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THEORETICAL AND EXPERIMENTAL ANALYSIS OF Mg/Al BIMETALLIC HANDLE FORGING PROCESS

The present paper reports the results of theoretical and experimental studies of the process of die forging a bimetallic door handle intended for the production of a helicopter. The aim of the studies was to develop and implement a technology for die forging of a product with a specific mass similar to that of magnesium alloys which will have, however higher corrosion resistance. Numerical modelling and industrial tests were carried out based on the previously forging processes for an AZ31 alloy door handle. The material for the tests was a bimetallic bar produced by the explosive welding method, in which the core was of alloy AZ31, and the cladding layer was made of 1050A grade aluminium. The studies were conducted for two variants: Variant I – the forging process was mapped by numerical modelling and industrial tests for the die shape and parameters used in the forging of the AZ31 alloy door handle, Variant II – the tool shape was optimized and process parameters were selected so as to obtain a finished product characterized by a continuous Al layer.

From the theoretical studies and experimental tests carried out it has been found that the application of the Variant I does not assure that a finished door handle characterized by a continuous cladding layer will be produced. Within this study, a novel method of bimetallic door handle die forging (Variant II) has been developed, which limits the amount of the flash formed and assures the integrity of the cladding layer.

Keywords: Mg/Al bimetallic forging, die forging, numerical modelling, FEM

1. Introduction

Die forging is one of the few metal forming processes that enables the manufacture of parts of complex shapes [1-3], and when using precision forging, also eliminates additional machining [4-6]. Die forging processes can be used for forging products both of steel [7,8], as well as of non-ferrous metals, chiefly aluminium, titanium and copper alloys, and in recent years, also of magnesium and nickel [9-11]. The processes of forging lightweight metals bear a close resemblance to forging steel, although, due to their peculiar features, are more difficult to accomplish. The limitations arise mainly from a high variability in properties in the range of applied forging parameters and narrow ranges of hot forming temperature. Thus, making complex-shape forgings is more difficult than in the case of steel, or in many instances, even impossible.

In the group of lightweight metals, magnesium alloys enjoy an increasing interest [12]. This is due to the possibility of applying Mg alloys, e.g., in the aircraft and automotive industries, where it is aimed at reducing the mass of finished parts. Therefore, many solutions concerning die forging of magnesium alloy products can be found in the specialist literature [11,13-15]. Aside from their advantages, which include, e.g., the lowest density among commonly used constructional materials or the ability to dampen vibrations and to absorb electromagnetic radiation, have also low corrosion resistance [16,17]. It constitutes a considerable limitation affecting their wider application in the aforementioned branches of the economy.

A promising solution to increase the corrosion resistance of magnesium alloys, while retaining a low mass, is by using an outer aluminium cladding layer. Thus, it seems appropriate to combine the advantages of magnesium and aluminium alloys in the form of a bimetallic (multilayered) product, in which the inner layer will be made of an Mg alloy, while the outer layer, responsible for corrosion resistance, will be made of aluminium. Products of this type have been manufactured for several years in the form of multilayered plates [18,19] and bimetallic bars [20-23]. By contrast, it is hard to find in specialist literature any studies concerned with the process of die forging Mg/Al bimetallic products.

In the one of the first studies [24,25] where the formability of Mg/Al bars (in die forging) was determined, a Mg/Al bimetallic specimens obtained in the hot hydrostatic extrusion process were used. A hard and little ductile layer of Mg/Al intermetallic phases was formed at the Mg/Al bond interface. The Mg/Al specimens were deformed using different forging methods, namely: upsetting, spreading and rising. Although the test results showed a possibility of presetting large deformations, in some

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instances, however, intermetallic phase cracks occurred at the bond interface.

The authors' earlier work [26,27] reports the results of tests for the plasticity of round AZ31 alloy specimens and for the effect of the aluminium cladding layer (in Mg/Al bimetallic specimens) on extending their formability range. The conducted experimental tests have shown that the application of the clad layer considerably extends the range of process parameters (such as temperature and strain rate), with which the AZ31 alloy can be deformed.

Extensive results of the experimental studies of the process of die forging of an Mg/Al bimetallic door handle are reported in work [28]. As a sample forged element, a handle being an element of the door of a currently manufactured helicopter was chosen. The study quoted above has shown that there is a technical capability to make correct Mg/Al bimetallic die forgings in an assumed shape on a screw press. Due to the fact that the currently used technology of die forging of the AZ31 alloy door handle (forging die shape and process parameters) was adopted for making Mg/Al bimetallic forgings [29], a loss of the cladding layer (exposing the magnesium core) was observed in the bimetal forging in the die division region.

