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Analysis of Plastic Forming During Rolling of Al1050-AZ31-Al1050 Layered Composites for Transport Purposes

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ABSTRACT

The aim of the research was to determine the possibility of producing and using layered composites made of aluminium and magnesium alloys Al1050-AZ31-Al1050. The use of layered composites often results from economic conditions. The work analyzed the current research, technological and production potential, as well as selected microstructural phenomena occurring in the tested multilayer materials and the effects of the rolling process. The material for the study was obtained using the explosion welding technology, one of the few enabling universal joining of often difficult-to-weld metals. The rolling process was carried out on a semi-industrial duo rolling mill with a roller diameter of Ø300 mm. The composite input material for the rolling process was heated to a temperature of 380 °C. The effect of the rolling process on the distribution of metal pressure forces on the rolls, the geometric parameters and the microstructural changes occurring in the plastically formed layered composite were an-alysed, and the energy gain from using a structure in which the currently used aluminium com-ponents were replaced with the tested composite was estimated. The research results presented in this paper prove that in the rolling process of the layered composite there are differences in the deformation values of the Al1050 and AZ31 layers. These differences are caused by the properties of the materials combined into the layered composite. The use of the proposed composite material in industrial conditions will enable the weight of selected elements to be reduced by up to 60%, which will have a positive impact on the energy efficiency of the entire structure.

Keywords: layered composites, rolling of composite sheets, explosion welding, modern materials, aluminium and magnesium alloys.

INTRODUCTION

Current climate policies in the EU, China, the USA and other highly developed countries are forcing the search for new construction and material solutions to reduce energy consumption. One direction of development in the materials field are aluminium and magnesium based alloys [1]. While aluminium alloys have good resistance to oxidising agents, magnesium does not, which is why surface protection is so important [2, 3]. Works on new lightweight construction materials, including composite materials with favourable strength properties have been conducted in many research and development centres. [4, 5]. These research works generated an increased interest in non-ferrous metals, mainly aluminium and magnesium alloys [6, 7]. The fact that magnesium alloys have the highest strength in relation to their density has resulted in a great interest in these materials [8, 9]. Magnesium alloys have become widely used in many industries, which include the automotive, aerospace, electronics, etc [9, 10]. The advantagious functional properties of magnesium alloys (low density and high strength) are the reason for the widespread use of these materials, especially in the fabrication of layered composites [11, 12]. Many research works are being carried out on improving the processes of plastically formed composite products. In recent years, there has been a continuous increase in interest in composite materials, especially layered ones. This has been confirmed by the number of publications listed in such databases as Google Scholar, Semantic Scholar, Elsevier, BAZ TECH. When analysing the number of publications according to the Google Scholar database, bimetals were discussed in 5,990 review articles, and in the content of 90,800 of all papers monitored by the database. These data lead to the conclusion that there has been a diametric growth in interest in topics relating to bimetals during the period under review. In the case of Al/Mg bimetal and layered composite Al/Mg/Al, the Google Scholar reports 19,200 results for review articles and 62,300 results in total, with the dynamic increase mainly in the last decade.

The afore-presented analysis on the number of publications relating on layered materials, including Al/Mg confirms the high scientific interest in the subject under study, although much lower among scientists in Poland [13, 14]. This therefore justifies the choice of the subject under study [15]. Very important to these considerations are the work relating to the numerical modelling of the processes of plastically forming composite products [16, 17]. Numerical research often makes it possible to determine technological parameters which in turn, to a certain extent, control the mechanical properties of the produced composite materials [18, 19]. Of relevance here are the methods of joining layered composites [20, 21]. Another very important matter is the selection of the method and conditions for plastically forming process [22, 23]. Both during the joining of the composite layers and its forming, a number of processes take place that affect the quality of the bonding areas of the composite layers, the changes that take place in the microstructure that determine the later properties of the finished product [24, 25]. The goal of this study was to determine the influence of the rolling process on the microstructural changes in the Al1050-AZ31-Al1050 composite layers. The quality of the bonding areas of the layered composites was also analysed [25, 26, 27].

The combination of low-density and high-strength layers into a single Al1050-AZ31-Al1050 composite results in invaluable structural materials suitable for automotive and aerospace industries. The Al1050 outer layers show very good corrosion resistance and are made of ductile material. The AZ31 layer used in the composite, on the other hand, have high strength and reinforces the layered composite.

