the successfully recovered specimen welded using underwater shock wave. The surface shows the same appearance of as-received condition. The lines along the transverse direction reflect the unevenness of the plate made through roll casting. The thickness of the plate is not perfectly the same throughout the area and the unevenness of the plate thickness is less than 10%. The use of cover plate is also effective to decrease the change of the mass with horizontal position. Fig. 6 shows the microstructure of rapidly solidified films welded on a metal base. Clear wavy structure typically found in explosively welded clad is found at the welded area, and only minor difference in the size of the waves was confirmed by using the varied-thickness explosive. These results are comparable to numerically simulated values,

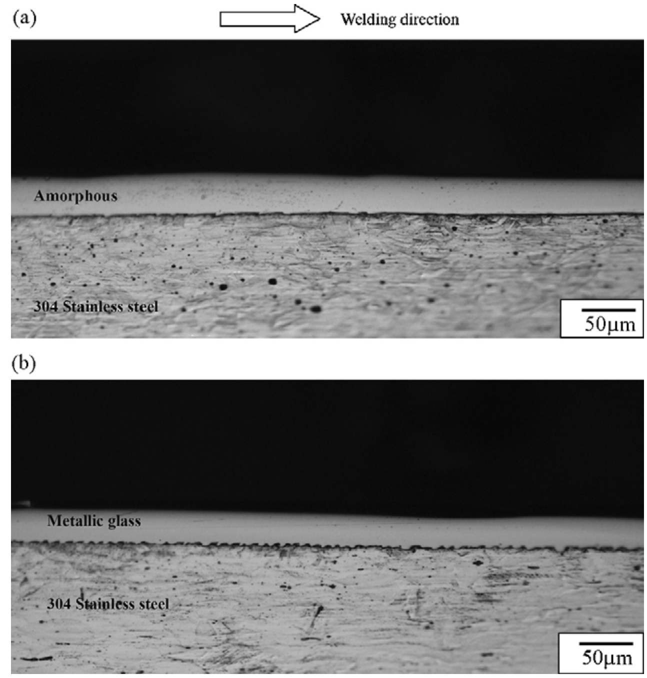

Fig. 6. Microstructure of longitudinal cross-section along with welding direction: (a) amorphous and (b) metallic glass.

which show a uniform distribution of the pressurizing condition. The enlarged micrographs presented in Fig. 7 shows less amount of molten or reacted zone at the interfacial zone. Small spots close to the molten jet trapped area are occasionally found as shown by arrows in Fig. 8. Cracks were found in such molten zone due to the tensile residual stress caused during the cooling process. For the case of explosive welding, high reliability of the bonding strength

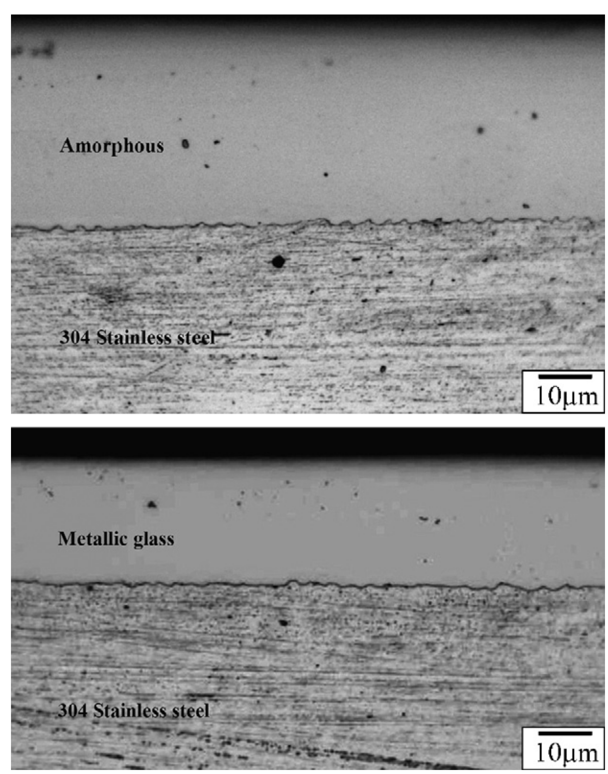

Fig. 7. Enlarged microstructure of interfacial zone.

