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Original Research

Mechanical Properties of Aluminium/Copper Bimetallic Sheets Subjected to Cyclic Bending

Krzysztof Żaba [1,*], Sandra Puchlerska [1], Stanislav Rusz [2], Romuald Fejkiel [3]

[1] Department of Metal Working and Physical Metallurgy of Non-Ferrous Metals, AGH—University of Science and Technology, al. Adama Mickiewcza 30, 30-059 Cracow, Poland
[2] Department of Mechanical Technology, Faculty of Mechanical Engineering, VŠB—Technical University of Ostrava, 17 listopadu 15, CZ 708 33 Ostrava–Poruba, Czech Republic
[3] Department of Mechanics and Machine Building, Carpatian State School in Krosno, Rynek 1, 38-400 Krosno, Poland

* Correspondence: krzyzaba@agh.edu.pl

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Abstract

The aim of this study is to evaluate the influence of the roll bonding (RB) process on the mechanical properties of Al/Cu bimetallic strip specimens. A specially designed test instrument for the cyclic bending test of strip specimens produced by RB has been proposed. The test consists of repeated pulling of a strip of sheet metal through a system of cylindrical countersamples. Samples cut along and across the sheet rolling direction were tested. The specimens were subjected to preliminary microstructural tests using an optical microscope with Nomarski contrast and scanning electron microscopy. The tests showed a slight influence of the orientation of the samples on changes to the mechanical properties of the bimetallic sheets in the cyclic bending process. For samples oriented along the sheet rolling direction, discontinuities in the transition layer were found. The samples oriented perpendicularly to the rolling direction were free of this defect.

Keywords: bimetallic sheet, cycling bending, hardness, work hardening

1. Introduction

Bimetallic sheets are a composite material with properties that are the result of the properties of the joined sheets (Khan et al., 2021; Vini et al., 2017). The main advantage of bimetallic sheets is the acquisition of the different physical and mechanical specifications of both materials at the same time, such as thermal expansion, electromagnetic conductivity, corrosion resistance and mechanical strengths. Several methods of joining bimetal sheets are commonly used, that is, surfacing, roll bonding (RB) and explosive plating. RB is used to produce bimetallic sheets in which the combined thickness is reduced. RB changes the shape of plastically processed materials as a result of the impact of external forces. The geometrical dimensions of the rolled sheet, internal microstructure and mechanical properties change as a result of the RB process (Stradomski et al., 2022; Walnik et al., 2021). Accumulative roll bonding is a technique used to produce laminates because the rolling pressure can create a mechanical bond between metals, such as Al/Cu (Vini et al., 2017), Al/Zn (Dehsorkhi et al., 2011), Al/Fe (Tang et al., 2015), and Al/Ni (Mozafarri et al., 2011).

The analysis of the influence of the rolling process on the properties of bimetallic sheets was the subject of investigations by Pan et al. (1989). They found that the use of the cross-shear cold rolling technique results in a significant reduction in the rolling load. Furthermore, the cold roll cladding of aluminium–stainless steel, copper–stainless steel, and mild steel–stainless steel led to the conclusion that the incorporation of an optimum final heat treatment considerably decreases the requirement for rolling. Polyzou et al. (2017) investigated the suitability of cold rolling processes for the formation and improvement in the properties of explosively welded bimetallic Al/Cu samples. Examination of the bimetallic sheets with regards to their microstructure and the hardness of the intermetallic layer on the bonding surface proved that cold rolling improves the hardness of both layers of explosively welded bimetallic Al/Cu specimens. Athar and Tolaminejad (2015) calculated the weldability criteria which should be met in order to achieve a good welding quality for an Al/Cu/Al explosively welded bimetallic sandwich. The effect of a cold rolling process on the bond strength and the mechanical properties of Al/Cu/Al sandwich sheets fabricated by explosive welding has been studied by Asemabadi et al. (2012). The results of the tensile, tensile-shearing and hardness tests along the thicknesses of the sheets indicate that the amount of hardness has increased in different layers, and the largest hardness increase can be observed in the copper layer. Fabrication of an Al/Cu bimetallic sheet by explosive welding and cold rolling process was performed by Mamalis et al. (1994). They concluded that the application of cold rolling as a post-cladding forming operation requires careful selection of the lubricants, rolling variables, and the roll-pass schedule.