MATERIALS AND METHODS

This paper presents the results of laboratory tests on the rolling process of three-layer Al1050-AZ31-Al1050 composite sheets. Subjecting the AZ31 layer to bilateral plating with Al1050 layers was due to the properties of the alloy [9, 11]. Among other things, the material used for the outer layers has a higher corrosion resistance compared to the higher-strength AZ31 alloy [21, 23]. The bilateral plating with Al1050 layers applied will not negatively affect the most important advantage, which is the low weight in relation to the strength properties [7, 9]. For this reason they should be of interest to both the automotive and aerospace industries. The material for testing was made using the explosion-welding method by the Polish Explomet company. The maximum shearing stress was approx. 62 MPa, this combined with the values presented, among others, in the publication [24]. Figure 1a shows a schematic diagram of the joining method and Figure 1b shows a sample cut from the finished sheet. The chemical composition of the materials tested is shown in Table 1.

The manufacture of flat multilayer products requires an appropriate metal joining method. For joining flat multilayer products, the method of explosion welding of metals and their alloys is commonly used. The second stage in the manufacture of multilayer sheets is the rolling process. The bimetals obtained by this method as well as multilayer composites consisting of more than two materials, have unique structural properties. They are characterised by high strength, corrosion resistance and excellent electrical conductivity. Explosion welding can be used for materials

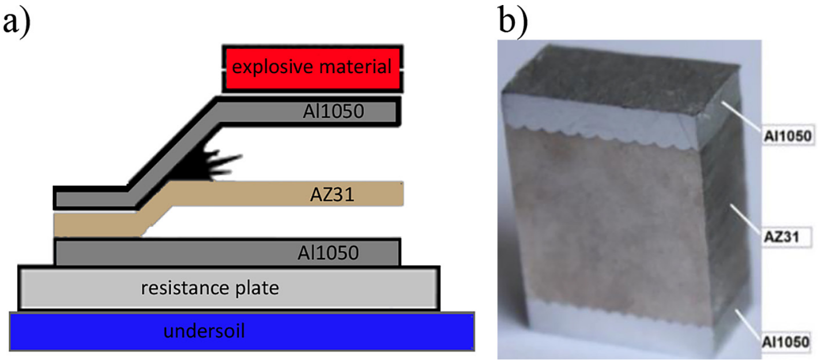


Figure 1. (a) Schematic diagram of the explosion-welding method, (b) sample cut from the finished sheet

Table 1. Chemical composition of alloys used in explosive welding processes (wt. [%])

Material	Al	Mg	Cu	Zn	Ni	Si	Mn	Fe
AZ31	3.50	95.00	0.05	0.80	0.01	0.10	0.40	0.01
Al1050	99.50	0.047	0.05	0.008	0.01	0.06	0.005	0.32

that can be also joined by traditional methods as well as metals and their alloys for which there is no alternative technology. The rolling process for flat multilayer products is often dictated by the impossibility of directly joining layers with thicknesses corresponding to the finished multilayer product. In addition, in the process of rolling multilayer sheets, it is possible to affect the mechanical properties and structure of finished products by causing large deformations. Depending on the intended use, the rolling process often followed by a heat treatment. After the explosion-welding process, samples 26 mm thick (where 20 mm was the AZ31 layer while the Al1050 plating layers were 3 mm thick each), 100 mm wide and 150 mm long were cut off. The rolling process was carried out on a semi-industrial DUO 300 reversible laboratory rolling mill with a roller diameter of 300 mm, in the rolling laboratory in the Department of Metallurgy and Materials Technology at the Czestochowa University of Technology (Figure 2). The mill's measurement system enabled the