Thus, the aim of this study is to optimize the Mg/Al bimetallic door handle die forging technology (Fig. 1) to restrict the flow of the outer Al layer into the flash, which will yield a finished product with a continuous cladding layer. The studies were divided into two variants. At the first variant, the forging process was mapped by numerical modelling and industrial tests for the die shape and parameters used in the forging of the AZ31 alloy door handle. At the second variant, on the other hand, the tool shape was optimized and process parameters were selected so as to obtain a finished product characterized by a continuous Al layer.

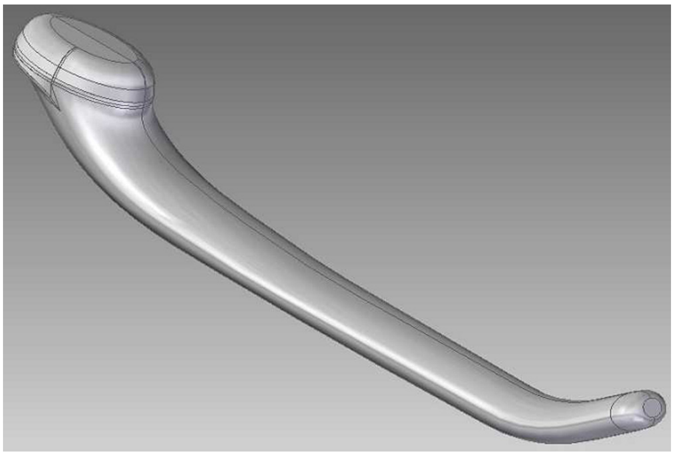

Fig. 1. Shape of door handle used to production of helicopter (model CAD) [28]

2. Materials and testing methodology

Bimetallic Mg/Al feedstocks were made using the explosive welding method. Materials used for the tests were the AZ31 magnesium alloy (the bar core) and an aluminium alloy in grade AW-1050A (the cladding layer). The parameters taken for explosive welding are described in detail in the authors' previous works [22,28]. Chemical composition of the materials used for the tests is given in Table 1. The initial dimensions of tubes and bars used for explosive welding are summarized in [22]. The diameter of Mg bars was 19.2 mm. And the outer diameter of aluminium tubes was 24 mm, while the tube wall thickness, 1.5 mm. The initial distance between the magnesium core and the inner tube diameter was 0.9 mm. After detonation, straight bimetallic bars with length of 500 mm and with a durable bond over the entire length was obtained, with no curving and necking. Mg/Al bars obtained from explosion welding were cut into 160 mm-long specimens, which constituted stocks for the door handle die forging process.

TABLE 1

Chemical composition of the materials used for the tests

Material	**Chemical composition, % mass.**								
AZ31	Mn	Mg	Cu	Zn	Ca	Al	Si	Fe	Ni
	0.24	balance	—	0.72	—	2.8	0.01	0.003	0.001
AW-1050A	Si	Fe	Cu	Mn	Mg	Zn	Ti	Al	Pb
	0.06	0.18	0.002	0.003	0.002	0.008	0.020	99.74	–

Bimetallic bars obtained as a result of explosive welding were characterized by a slight difference in aluminium layer thickness on the magnesium core perimeter. The average thickness of the aluminium layer was 1.67 mm, and the share of the aluminium layer in the bimetallic bar cross-section was 28%. Whereas, the average diameter of the Mg/Al bimetallic stocks after explosive welding was 22.6 mm (Fig. 2).

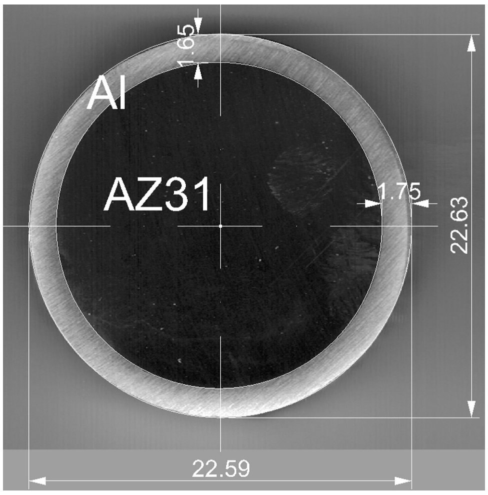

Fig. 2. A sample shape (cross-section) of Mg/Al bimetallic stock after explosive welding

The bimetallic stock was made in cooperation with the ZTW Explomet company of Opole. While the door handle die forging process was carried out in industrial conditions in collaboration with the company ZOP Sp. z o.o. in Świdnik.

