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Investigation of Cold Rolling Influence on near Surface Residual Stress Distribution in Explosive Welded Multilayer

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Исследование влияния холодной прокатки на распределение остаточных напряжений в приповерхностных слоях многослойного материала, полученного с помощью сварки взрывом

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Исследуется влияние холодной прокатки на распределение остаточных напряжений в трехслойных ламинатах из алюминиевого и медного сплавов, полученных сваркой взрывом. После получения многослойных образцов Al–Cu–Al с помощью сварки взрывом их подвергали холодной прокатке до уменьшения толщины на 11, 30, 40 и 56%. Профили распределения остаточных напряжений по глубине сваренных взрывом и холоднокатаных многослойных образцов измеряли при последовательном высверливании в них отверстия. Полученные результаты показывают, что на поверхности сваренного взрывом многослойного материала отмечаются высокие растягивающие остаточные напряжения, уровень которых снижается в результате холодной прокатки. Установлено, что уровень растягивающих остаточных напряжений на поверхности холоднокатаных многослойных образцов оказывается выше при холодной прокатке, обеспечивающей большее уменьшение толщины образцов.

Ключевые слова: остаточные напряжения, сварка взрывом, снижение толщины, коэффициент калибровки.

Introduction. New explosive-welded multilayer materials superior corrosion/wear resistance and mechanical properties and are used in aerospace and nuclear industries [1]. The explosive welding is known as an unconventional technique [2]. Similar and dissimilar materials such as aluminum and copper are bonded together using this process [3–6]. Because of high energy density of explosive material, the process can join high surface area of plates [7].

Residual stresses are produced in explosive-welded multilayer due to different linear expansion coefficients of dissimilar materials [8–10]. The created residual stresses in the explosive-welded multilayers affect the mechanical properties of multilayers. Therefore, it is necessary to evaluate residual stresses in explosive-welded multilayers. Residual stresses in engineering structures are created by a variety of different mechanisms and influence crack initiation, crack growth and fracture [11]. Incremental hole-drilling (IHD) method can be used to evaluate non-uniform residual stress in thickness direction of explosive-welded multilayers

[12]. Measurement of residual-stress distribution by the incremental hole-drilling method was carried out by Niku-Lari et al. [13]. They proposed a new method of calibration and have shown how the finite element analysis can be used for the determination of the correlation coefficients. Development of the high-precision incremental-step hole-drilling method for the study of residual stress in multi-layer materials was performed by Montay et al. [14]. They obtained the residual stress gradient in the test specimen. Numerical evaluation of residual stress in an explosive-welded multilayer has been done by Wang et al. [15], who predicted that the maximum residual stress occurred in the interface of multilayer. The IHD method has been described in the ASTM E837-08 [12]. Therefore, the IHD method is a standard approach to estimate the non-uniform residual stress in the depth of explosive-welded multilayers.

To the best of authors' knowledge, experimental measurement of the in-depth residual stress in the explosive-welded multilayers and effect of cold rolling on the residual stress distribution are not reported so far. Therefore, the aim of the present paper is to study the measurement of residual stress gradient in Al–Cu–Al multilayers by using the IHD method. In this paper, the material and explosive welding tecnique, as well as theory of measurement of residual stress, are discussed. Then the cold rolling process was used to reduce the thickness of explosive-welded multilayer. Through-depth residual strain was measured using strain indicator. Calibration coefficients have been obtained using finite element modeling. Finally, through-depth residual stress was obtained in the explosive-welded and cold-rolled multilayers.

1. **Residual Stress Measurement**. In this section, firstly the theory of measurement method is explained. Then the material and explosive welding conditions are discussed.

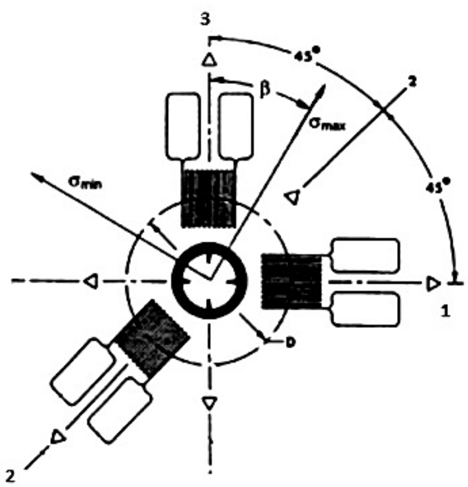

Fig. 1. Strain gauge rosette arrangement for determining residual strain [12].