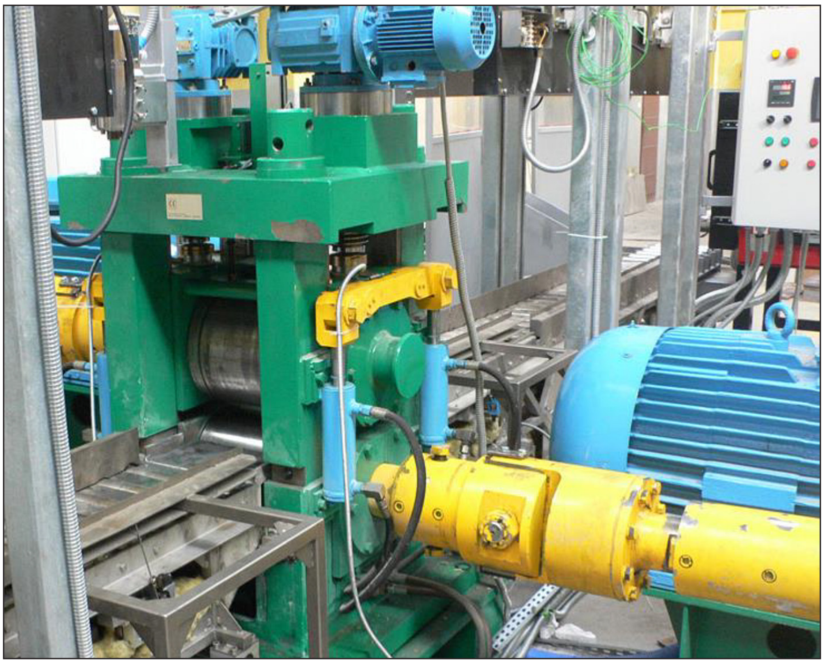


Figure 2. View of a laboratory rolling line with DUO 300 rolling mill

measurement of the energy and force parameters of the process, i.e. the pressure force exerted by the metal on the rolls measured directly by the force sensors and the rolling torque, measured indirectly from signals received from the frequency converters supplying the drive motors of the upper and lower rolls.

As part of the work, examination of the connection areas of the composite layers was carried out, both immediately after connection by explosive welding and after subsequent stages of the rolling process. The research was carried out using a JEOL JSM-6610LV (Japan) scanning electron microscope (SEM) working with the EDX microanalyzer from Oxford Instruments X-Max.

RESULTS

The rolling process was carried out in two stages as shown in Table 2. In the first series, the feedstock was subjected to rolling through two passes after being heated in the furnace to 380 °C. Then it was put back into the furnace and, after heating to a temperature of 380 °C was subjected to rolling in a second series consisting of three passes. The rolling speed in each case was constant at 0.3 m/s.

The results of the research made it possible to select the conditions for the process leading to a defect-free product with high quality requirements.

During laboratory tests, the optimum conditions for the rolling process were determined. As a result of the experimental tests, the values of the metal pressure forces on the rollers during subsequent passes were recorded. (Figure 3).

On the basis of the results of the tests on the rolling of triple-layer sheets composed of Al1050-AZ31-Al1050 presented in Figure 3, it can be observed that the values of the metal pressure force on the rolls in successive passes increase in series 1 as well as series 2. For this reason the rolling process required the reheating of the rolled samples. This was due to the rapid cooling of the feedstock and, as a result, led to a sharp increase in the metal pressure forces on the rollers (particularly evident in the case of the second rolling series).

The rolling process resulted in composite sheets with a final thickness of 10 mm were obtained, without delaminations and cracks in the joining area (Figure 4). In addition, thanks to bilateral plating of the AZ31 layer with Al1050 layers, there was no bending of the composite strip after exiting the rolling line. This was due to the same deformation pressures from both the top and bottom rollers. In general, it can be concluded that the tested composite plates can be successfully rolled without affecting the durability of the bond between the layers forming the three-layered composite. The research was carried out using a JEOL JSM-6610LV (Japan) scanning electron microscope (SEM) working with the EDX microanalyzer from Oxford Instruments X-Max.

This was followed by an in-depth analysis using SEM microscopy. The bonded area (Figure 5) was assessed as the most important from the point of view of the durability of the entire composite. The sample was subjected to analysis after the last pass, due to the fact that macroscopic evaluation of the sample after each pass did not show any separations.

As it can be noticed, there are no distinct small zones of separation, but an area of varying colour can be observed. This zone, to the authors' knowledge, is most likely an area of remelting in which intermetallic phases are formed. These phases are in most cases characterised by

Table 2. Process parameters for rolling composite sheets

Series no.	Pass no.	Relative deformation ε [%]	Composite sheets thickness [mm]	Thickness of individual composite layers [mm]		
				Al1050		AZ31
				Top	Bottom	
380 °C			26.00	3.00	3.00	20.00
I	1	20.00	20.80	2.38	2.38	16.04
	2	17.30	17.20	1.95	1.94	13.31
Reheating to 380 °C						
II	3	18.02	14.10	1.58	1.58	10.94
	4	16.31	11.80	1.28	1.28	9.24
	5	15.17	10.01	1.06	1.06	7.89