TABLE 2

Coefficients of the flow stress function (1)

Material	A_1	m_1	m_2	m_3	m_4	m_5	m_7	m_8	m_9
AW-1050A	0.08743	–0.0099	0.11325	–0.08845	–0.00058	–0.00153	0.196267	0.00048	1.71527
AZ31	0.68478	–0.0072	0.34242	0.02864	–0.08199	–0.00023	–0.00439	0.00022	1.41094

The thermo-mechanical simulation of the forging process was carried out with the use of a visco-plastic model in the triaxial state of strain by using the Forge2011® program, whereas the properties of the deformed material were described according to the Norton-Hoff [30,31] conservation law.

For the Mg/Al bimetallic door handle forging process, the currently used technology of forging the AZ31 magnesium alloy door handle was utilized [29]. The forging process and its computer simulations were carried out for the conditions of an arc-stator drive screw press with a maximum pressure force of 4 MN and a working tool speed of approx. 0.5 m/s. For making forgings, tool sets in the form of double-half forging dies made of hot-work tool steel in grade WNL were used. In the first testing variant, two impressions, namely a bending impression and a final impression, were used. In the second variant, on the other hand, the shapes of individual impressions were modified to eliminate the flash (exposure of the magnesium core). In either of the variants, the forging temperature was 400°C. While in numerical computations for the second variant, using the results of the authors' previous studies [26,27], a reduced forging temperature was also adopted, which was 300°C. The die temperature for each of the variants was 300°C. For numerical computations, the Coulomb and the Tresca mixed friction model was adopted; the value of the friction coefficient was assumed to be 0.08, while that of the friction factor, 0.15 [32].

From the results of studies [26,27] it was found that, in the compression tests Mg/Al bilayered specimens, a break in the integrity of the cladding layer and a cracking of the magnesium core might occur. Therefore, the analysis of the possibility of these phenomena occurring in the bimetallic door handle forging process was made in this study based on the normalized Cockcroft-Latham fracture criterion [33]. Based on the results of studies [34,35], the critical fracture value for alloy AZ31 was taken as equal to 0.8 [34], while for the aluminium layer, this value was equal to 1.8 [35].

The properties of individual bimetallic components have been determined in the authors' previous studies [26]. The tests in the Gleeble3800 simulator were planned so that the flow stress function and its coefficients could be developed for the conditions of the deformation process during a laboratory hot rolling. For the description of the properties of the investigated materials, the Hensel-Spittel function [36] in the following form was employed:

$$\sigma_f = A_1 \exp^{m_1 T} \varepsilon^{m_2} \exp^{\varepsilon m_4} \dot{\varepsilon}^{m_3} \left(1+\varepsilon\right)^{\frac{m_5}{\varepsilon}} \exp^{\varepsilon m_7} \dot{\varepsilon}^{m_8 T} T^{m_9} \quad (1)$$

where: σ_f – flow stress [MPa], T – temperature [°C], ε – true strain, $\dot{\varepsilon}$ – strain rate [s^{-1}], A_1, $m_1 \div m_9$ – coefficients.

Based on the performed approximation of the results of plastometric testing of the materials used for the investigation with function (1), the values of the flow stress function coefficients were obtained, which are given in Table 2.

Figure 3 shows sample plastometric testing results and plastic flow stress-strain curves and obtained from their approximation for the materials under investigation. The solid lines with empty markers denote the curves representing the plastometric testing results, while the solid lines with filled markers denote the curves obtained from the approximation of the plastometric testing results.

When analyzing the data in Fig. 3 it can be noticed that in the case of aluminium for the examined temperatures, the derived approximating equation describes the actual material with high conformity, both qualitative and quantitative. By contrast, for the Mg alloy, there occur significant differences, especially quantitative, between the actual testing results and the approximated data, in particular for the temperature 300°C. Therefore, for numerical examinations, a combined method was used, in which the rheological properties of the examined material are input in a tabular form. This method allows actual data to be entered for the temperature-strain interval under examination, while for the remaining interval, the data is entered based on the results of plastometric testing approximation.