1.1. ***Incremental Hole-Drilling***. In the IDH method, calculation is based on the experimental strain measured at each increment of depth ε_n^1, ε_n^3 and calibration coefficients A_n and B_n [13]. If a 45° rosette is used (Fig. 1), the unknown principal stresses σ_{1n} and σ_{2n} can be calculated from Eq. (1):

$$\begin{cases} \sigma_{1n} = \dfrac{\varepsilon_n^1 (A_n + B_n \sin 2\theta_n) - \varepsilon_n^2 (A_n - B_n \cos 2\theta_n)}{2A_n B_n (\sin 2\theta_n + \cos 2\theta_n) \Delta h_n}, \\ \sigma_{2n} = \dfrac{\varepsilon_n^2 (A_n + B_n \cos 2\theta_n) - \varepsilon_n^1 (A_n - B_n \sin 2\theta_n)}{2A_n B_n (\sin 2\theta_n + \cos 2\theta_n) \Delta h_n}. \end{cases} \quad (1)$$

A 3D finite element model can be used to compute the A_n and B_n calibration coefficients [13, 14]. Therefore, these coefficients are derived via Eqs. (2) and (3):

$$A_n = \frac{\varepsilon_n^1 + \varepsilon_n^3}{2\Delta h_n (\sigma_{1n} + \sigma_{2n})} \quad (2a)$$

or

$$A_n = \frac{\varepsilon_n^1 \sin 2\theta_n + \varepsilon_n^2 \cos 2\theta_n}{\Delta h_n (\sigma_{1n} + \sigma_{2n})(\sin 2\theta_n + \cos 2\theta_n)}, \quad (2b)$$

$$B_n = \frac{\varepsilon_n^1 - \varepsilon_n^3}{2\Delta h_n (\sigma_{1n} - \sigma_{2n}) \cos 2\theta_n} \quad (3a)$$

or

$$B_n = \frac{\varepsilon_n^1 - \varepsilon_n^2}{\Delta h_n (\sigma_{1n} - \sigma_{2n})(\sin 2\theta_n + \cos 2\theta_n)}. \quad (3b)$$

2. **Materials and Procedures**. In this study, the parallel arrangement was used for experimental setup of explosive multilayer. The structure of the composite multilayer was such that the copper layer setting in the middle with aluminum alloy layers on both sides is produced by a single explosive welding method. The explosive material was AMATOL, of detonation velocity 2500 m/s. Density of AMATOL is equal to 800 kg/m^3. The explosive thickness was equal to 14 mm. The initial thickness of explosive-welded multilayer was equal to 3.78 mm (t_{Al} = 1.35 mm–t_{Cu} = 0.97 mm–t_{Al} = 1.46 mm) and the multilayer was rolled to provide 11, 30, 40, and 56% thickness reduction (Fig. 2).

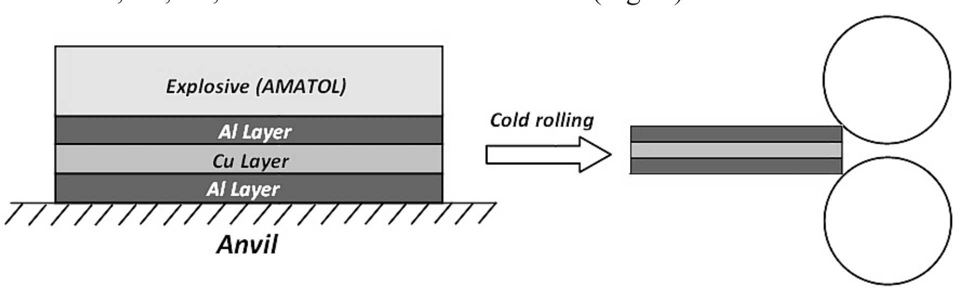

Fig. 2. Schematic view of parallel arrangement of explosive welding and cold rolling process.

The hole-drilling operation was performed at the speed equal to 20,000 rpm and the strain data were measured using the strain indicator Vishay.