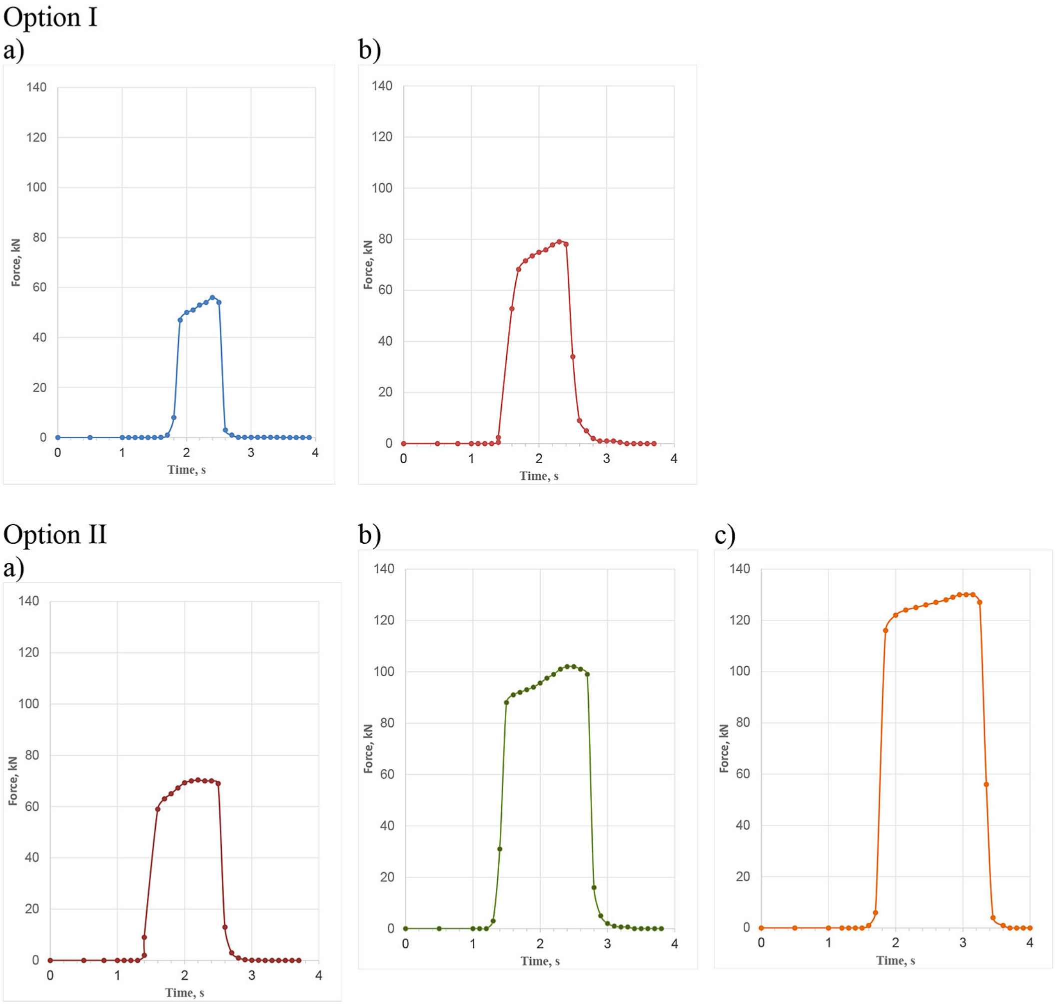


Figure 3. Distribution of metal pressure forces on the rollers during the rolling process, (a) and (b) after heating to 380 °C; (c-e) after reheating to 380 °C

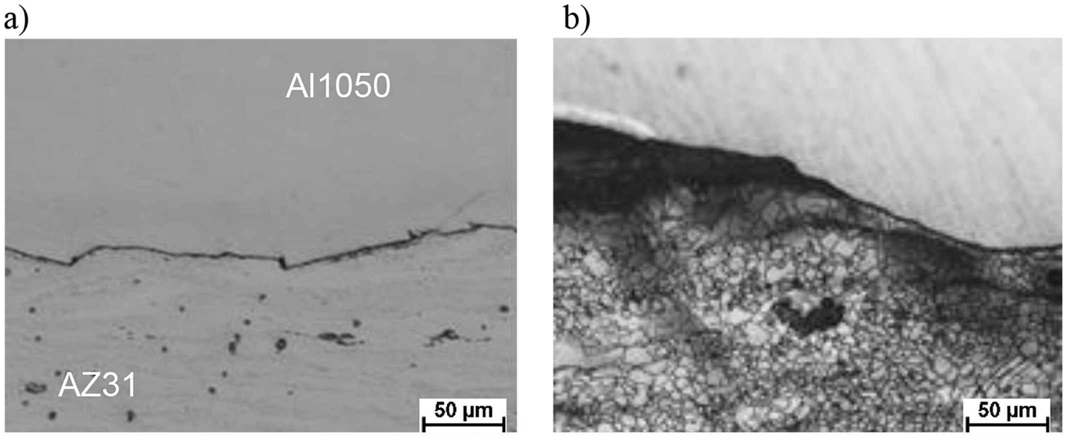


Figure 4. View of the areas bonded by explosion welding (a) before rolling, (b) after rolling

significant hardness and thus brittleness. Therefore, an EDX analysis of this area was carried out for identification purposes. Fig. 6 presents the obtained results.