The use of the explosive welding method for making bimetallic stocks ensures a firm bond of the components to be achieved. Thus, in numerical simulations, the bond between the magnesium core and the aluminium cladding layer was defined as firmly adhering [22]. The nodes of both meshes were not connected. In order to increase the speed of computations, ½ of the stock cross-section was used in the simulations. In addition, it was assumed that the contact surfaces between the bimetallic stock components were permanently bonded with no possibility of nodes moving relative to one another.

3. Discussion of results

The tests concerning the use of 22.6 mm-diameter and 160 mm-long Mg/Al bimetallic bars comprised the process of industrial forging for conditions used for manufacturing door handles of a homogeneous material, which was the AZ31 alloy (Variant I). Figure 4 shows the previously used set of dies forming the AZ31 alloy door handle.

The pre-forming of round stock of either a homogeneous or bimetallic material takes place in a pre-forming (bending) impression, which is situated in the die corner, as shown in Figure 4b. Proper imparting of the final shape to the forging occurs in the final impression in the centre of the die.

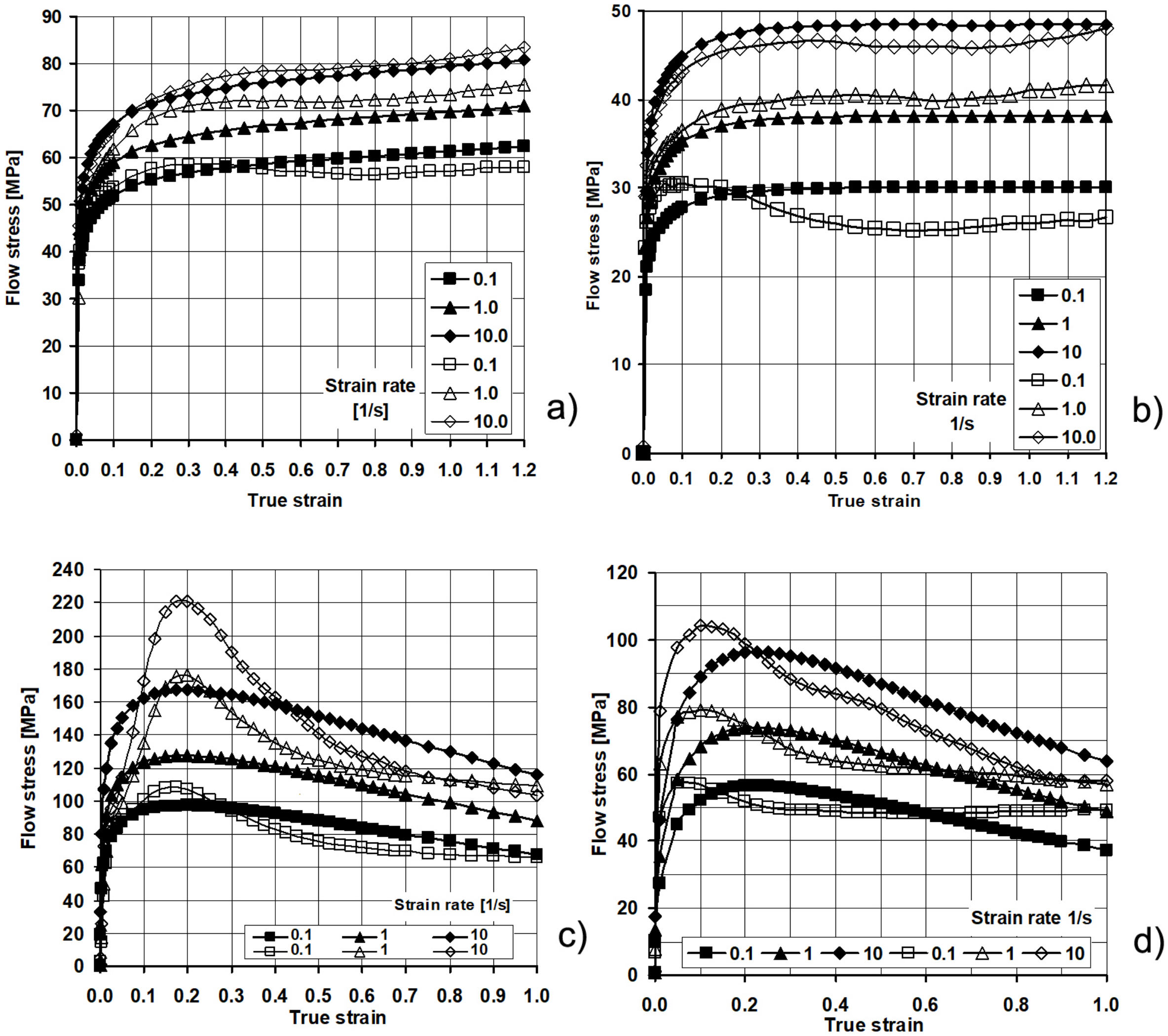