Obtaining precise adhesion of two plates and their connection is possible only when the oxides and adsorbed gases are removed from the surfaces of the metallic sheets. Sometimes post-welding processes are necessary to improve the properties of the bimetal sheet (Polyzou et al., 2017). Sheets that are a combination of aluminium and copper layers are the most commonly used in the electronics, automotive, chemical and shipbuilding industries.

The materials of the bimetallic sheet layers should be characterised by high plasticity and crack resistance. The decisive mechanical property determining the suitability of a given sheet for the rolling process is susceptibility to work hardening (Paul et al., 2011). When rolling bimetallic sheets, it is sometimes necessary to use the asymmetric rolling process as a method of reducing the curvature of the double-layer strip (Sun et al., 2020). During the rolling process, structural and dynamic changes may occur in the sheets (Dyja & Wilk, 1998; Salimi & Sassani, 2002; Vini et al., 2017). When rolling two-layer sheets with a large difference in the properties of the joined layers, one of the layers may not deform or deform only to a small extent. Increasing the uniformity of the deformation of bimetallic sheets is obtained by using the asymmetry of the circumferential speed of the working rollers (Sun et al., 2020; Yu et al., 2013). Sometimes dynamic recrystallisation of the workpiece subjected to the rolling process may be eliminated (Stradomski et al., 2022).

One of the methods for testing the resistance of bimetallic sheets is the continuous bending test (Poulin et al., 2019). The test consists of repeated pulling of a strip of sheet metal through a system of cylindrical countersamples. As a result of the deformation process, the plastic properties of the sheet change because of the work hardening phenomenon. This article presents a specially designed test instrument for the cyclic bending test of strip specimens produced by roll bonding. The aim of this study is to evaluate the influence of the RB process on the mechanical properties of Al/Cu strip specimens. Samples cut along and across the sheet rolling direction were tested.

2. Experimental

2.1. Material

Cu/Al bimetallic strips in a z6 state (after rolling) and a ratio for the Cu and Al layers equal to 1:1 have been used in this study. The bimetallic sheets with a thickness of 1 mm were produced by the roll bonding method in industrial conditions by Walcowania Metali Dziedzice S.A in Gliwice (Poland). The input materials for the production of Al/Cu bimetallic sheets were sheets of technical grade aluminium EN AW-1050A and sheets of electrolytic copper M1E. The chemical compositions of the layers of test material are shown in Tables 1 and 2.

Table 1. The chemical composition of EN AW-1050A aluminium alloy (wt.%)

Al	Mg	Mn	Fe	Si	Cu	Zn	Ti	rest
99.43	0.025	0.027	0.23	0.17	0.028	0.033	0.029	0.028

Table 2. The chemical composition of M1E copper (wt.%)

Cu	Bi	O	Pb	rest
99.93	0.0004	0.036	0.004	0.029

2.2. Cyclic bending process

Experimental tests for drawing sheet metal with bending were carried out on a device shown in Fig. 1. A strip of the sheet is bent and straightened many times when passing through the working rollers

(1), (2) and (3). With freely rotating rollers, the pulling force overcomes the deformation resistance of the sheet, because the frictional forces are negligible. The guide roller (4) counteracts the deflection of the end of the sheet metal at the entrance to the working roller (3). The body (5) of the device is mounted on the lower gripper of the Zwick/Roell Z100 uniaxial tensile testing machine (Fig. 2a). The strip specimen (6) with width w_s = 10 mm was mounted in the upper gripper of the testing machine. The pulling force was measured using the testing machine's measuring system. The position of the central roller (2) in relation to the working rollers (1) and (3) is regulated by the nut (7).