3. **Result and Discussion**. In this study, measurement of the through-depth residual stress has been performed in the explosive-welded and cold-rolled multilayers. For this purpose, measurement of strain in the multilayers has been performed using strain-gauge of type A (Fig. 1).

To investigate the residual stress distribution in the multilayers, it is necessary to obtain the calibration coefficient in multilayers. The finite element method (FEM) analysis can be applied to obtain calibration coefficients [13, 14]. Figure 3 shows this value in through-depth of multilayers for explosive-welded and each thickness reduction.

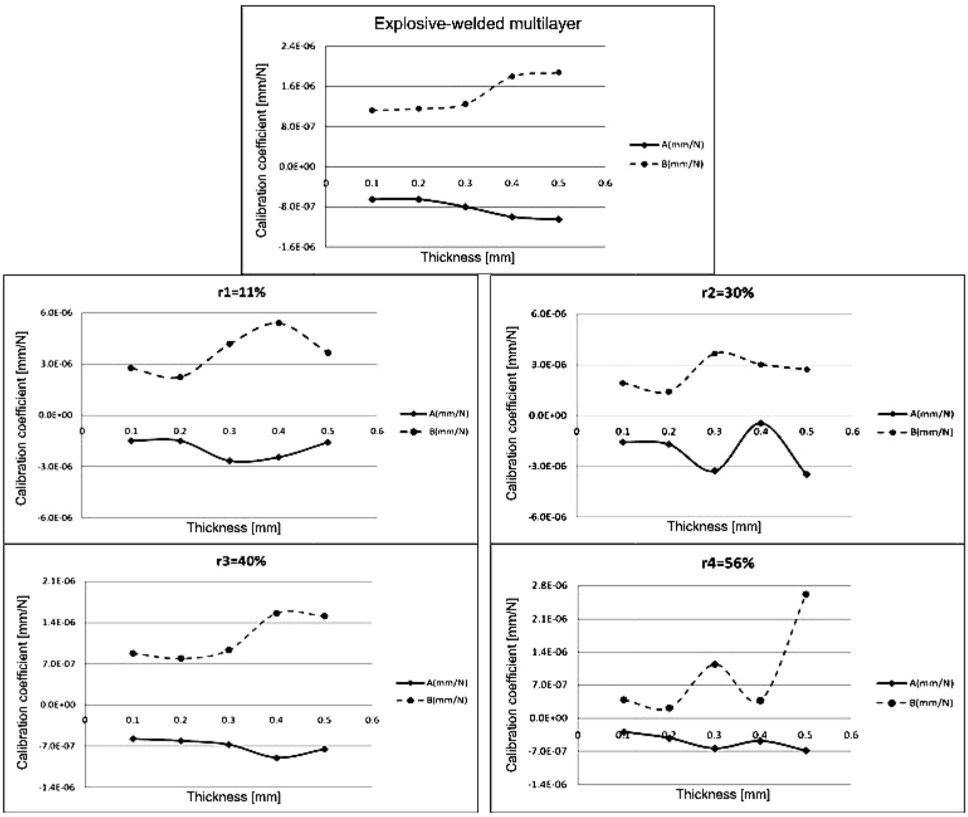

Fig. 3. Through-depth calibration coefficients in explosive-welded and cold-rolled multilayers.

The distributions of residual stress in the Al–Cu–Al multilayers strip (near the surface of multilayers) are depicted in Fig. 4 by using the measured strain data, the calibration coefficients (Fig. 3), and Eq. (1).

The results obtained show that the surface of explosive-welded multilayer (aluminum layer) is subjected to high tensile residual stresses. The residual stress values decrease through the thickness of multilayer. The cold rolling process decreases the tensile residual stresses at the surface of explosive-welded multilayer. Noteworthy is that the level of surface residual stresses is higher in specimens with higher values of thickness reduction (Fig. 5).