As it can be observed, two types of Al3Mg2 (β) and Al12Mg17 (γ) are visible in the bonding area, depending on the place where the intermetallic phases are present. Importantly, despite the

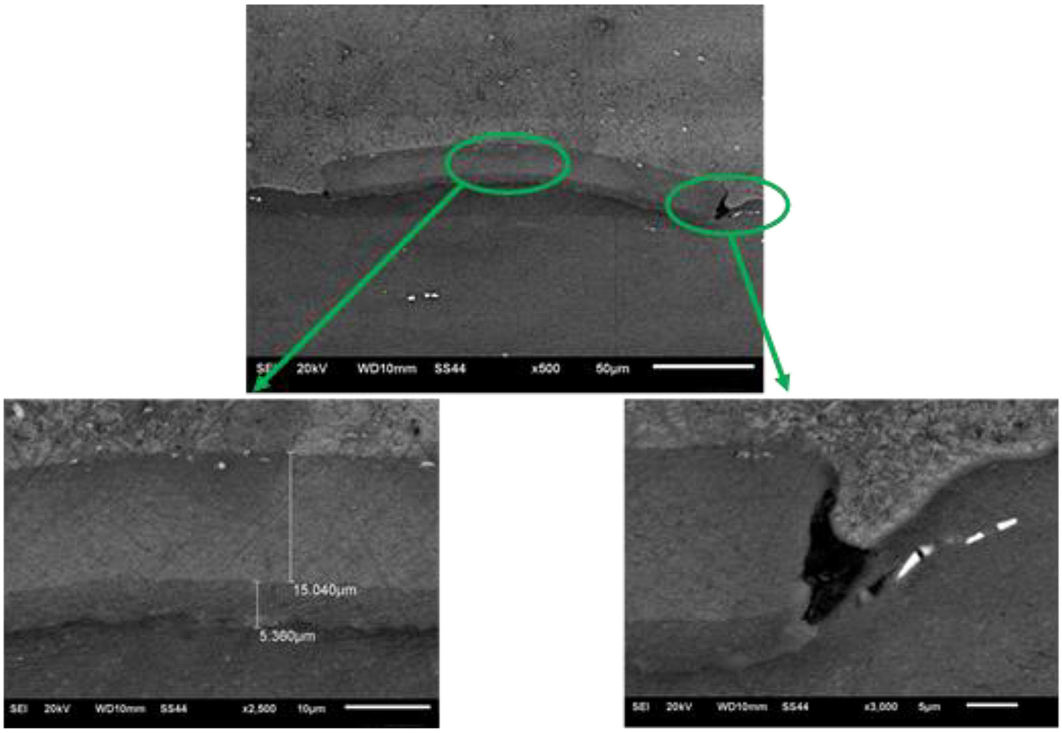
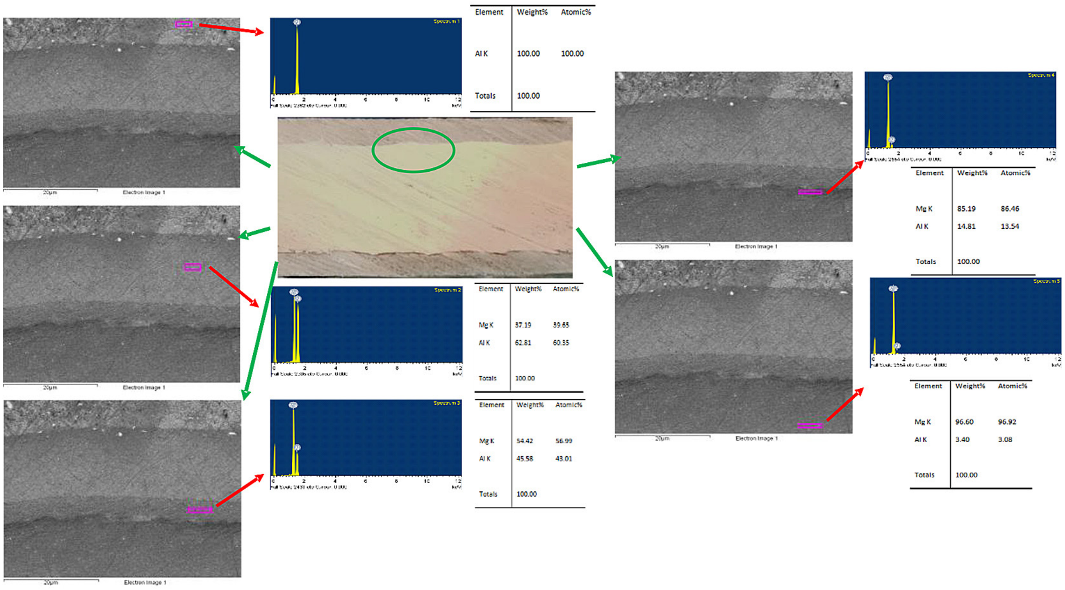