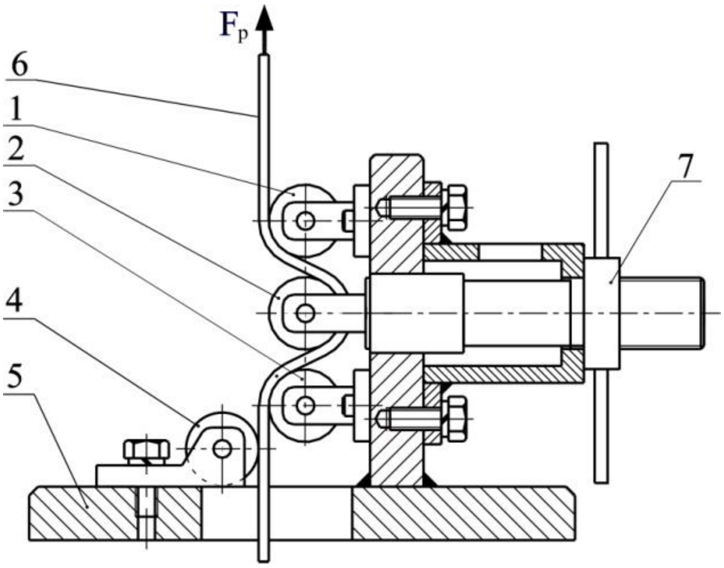

Fig. 1. Diagram of the test device for cyclic bending: (1), (2) and (3) – working rollers; (4) – guide roller; (5) – body; (6) – specimen; (7) – nut

During the maximum penetration h_r (Fig. 2b) of the middle roller (2), the angle of contact α is greatest. However, it does not reach the value of the angle α = 180° due to the clearance c_l between the rollers. During the tests, adequate side clearance c_l should be ensured between the rollers to prevent blocking of the sheet strip between the rollers (Kręcisz, 2005).

The samples were pulled through the roller system at a speed of 10 mm/s. Before the tests, the penetration of the central roller (2) was determined to be h_r = 18 mm. Changes in the pulling force F_p were recorded at a frequency of 50 Hz. The scheme of the cyclic bending process of Cu/Al bimetallic sheets is shown in Fig. 3. Cycling bending parameters and sample markings are listed in Table 3. The sample was pulled ten times for each layer setting and sample orientation.

a) b)

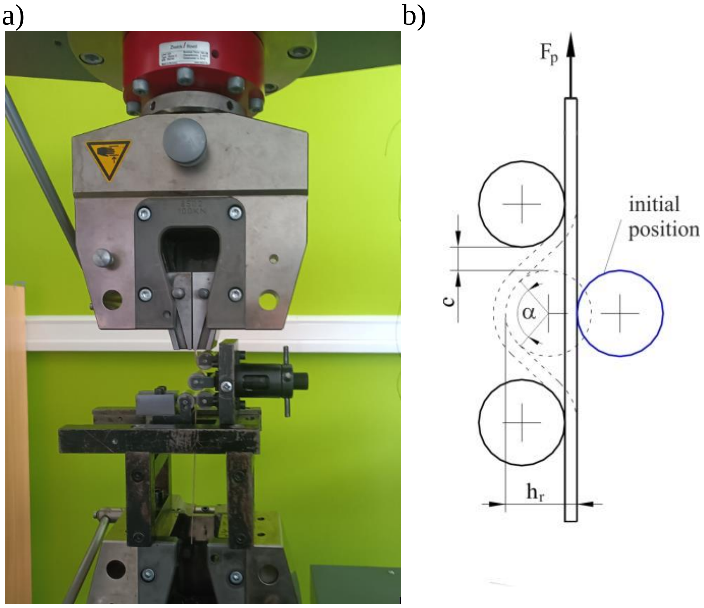

Fig. 2. a) photograph of the device for the cyclic bending process and b) the geometrical parameters of the cyclic bending process

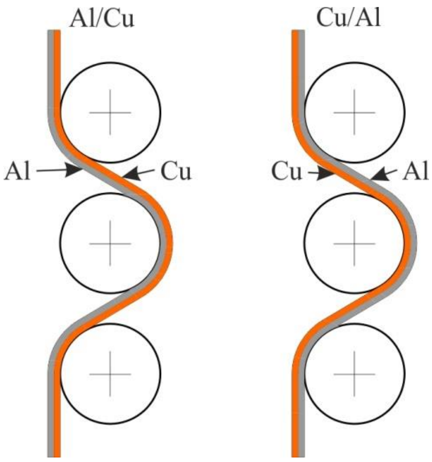

Fig. 3. The diagram of the bending process and the marking of Cu/Al sheets

Table 3. The process parameters and the determination of the samples

Indication	Layering	Specimen orientation	Number of passes	Penetration h_r, mm
Al/Cu-0	Al-Cu	0°	10	18
Al/Cu-90	Al-Cu	90°	10	18
Cu/Al-0	Cu-Al	0°	10	18
Cu/Al-90	Cu-Al	90°	10	18