Tensile residual stresses in the products are generally undesirable because they reduce the elastic limit of the products and promote tendency to warpage during

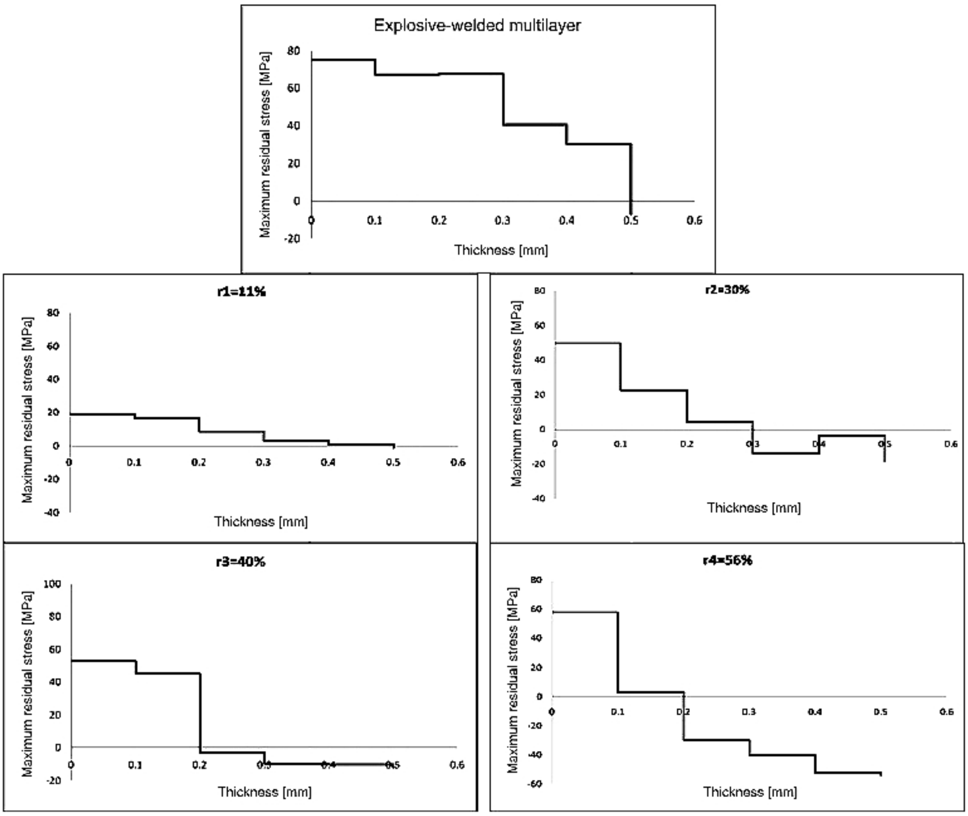

Fig. 4. Through-depth residual stress in explosive-welded and cold-rolled multilayers.

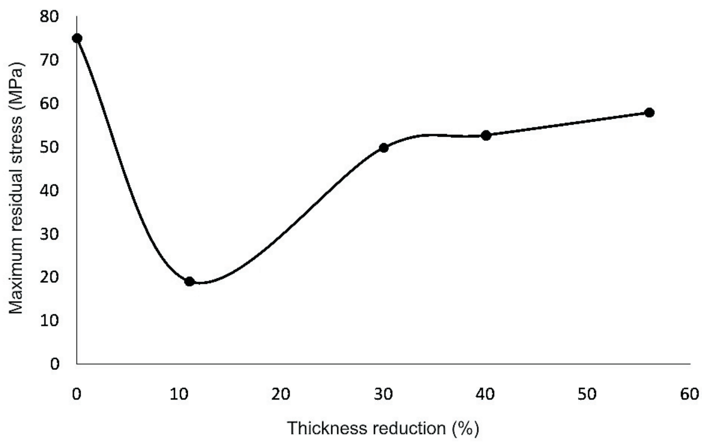

Fig. 5. Thickness reduction influence on surface residual stress.

subsequent machining operations. The tensile pattern of residual stresses at the surface is particularly undesirable, insofar as it causes an increased susceptibility to fatigue and stress corrosion. Explosive welding process induces generation of temsile residual stresses at the surface of multilayer material, which may cause cracking of this surface. Therefore, tensile residual stress can be reduced by using a low thickness reduction.

Conclusions. In this study, measurement of through-depth residual stresses in explosive-welded and then cold-rolled Al–Cu–Al multilayers have been performed by using incremental hole-drilling method. The following points can be concluded from this study:

(i) the IHD method has been used to predict the through-depth residual stress in the explosive-welded and cold-rolled multilayers;

(ii) the calibration coefficients A_n and B_n were calculated by using the FEM analysis;

(iii) high tensile residual stresses have been shown to occur at the surface of explosive-welded multilayers;

(iv) the cold rolling process reduces the surface residual stresses of explosive-welded multilayer;

(v) cold rolling with higher thickness reduction produces higher level of surface residual stresses.