Fig. 3. Flow stress curves of materials used for tests: a) aluminium, 300°C, b) aluminium, 400°C, c) magnesium alloy AZ31, 300°C, d) magnesium alloy AZ31, 400°C

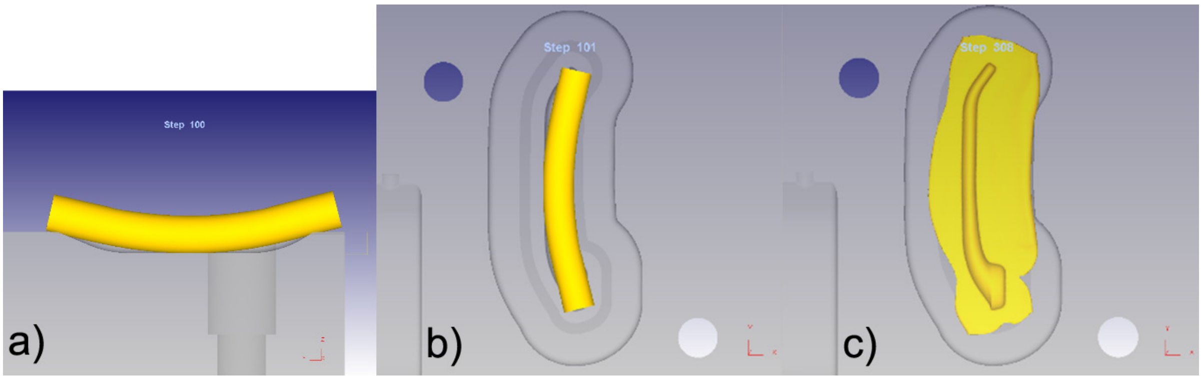

Fig. 4. The door handle forging process (simulation results): a) feedstock bending in the bending impression, b) positioning of the material after bending in the final impression, c) the final impression

The adopted feedstock heating temperature of 400°C lies within the temperature range for forging of both magnesium alloy AZ31, as well as aluminium AW-1050A. The identical temperature was used for heating up both the AZ31 magnesium alloy feedstock and the Mg/Al bimetallic feedstock. Based on the designed process, forging trials were carried out. The successive stages of the forging process are shown in Fig. 5.

Within theoretical studies, at the first stage, numerical computations of the process of Mg/Al bimetallic door handle die forging in previously used dies and for process parameters used in the AZ31 alloy door handle forging process were performed. Figure 6a shows a bimetallic door handle obtained from numeri-

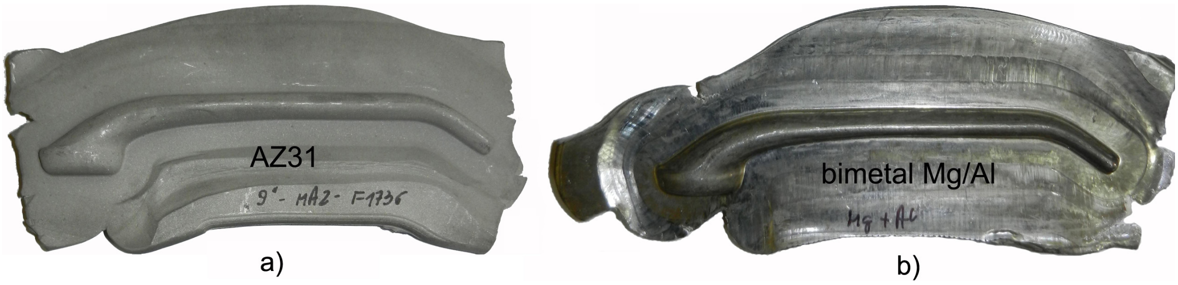

Fig. 5. A view of the forged door handles with a visible flash: a) the AZ31 alloy forging, b) the Mg/Al bimetallic forging