Figure 5. SEM view of the bonded area after the last pass



Element	Weight%	Atomic%
Al K	100.00	100.00
Totals	100.00	

Element	Weight%	Atomic%
Mg K	37.19	39.65
Al K	62.81	60.35
Totals	100.00	

Element	Weight%	Atomic%
Mg K	54.42	56.99
Al K	45.58	43.01
Totals	100.00	

Element	Weight%	Atomic%
Mg K	85.19	86.46
Al K	14.81	13.54
Totals	100.00	

Element	Weight%	Atomic%
Mg K	96.60	96.92
Al K	3.40	3.08
Totals	100.00	

Figure 6. EDX analysis of areas of intermetallic phases

fact that these phases have significantly different properties in relation to the matrix material, i.e. aluminium or magnesium, and although they were subjected to deformation no fractures are observed around them. It is possible to limit the precipitation of intermetallic phases. However, their complete elimination in real conditions, and this is the material we are dealing with in our article, is basically impossible. The first stage affecting their quantity is welding, e.g. explosive welding, the second is the hot rolling process. The use of optimal parameters of both processes guarantees a significant reduction in the formation of brittle phases [28, 29].

This shows that the analysed composite has great potential for use in plastically formed lightweight structural components, e.g. those used in cars and airplanes.

Assessing the potential for use of the analysed material in transport structure

Among the important factors affecting fuel consumption and hence air pollution is vehicle weight. The authors of works [i.e. 31, 32] have estimated that a 10% reduction of vehicle weight (assuming constant load weight) results in a 2% reduction in fuel consumption in case of railway trains and light, medium and heavy trucks, 4% for buses and 7% for airplanes. Aluminium, as a lightweight metal, it is a potential candidate for weight reduction; it can be used in a large number of vehicle components and thus significantly reduce their weight [33, 34]. Studies have shown that increasing the aluminium content in a vehicle significantly reduces greenhouse gas emissions and energy consumption [32]. When a 10 per cent reduction in vehicle weight is offset by an increase in the equivalent weight of the load, fuel consumption (per unit weight of load) increases from 6% to 23%, with the largest increase for airplanes. Furthermore, according to the literature, with each 45 kg of additional load, the fuel consumption of a vehicle increases by approximately 2% [33, 35]. The greatest use of aluminium alloys, including Al1050, for car structural components can be observed in hybrid and electric vehicles. To compensate for the extra weight resulting from a large, massive, battery pack, electric vehicle manufacturers tend to use even more aluminium in the body of a car. It is known that in new construction use also magnesium as one of the weight saving options. The combination of these factors has resulted in an overall increased use of this metal in electric compared to ICE vehicles, and a greater proportion of the plastically formed alloys in their production [36].

The work [37] includes projections of the total future aluminium demand for passenger cars for all 8748 scenarios are shown on Figure 7a. All model runs lead to a significant increase of automotive Al demand, but the speed and scale of this increase shows large variations between scenarios. As shown in Figure 7b, 50% of the scenarios considered result in a demand within the range of 55.1 to 98.5 Mt/yr in 2050, with a median of 74.3 Mt/yr. For the three IEA electrification scenarios (excluding the Constant scenario used for reference), the median increases to 80.1 Mt/yr, almost