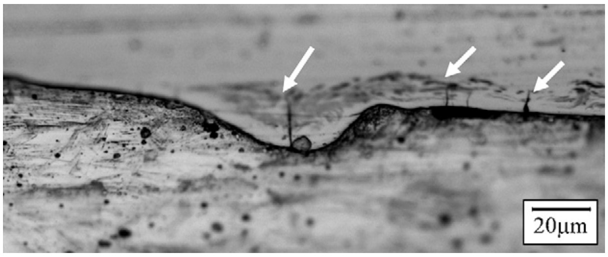

Fig. 8. Cracks found in melting spot as suggested by arrows at welded interface between amorphous and stainless steel.

can be realized if the bonding is achieved without the formation of brittle intermetallics [9]. The bonding strength for the welded samples seems good because no separation through the molten spots was found even by the passage of an intensive reflected tensile wave from the bottom. One of the authors [5] reported the separation of the amorphous film by the reflected wave from bottom in the welding of an amorphous film onto a steel plate. However, in this case, the separation or the crack appeared inside the amorphous film along with the interface showing clear evidence of high bonding strength at the interface.

4.2. Welding limits

It is well established that explosive welding can be achieved when some of the important parameters such as dynamic bending angle β and horizontal collision velocity V_c are in the range as defined in the welding window [9]. β is almost proportional to the vertical velocity V_p as mentioned before [9]. Since the horizontal collision velocity V_c is fixed for a certain inclined angle of explosive pack and particular explosive, the control of the dynamic bending angle β and vertical velocity V_p is discussed. As reported earlier [11], an increase in V_p increases the kinetic energy loss by collision ΔKE, therefore, the energetic condition is substantially high enough to induce an intensive flow. This may often lead to undesirable melting layer at the interface. In the case of underwater explosive welding technique, it is not necessary to consider the upper limit seriously because of the use of thin plate, which has relatively lower kinetic energy than the regular cases. The lower limit should be considered carefully to achieve the welding. The lower limit is represented by the following expression:

$$\beta = k_1 \left(\frac{\mathrm{Hv}}{\rho \mathrm{V_c^2}} \right)^{0.5} \quad (1)$$

where $k_1 = 1.2$, Hv and ρ represents the Vickers hardness and density of the flyer plate [9]. Fig. 9 shows the welding window with the lower limit drawn for the present experiments. In the present investigation, the open circles are the condition for horizontal position x at 5 mm intervals using varied-thickness explosive. The plots overlap together and lie near the lower limit of welding. For comparison, the triangle plots based on the numerical data for the case when using fixed-thickness explosive at 5 mm using the same assembly is given. The points move toward the lower limit with increase of x from $x = 0$ to 50 mm, and thus suggests that the welding of long-sized sample is limited as far as using the fixed-thickness explosive. The experiments using fixed-thickness explosive were not performed due to the limitation of the samples used in this research. The amount of kinetic energy lost by collision ΔKE is calculated and the contour lines are drawn as shown in Fig. 9. It is confirmed from the figure that the kinetic energy loss ΔKE values are almost the same under the similar experimental condition, although lower collision angle β is expected for the use of relatively heavier amorphous film.