2.3. Microstructural analysis

The sheets were subjected to preliminary structural tests using an optical microscope with Nomarski contrast. The microstructure of the specimens was examined using a scanning electron microscope (SEM) HITACHI S-3400N along with analysis of the chemical composition by energy dispersion spectroscopy (EDS). The thickness of the individual layers was measured using the measurement methods available in the microscope software. Hardness was measured with a load of 10g (HV0.01) using a Shimadzu HMV-C microhardness tester.

3. Results and discussion

The mean thickness and mean microhardness of the layers of the bimetallic sheets are shown in Figs. 4a and 4b, respectively. The microhardness analysis showed that its value varies depends on the measurement point, which is shown in Figure 5. These differences are not insignificant, but it can be seen that the microhardness of the copper layer at the contact boundary with aluminium decreases compared to measurements at a longer distance. Meanwhile, the microhardness of the aluminium layer in the boundary zone with the copper layer increases.

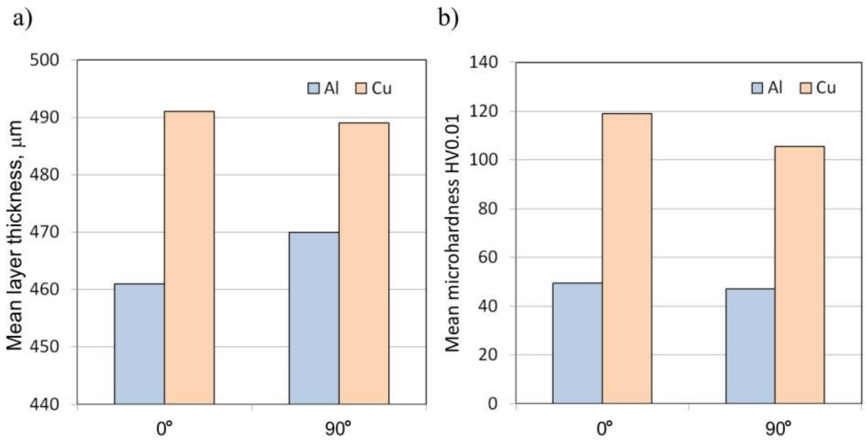

Fig. 4. a) mean thickness and b) mean microhardness of specific layers of samples oriented at 0° and 90°

The microstructural analysis showed that for the material denoted as Al/Cu-0, there is a lack of good bonding between the individual metals (Fig. 6). Analysis of the chemical composition in this area showed the presence of an increased amount of oxygen (Fig. 7, Table 4). It should be noted that this discontinuity occurs in fragments along the entire length of the test material. For the sample denoted as Al/Cu-90, this type of discontinuity was not observed (Fig. 8). In addition, in this case, the SEM micrographs showed an area parallel to the sheet surface in which an increase in the aluminium content was identified (Fig. 9, Table 5). In the transition layer of the Cu/Al-0 sheet, the copper content was about 76 wt.%. Meanwhile, in the same place on the Cu/Al-90 sheet, the content of copper is about 81wt%. Similarly, the aluminium content in this zone is almost twice as high for the Cu/Al-90 material compared to Cu/Al-0. In the EN AW-1050A layer, the aluminium content is 50% higher than for the Cu/Al-90 bimetal sheet. On the other hand, in the layer of the M1E sheet, the copper content is similar for both sheet orientations considered.