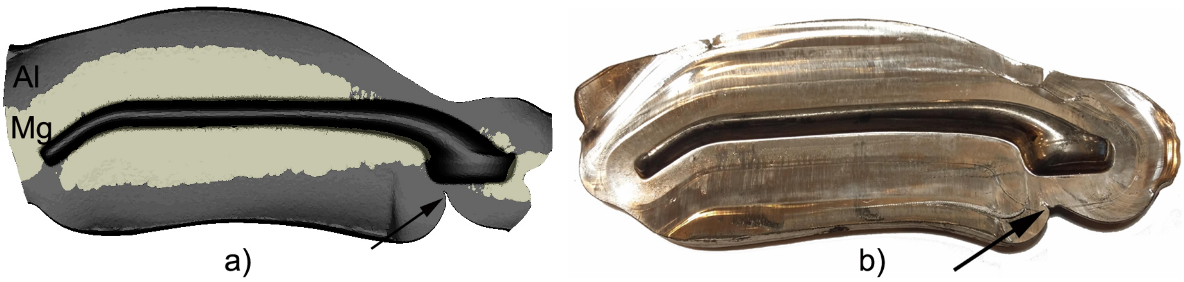

Fig. 6. Shape of forgings obtained in the numerical modelling (Variant I) – a) and experiment – b)

cal modelling, as well as a result of the experimental forging process prior to the trimming of the flash (Fig. 6b).

The obtained testing results show that both forging shapes are similar. In both cases, the complete filling of the die occurred. While when analyzing the shape of the flash, particularly good agreement was reached for the lower die part, as indicated by the arrow. The data represented in Fig. 6a shows that a loss of cladding layer continuity occurs in the die division plane regions in the door handle forging process, which causes an exposure of the magnesium core. When examining the door handle forging shown in Fig. 6b, no break in aluminium layer continuity can be explicitly found. Therefore, in order to determine whether the core exposure took place in the forging process for the door handle after the flash trimming operation, or not, 12-hour corrosion tests were carried out in a salt spray chamber [28]. Figure 7 shows a view of door handles after the flash trimming operation.

By comparing the obtained results it can be found that both in the theoretical studies and in the experimental tests the exposed core occurs on the flash trimming surfaces in the die division plane and in cladding layer continuity loss locations. In spite of the break in cladding layer integrity, in both cases, more than 70% of the door handle surface were covered with the Al cladding layer, all the same. The obtained theoretical and experimental Mg/Al bimetallic door handle forging results were unsatisfactory, in spite of the fact that corrosion tests were found that the corrosion resistance of the Mg/Al bimetallic door handle had increased by over 50%, compared to the door handle of the homogeneous AZ31 material [28].

The bimetallic door handle obtained from the numerical modelling of the process of forging according to Variant I was examined for the distribution of cladding layer thickness in characteristic cross-sections. Figure 8 illustrates the distribution of strain intensity, while Fig. 9 shows the cross-sections of the bimetallic door handle together with the distribution of cladding layer thickness. The exposed regions on the lateral door handle surfaces (Fig. 8) result from a break in the continuity of the clad-

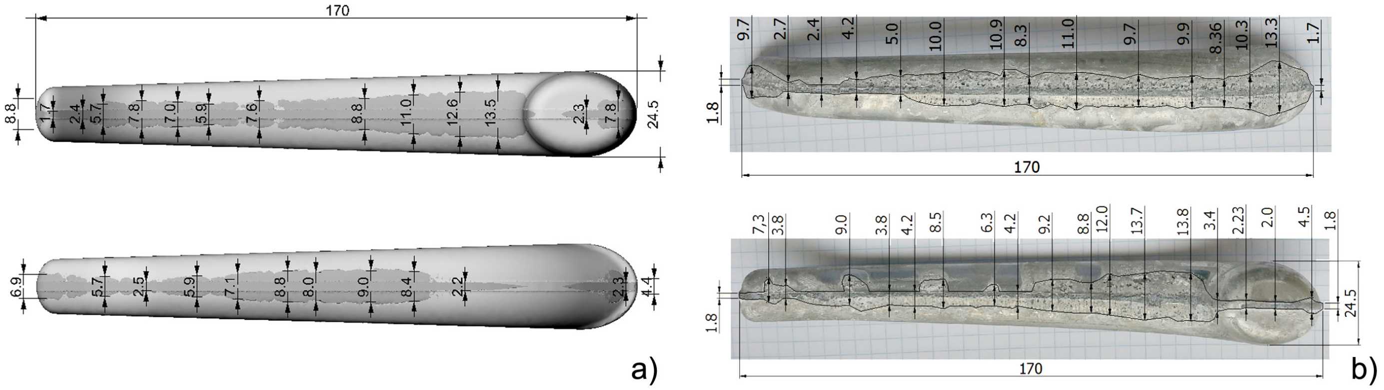

Fig. 7. A view of the exposed Mg alloy core in the forged Mg/Al handle (Variant I) after: a) numerical modelling, and b) experiment after corrosion tests