Резюме

Досліджується вплив холодної прокатки на розподіл залишкових напружень у тришарових ламінатах з алюмінієвого та мідного сплавів, що отримані вибуховим зварюванням. Після отримання багатошарових зразків Al–Cu–Al вибуховим зварюванням їх піддавали холодній прокатці до зменшення товщини на 11, 30, 40 и 56%. Профілі розподілу залишкових напружень по глибині холоднокатаних багатошарових та отриманих вибуховим зварюванням зразків вимірювали при послідовному висвердлюванні в них отвору. Результати показують, що на поверхні багатошарового матеріалу, отриманого вибуховим зварюванням, відмічаються високі розтяжні залишкові напруження, рівень яких зменшується під час холодної прокатки. Установлено, що рівень розтяжних залишкових напружень на поверхні холоднокатаних багатошарових зразків є вищим при холодній прокатці, що забезпечує значно більше зменшення товщини зразків.

1. F. Findik, “Recent development in explosive welding,” *Mater. Design*, **32**, 1081–1093 (2011).
2. K. Raghukandan, “Analysis of the explosive cladding of Cu–low carbon steel plates,” *J. Mater. Proc. Technol.*, **139**, 573–577 (2003).
3. A. G. Mamalis, A. Szalay, N. M. Vaxevanidis, and D. E. Manolakos, “Fabrication of bimetallic rods by explosive cladding and warm extrusion,” *J. Mater. Proc. Technol.*, **83**, 48–53 (1998).
4. J. Z. Ashani and S. M. Bagheri, “Explosive scarf welding of aluminum to copper plates and their interface properties,” *Materialwiss. Werkstoff.*, **40**, No. 9, 690–698 (2009).
5. B. Gulenc, “Investigation of interface properties and weldability of aluminum and copper plates by explosive welding method,” *Mater. Design*, **29**, 275–278 (2008).
6. R. Kacar and M. Acarer, “An investigation on the explosive cladding of 316L stainless steel-din-P355GH steel,” *J. Mater. Proc. Technol.*, **152**, 91–96 (2004).

7. D. G. Brasher and D. J. Butler, "Explosive welding: principles and potentials," *Adv. Mater. Proc.*, **147**, 37–38 (1995).

8. S. Kundu, M. Ghosh, and S. Chatterjee, "Diffusion bonding of commercially pure titanium and 17-4 precipitation hardening stainless steel," *Mater. Sci. Eng. A*, **428**, 18–23 (2006).

9. M. Ghosh and S. Chatterjee, "Effect of interface microstructure on the bond strength of the diffusion welded joints between titanium and stainless steel," *Mater. Char.*, **54**, 327–337 (2005).

10. M. Ghosh, S. Das, P. S. Banarjee, and S. Chatterjee, "Variation in the reaction zone of solid state bonded commercially pure titanium and 304 stainless steel," *Mater. Sci. Eng. A*, **390**, 217–226 (2005).

11. A. H. Mahmoudi, C. E. Truman, and D. J. Smith, "Using local out-of plane compression (LOPC) to study the effects of residual stress on apparent fracture toughness," *Eng. Fract. Mech.*, **75**, 1516–1534 (2008).

12. *ASTM E837-08. Standard Test Method for Determining Residual Stresses by the Hole Drilling Strain-Gauge Method*, ASTM, West Conshohocken (2008).

13. A. Niku-Lari, J. Lu, and J. F. Flavenot, "Measurement of residual-stress distribution by the incremental hole-drilling method," *J. Mech. Work. Technol.*, **11**, 167–188 (1985).

14. G. Montay, A. Cherouat, J. Lu, et al., "Development of the high-precision incremental-step hole-drilling method for the study of residual stress in multi-layer materials: influence of temperature and substrate on ZrO_2–Y_2O_3 8 wt.% coatings," *Surf. Coat. Technol.*, **155**, 152–160 (2002).

15. Y. Wang, H. Cai, N. Ma, "Measurement of residual stresses in a multi-layer explosive welded joint with successive milling technique," *Strain*, **35**, 7–10 (1999).

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