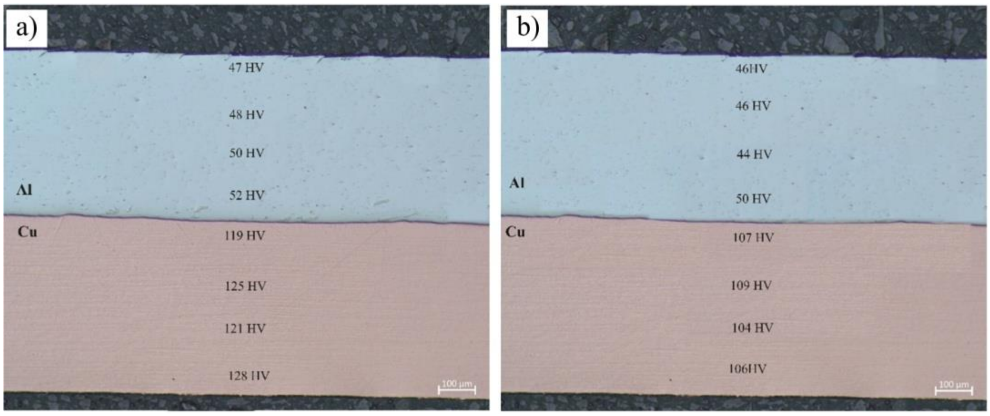

Fig. 5. Microstructure of the Al/Cu bimetallic sheet, including the microhardness measurement results: a) Al/Cu -0, b) Al/Cu-90

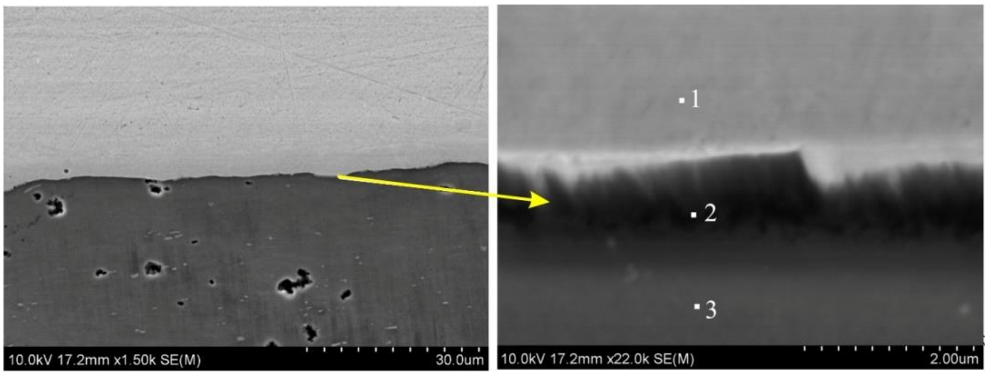

Fig. 6. SEM micrographs of the Cu/Al-0 bimetallic sheet

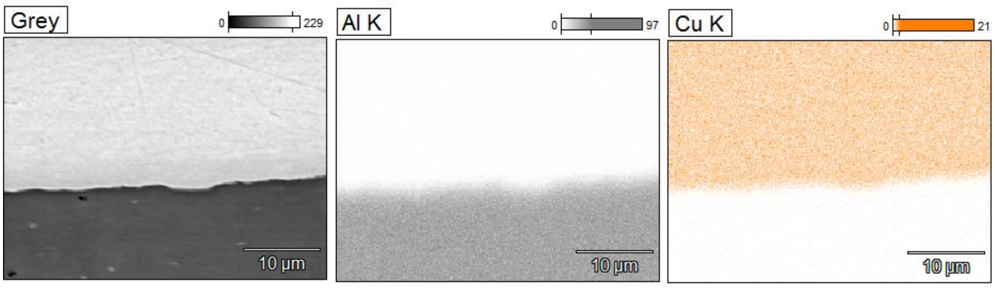

Fig. 7. EDS elemental mapping of the interface area of Cu/Al-0 bimetallic sheet

Table 4. EDS point scanning of the interface area of Cu/Al-0 bimetallic sheet (wt.%)