ding layer, where the limiting deformation was exceeded. It is particularly visible for the region shown in cross-section A-A, where it is necessary to preset a larger deformation, compared to the region in cross-section B-B, resulting from a smaller height in this door handle region. Breaking the cladding layer integrity is also a consequence of conducting the process of forging with a flash, as is the case for forging the AZ31 alloy door handle, during which a further forging height reduction occurs at the point of the complete filling of the impression volume with the material, which leads to an intensive "flowing" of the cladding layer down the magnesium core. A simultaneous thinning occurs on its lateral surfaces, which results in a break of its integrity. This effect in clearly seen in cross-section A-A, as shown in Figure 8.

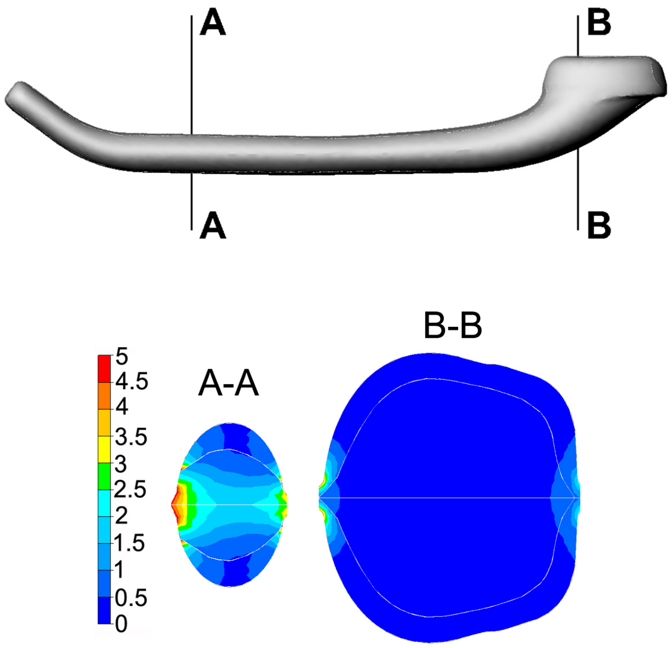

Fig. 8. Distribution of effective strain on cross-section of characteristically places of door handle (Variant I)

Figure 9 depicts comparison of the thickness distribution for selected door handle cross-sections from Fig. 8. From the data in Fig. 9, a good agreement can be found between the results of cladding layer thickness in selected cross-sections, obtained from the numerical studies and the experimental tests. As a result of intensive cladding layer "flowing down", a cladding layer thinning is visible towards the die division regions, which leads to a break in cladding layer integrity and an exposure of the magnesium core. For the door handle obtained from the experimental tests, no delamination at the joint boundary was observed (Fig. 9b).

The studies carried out for Variant I using numerical simulations have shown that the adopted temperature-strain parameters and the tool shape, admittedly, do yield a finished Mg/Al door handle characterized by the correct shape, but a loss in cladding layer integrity in die division regions occurs in this process, which leads, as a consequence, to an exposure of the magnesium core (Fig. 7 and 9). This contributes to an impairment of the functional properties (corrosion resistance) of the bimetallic door handle, which will be considerably higher anyway, compared to the homogeneous Mg alloy door handle, as has been demonstrated in work [28]. The obtained numerical study results were distinguished by high consistence, compared to the results obtained from the experimental tests. The similar cladding layer discontinuity regions formed during forging both in the numerical modelling and in the experimental tests confirm the correctness of the adopted value of the normalized Cockroft-Latham criterion for the cladding layer.