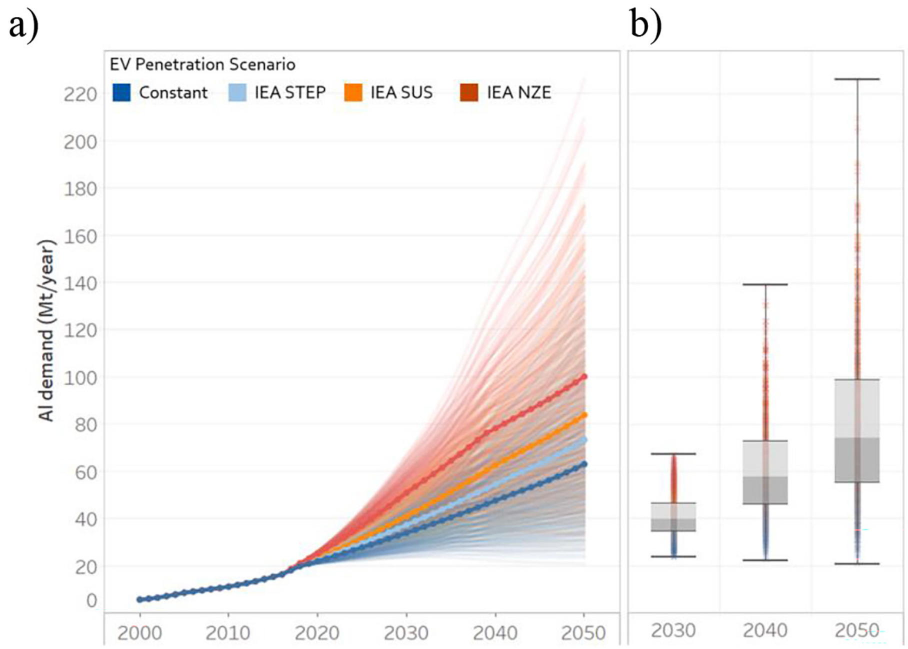


Figure 7. Yearly global aluminium demand for passenger cars [32]; (a) each line represents a model run for every unique combination of model parameters. Thick dotted lines represent the average of all scenarios for a given electrification scenario (dark blue: Constant, light blue: STEP -Stated Policies, orange: SUS - Sustainable Development, red: NZE - Net Zero); (b) box and whisker plot showing the statistical distribution of aluminium demand computed for all scenarios in 2030, 2040, and 2050. Each colour dot represents one scenario. For each year, the box indicates the mean quartiles (the demand lies within the box for 50% of the scenarios): the bottom of the box is the lower quartile, the separation in the middle the median and the upper of the box the upper quartile. The whiskers represent the extreme data points

a f times increase compared with 2020. Electrification has a clear effect on aluminium demand: the fastest electrification scenario (represented in red) leads to an average additional increase of 37 Mt/yr in 2050 compared with a constant powertrain split [36].

This can be substantiated by both economic and mechanical reasons. One of the main factors having a significant impact on fuel consumption and wear and tear of vehicle components is its weight. For example, the biggest influence on fuel consumption and wear and tear of vehicle components is the weight difference in the transient state, i.e. when accelerating or decelerating the vehicle. This follows from a simple dependency. Let's assume, in urban traffic the vehicle accelerates from V0 to V50 – 50 km/h.

$$\delta EK = M\left(\frac{V_{50}^2}{2} - \frac{V_0^2}{2}\right) \qquad (1)$$

where: M – vehicle mass; V_0 – initial speed km/h; V_{50} – the speed to which the vehicle is accelerated = 50 km/h.

The energy required to accelerate the vehicle converted into the instantaneous fuel consumption can therefore be written as:

$$Ep = \frac{\delta EK}{\eta} \qquad (2)$$

where: η – engine efficiency = 0.28 for the internal combustion engine.

With such assumptions, the instantaneous combustion of the car will be:

$$S = \frac{E_p}{W_o} \qquad (3)$$

where: W_o for petrol is 43 MJ/kg.

On the basis of the analysis carried out, it can be concluded that reducing the weight of a passenger car by 100 kg can result in fuel savings of between 0.2 and 0.6 L per 100 km, while for lorries it is between 0.7 and 1.2 L per 100 km.

The situation is similar in case of airplanes [38], for which the highest fuel consumption occurs during take-off. While calculating fuel consumption the Boeing 737–800 airplanes, for example, the assumed fuel consumption amounts to 5 tonnes for every 1,000 km. By comparison, according to the data provided by Airbus, an Airbus 380 uses approximately 3 litres of fuel per passenger for each 100 km of flight. Analysing the fuel consumption in relation to the phase of flight, it is assumed that the climb alone consumes ca. 19% of fuel carried in its tanks at the take-off. The flight ca. 79%, Landing with engines on idle mode ~ 2%.