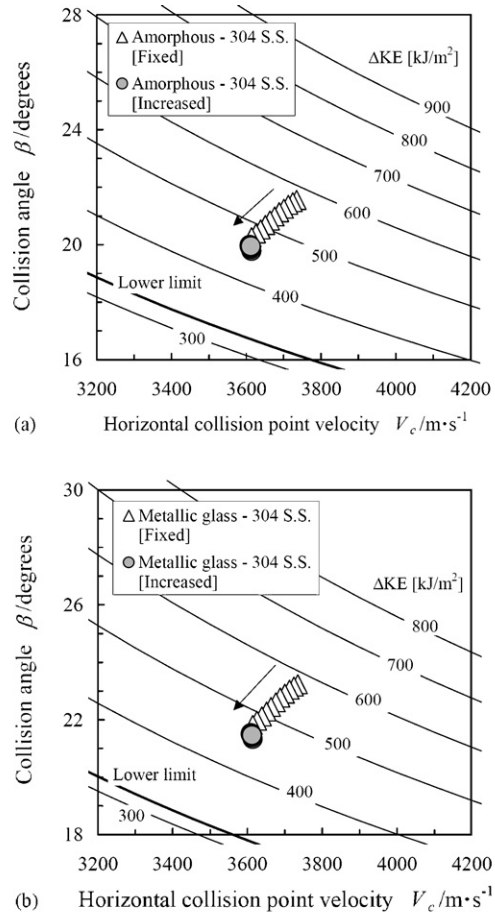

Fig. 9. Welding window showing lower limit of welding comparing the conditions of present experiments using varied-thickness explosive (○) and using fixed-thickness explosive (△) for (a) amorphous and (b) metallic glass.

The authors are researching the possibility of double-layered welding by overlapping plates as it is necessary considering the size limitation of rapidly solidified films. Also, the microstructural changes at the welded interface in nanometer order caused by the extremely short processing time is quite interesting and hence analysis using TEM is currently under progress.

5. Conclusions

The possibility of the underwater explosive welding to weld a thin amorphous or a metallic glass foil onto a 304 stainless steel base plate is demonstrated in the present investigation. The welding was successful by using varied-thickness explosive assembly, capable of applying uniform pressurizing condition along the welding area. The conditions of the welding was numerically analyzed and discussed based on the important experimental parameters such as dynamic bending angle and horizontal collision point velocity. Based on the conditions given by the simulation, the use of varied-thickness explosive is quite effective to attain uniform welding conditions along the welding length.

Acknowledgements

The help of Mr. Susumu Akimaru, Shock Wave and Condensed Matter Research Center, Kumamoto University for the explosion experiments is gratefully acknowledged.

References

[1] K. Hokamoto, Y. Ujimoto, M. Fujita, Mater. Sci. Forum 426–432 (2003) 4039–4044.
[2] K. Hokamoto, Y. Ujimoto, M. Fujita, Mater. Trans. 45 (2004) 2897–2901.
[3] A. Mori, K. Hokamoto, M. Fujita, Mater. Sci. Forum 465–466 (2004) 307–312.
[4] K. Hokamoto, M. Fujita, H. Shimokawa, H. Okugawa, J. Mater. Process. Technol. 85 (1999) 175–179.
[5] K. Hokamoto, M. Fujita, T. Ono, B. Shao, Z. Liu, in: L.E. Murr, K.P. Staudhammer, M.A. Meyers (Eds.), Metallurgical and Materials Applications of Shock-wave and High-strain-rate Phenomena, Elsevier, New York, 1995, pp. 831–837.
[6] Y. Kawamura, A. Chiba, in: A. Chiba, S. Tanimura, K. Hokamoto (Eds.), Impact Engineering and Application, Elsevier, Amsterdam, 2001, pp. 273–278.
[7] R.A. Pruemmer, D. Stoeckel, in: L.E. Murr, K.P. Staudhammer, M.A. Meyers (Eds.), Metallurgical Applications of Shock-wave and High-strain-rate Phenomena, Marcel Dekker, New York, 1986, pp. 877–886.
[8] D.J. Vigueras, O.T. Inal, A. Szeket, in: L.E. Murr, K.P. Staudhammer, M.A. Meyers (Eds.), Metallurgical Applications of Shock-wave and High-strain-rate Phenomena, Marcel Dekker, New York, 1986, pp. 927–942.
[9] B. Crossland, Explosive Welding of Metals and its Application, Oxford University Press, London, 1982.
[10] H. Hamashima, Y. Kato, Y. Nadamitsu, S. Itoh, Sci. Technol. Energetic Mater. 64 (2003) 248–253.
[11] K. Hokamoto, T. Izuma, M. Fujita, Metall. Trans. A 24 (1993) 2289–2297.