Point	O-K	Al-K	Cu-L
1	0.37	0.29	99.34
2	14.76	8.59	76.64
3	4.95	89.54	5.50

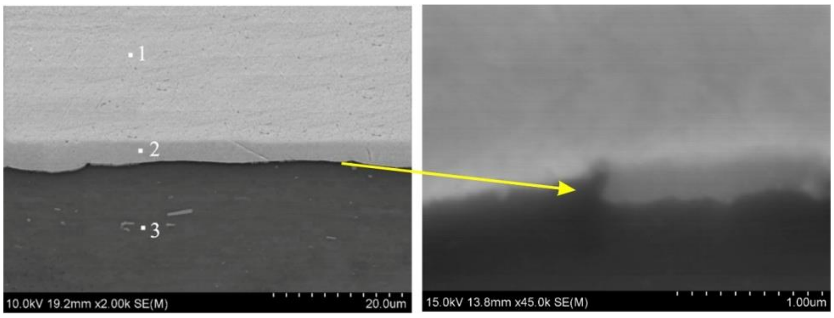

Fig. 8. SEM micrographs of the Cu/Al-90 bimetallic sheet

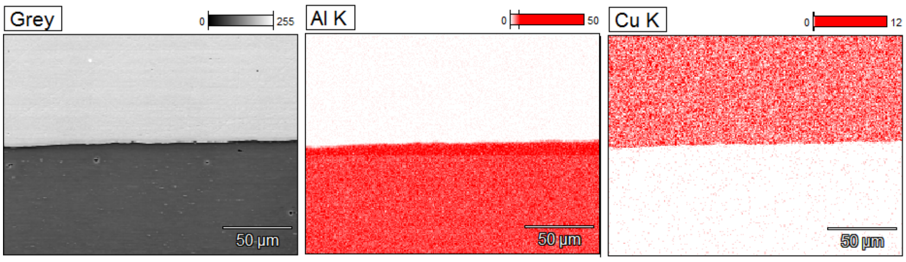

Fig. 9. EDS elemental mapping of the interface area of Cu/Al-90 bimetallic sheet

Table 5. EDS point scanning of the interface area of Cu/Al-90 bimetallic sheet (wt.%)

Point	O-K	Al-K	Cu-L
1	0.39	0.75	98.85
2	0.99	17.80	81.20
3	5.22	62.02	32.76

Fig. 10 shows the variation in the pulling force F_p at the tenth bending. Due to the large plastic deformation of the sheet during the cyclic bending process, the mechanical properties of the sheet change as a result of the work hardening phenomenon.