Of importance here is the change in gravitational potential energy = ΔEp which can be expressed by the equation

$$\Delta Ep = m \cdot g \cdot h \qquad (4)$$

where: m – mass; g – standard gravity; h – altitude.

Thus, at every stage of the design and use of an engine driven vehicle or aircraft, its total weight is an important factor. Weight reduction can in a significant way reduce mechanical wear and tear of the components, extend the service life of the structure and decrease fuel consumption. Bearing this in mind, the use of analysed composites, which enable up to a 60% reduction in the weight of structural components without affecting their properties, is completely justified.

DISCUSSION

Current trends in the field of materials research indicate a very significant interest in the composite materials including those made of light metals such as aluminium and magnesium. An in-depth analysis of the research potential in this area, presented in the first part of the article, showed a very noticeable increase. This is related to the issues of changes to more environmentally friendly modes of transport due to continuing need to reduce greenhouse gas emissions. The analysis of a potential for reducing emissions of harmful substances in the field of transport, presented in the last part of this paper, carried out only on the assumption of changing the materials currently used to aluminium alloys, has shown that this is the correct way forward. In addition, the possibility of reducing the weight of even just a part of the components by an additional 60% has a measurable effect in this respect.

The process of plastically forming thick three-metal Al1050-AZ31-Al1050 sheets is presented. The rolling process of Al1050-AZ31-Al1050 composite thick plates proposed in this paper proceeded correctly, and no cracks or separations occurred. The authors of this work also carried out an analogous rolling process without additional sheet reheating, which, however, proved to be inappropriate. Without reheating the rolled samples, transverse cracks occurred, mainly in the AZ31 layer, which spread to the other layers during rolling. The analysis of the thicknesses of the three-metal sheet layers after rolling lead us to another conclusion. The differences in the relative deformations of individual layers were negligible. Due to the alignment of the layers in the three-layer sheets, it was observed that the deformation coming from the top and bottom roll was almost the same. (or However, due to the differences in the relative deformations of the individual layers, we cannot call the process symmetrical.) And since the differences in deformations of the individual layers on the side of the upper and lower roll were identical, no bending of the sheets was observed during the rolling process. Furthermore, it can be stated that the three-layer Al1050-AZ31-Al1050 sheets can be successfully rolled to smaller thicknesses depending on the demand. As a result of the adopted arrangement of layers in three-layer composite sheets, it was observed that the deformation from the upper and lower rolls was almost the same (therefore, the rolling process of three-layer composite sheets can be named as “symmetrical”). One of the main conditions necessary to ensure that the process is symmetrical is that the deformations of the upper and lower rolls must be the same. Only in the second pass there is a slight difference in the strain values in the upper and lower Al1050 layers, what is presented in obtained results. Nevertheless, the results presented in this paper show the need for reheating of three-metal sheets, as they have a high cooling rate. It is necessary to continuously control the temperature of the rolled sheets.

CONCLUSIONS

The experimental analyses carried out both for samples after the bonding process using the explosion welding method and after the rolling process of three-layer sheets for the adopted deformation options confirm the high functional properties of the manufactured products. The rolling process of Al1050-AZ31-Al1050 three-layered thick sheets proposed in this paper proceeded correctly without cracking or separations of the layers constituting the three-metal composite. Thus, the assumed goal of the work was achieved.

On the basis of the research on the rolling process of three-layered Al1050-AZ31-Al1050 sheets and the assessment of the current state of knowledge, the following conclusions and statements can be made:

- the analysed research issue is important from the cognitive point of view, as evidenced by the significant increase of relevant publications in the world’s databases;
- due to the alignment of the layers in the three-layer sheets, the same deformations caused by the working rollers were observed, which contributed to the absence of bending of the three-layer sheets after successive passes between the rollers;
- interlayers resulting from remelting were observed in the bonding areas. These areas contained so-called inter-metallics, which are mixtures of the metal layers subjected to bonding process;
- no significant separations and cracking causing gaps between layers after the rolling process were observed in the bonding areas. However, few gaps observed in the remelted areas were during filled rolling process with deformed materials.
- the use of the analysed composite material, which enables weight reduction of selected components by up to 60%, will clearly increase energy efficiency of the overall structure.

To sum it up, the method of plastically forming flat, three-layer Al1050-AZ31-Al1050 sheets proposed in this study is an economically and technologically justified solution, which can greatly improve the quality and functional properties of the finished product and may form the basis for their industrial implementation.

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