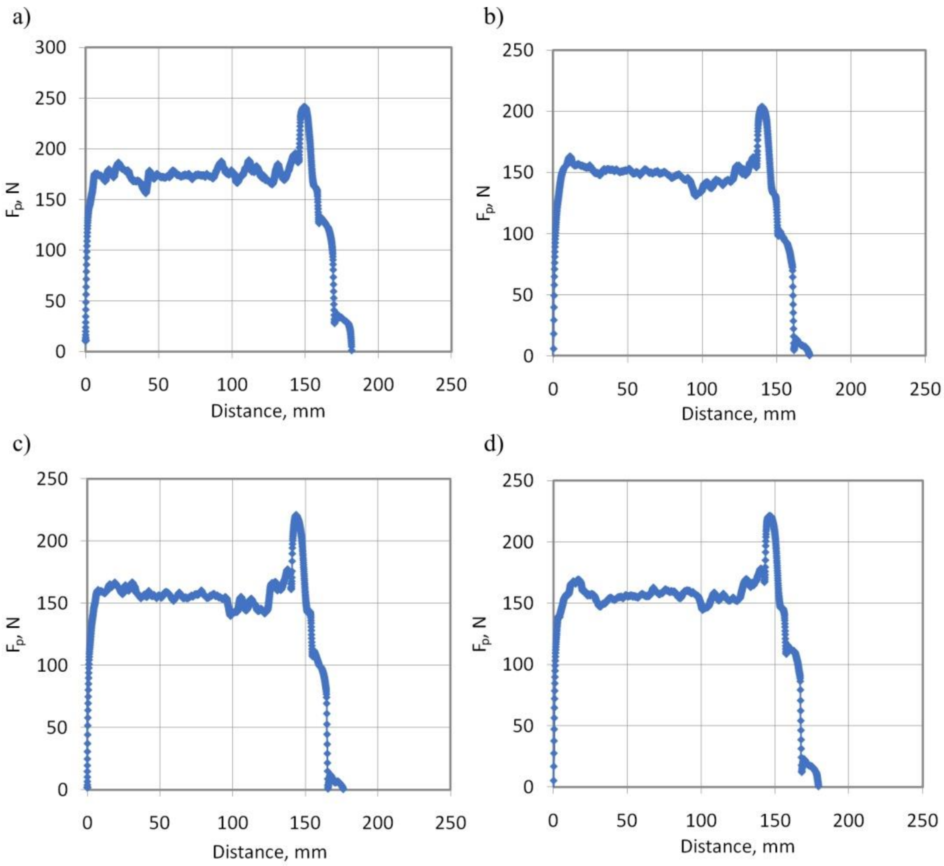

Fig. 10. Variation in the pulling force F_p at the tenth bending: a) Al/Cu-0, b) Cu/Al-0, c) Al/Cu-90 and d) Cu/Al-90

The strength of the sheet metal increases and at the same time the material is susceptible to cracking. The EN AW-1050A aluminium alloy is characterised by very high plasticity. On the other hand, M1E copper shows better strengthening properties. This is visible in the form of a higher average pulling force of the Al/Cu-0 sheet (Fig. 10a) by about 17% compared to the Al/Cu-90 sample (Fig. 10c). This indicates a clear influence of the orientation of the sample in relation to the direction of sheet rolling on the tendency of the bimetallic material to strain hardening. A different character of the force occurs for the Cu/Al-0 (Fig. 10b) and Cu/Al-90 (Fig. 10d) samples. The average pulling force values for both cases are almost the same.

4. Conclusions

This article presents the results of preliminary research on the cyclic bending of Al/Cu bimetallic sheets. The results allow the following conclusions to be drawn:

- The microhardness of the copper layer at the contact boundary with the aluminium alloy decreases in comparison to measurements at a longer distance, while the microhardness of the aluminium layer at the boundary with the copper layer increases.
- The orientation of the sample affects the occurrence of discontinuities on the interface between the layers of the bimetallic sheet.
- Significant differences in element content were observed in samples oriented in the direction along the sheet rolling direction and in the perpendicular direction.
- The influence of the cyclic bending process on the mechanical properties of the sheet is not unambiguous. When testing Al/Cu-0 and Al/Cu-90 bimetallic sheets, a higher pulling force was observed for the Al/Cu-0 sheets compared to Al/Cu-90. Meanwhile, for the Cu/Al-0 and Cu/Al-90 sheets, the average value of the pulling force was similar and amounted to about $F_p = 150$ N.

Future works should focus on understanding the layer-wise bonding mechanism, the extent of the bonding between subsequent layers and the bond variation throughout the joint. The effect of cyclic bending on the fatigue properties of the layer-wise bond should be further investigated for different degrees of sheet strain and strain rates.

Acknowledgments

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Właściwości Mechaniczne Blach Bimetalowych Aluminium/Miedź Poddanych Procesowi Gięcia

Streszczenie

Celem artykułu jest ocena wpływu procesu walcowania na właściwości mechaniczne próbek w postaci pasów blachy bimetalowej Al/Cu. Zaproponowano specjalnie zaprojektowany przyrząd do cyklicznego gięcia próbek wytwarzanych metodą walcowania. Test polega na wielokrotnym przeciąganiu paska blachy przez układ cylindrycznych przeciwpróbek. Badaniom poddano próbki cięte wzdłuż i w poprzek kierunku walcowania blachy. Próbki poddano wstępnym badaniom mikrostrukturalnym przy użyciu mikroskopu optycznego z kontrastem Nomarskiego oraz skaningowego mikroskopu elektronowego. Badania wykazały niewielki wpływ orientacji próbek na zmianę właściwości mechanicznych blach bimetalicznych w procesie cyklicznego zginania. W przypadku próbek zorientowanych wzdłuż kierunku walcowania blachy stwierdzono nieciągłości w warstwie przejściowej. Próbki zorientowane prostopadle do kierunku walcowania były wolne od tej wady.

Słowa kluczowe: blacha bimetalowa, gięcie cykliczne, twardość, umocnienie odkształceniowe