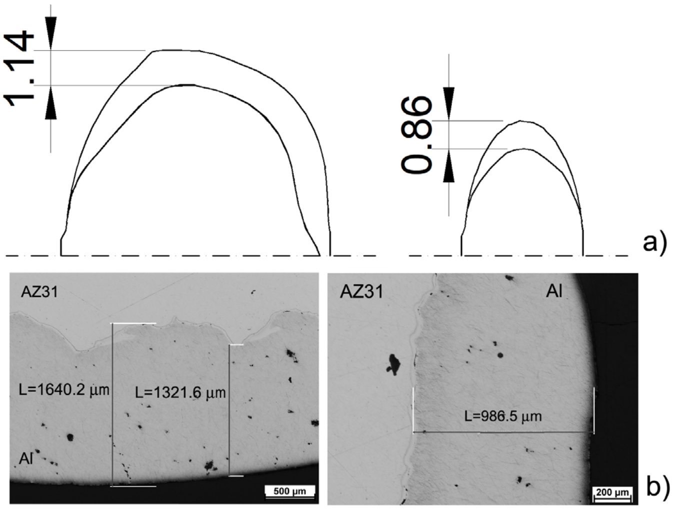

Fig. 9. Comparison of cladding layer thickness for selected cross-sections from Fig. 8: a) numerical computation results (1/2 of the door handle), b) experimental test results

Because of the break in cladding layer continuity during the process of rolling according to Variant I (with the preliminary bending impression used so far), an investigation into the modification of the tool shape, the Mg/Al bimetallic stock and the process parameters (forging temperature) (Variant II) was undertaken. The shape of the finished product was retained unchanged due to the geometric requirements for the finished product. By contrast, the dimensions of the bimetallic stock, as well as the pre-forming (bending) impression shape itself, were changed. The investigation of the process of forging according to Variant II included the selection of the bimetallic stock shape so that no overfilling (flash-less forging) occurred during forming the final impression, or the flash formed on the door handle perimeter was the result of a limited cladding layer "flow-down" not involving the core material, in this case AZ31, which would eliminate the cladding layer breaking. Achieving such an effect is possible through the appropriate selection of the bimetallic stock shape, i.e. the selection of cross-section areas in characteristic door handle regions. The cross-section areas were computed from the cross-sections of the finished door handle, while allowing for the directions of bimetal flow during plastic forming in two forging operations. The characteristic regions of cross-section analysis are shown in Figure 10 and the detailed values of these cross-sections are given in Table 3.

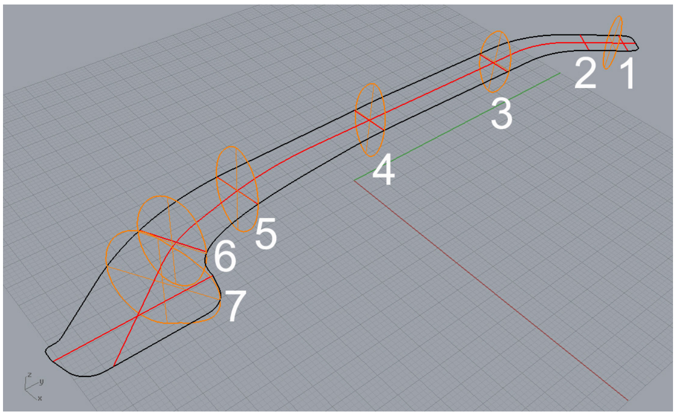

Fig. 10. Areas of characteristically areas of door handle cross section

TABLE 3

Areas of door handle cross section

	No. of cross-sections						
	1	2	3	4	5	6	7
Area [mm^2]	96.8	96.8	134.2	151.8	210.1	270.9	415.2
Diameter [mm]	11.1	11.1	13.1	13.9	16.4	18.6	23.0
Distance between cross-section [mm]	3.4	14.3	44.2	87.0	125.0	144.0	155.0

Based on the determined cross-sectional areas for the finished Mg/Al door handle, a model of the bimetallic stock shape was developed, which is depicted in Figure 11. It was assumed that bimetallic stock had to be axially symmetrical and bevelled at the ends. The designed bimetallic stock shape should ensure the correct fill of the final impression with no possibility of a flash occurring, and without a loss of cladding layer continuity in the regions, where the AZ31 core would be exposed after flash trimming.

The purpose of the bevels introduced at the stock ends is to limit the amount of the core material (AZ31) pushed out during forming, and to ensure the welding of the Al cladding layer ends during forging, thus assuring the integrity of the protective coating. In view of the fact that the process of die forging according to Variant II will be a flash-less process (with limited cladding layer flowing down the magnesium core), the thickness of the cladding layer in the stock was reduced to 1 mm.

From the tests carried out to determine the possibility of deforming multilayered materials it has been found that a thick cladding layer tends to "flow down during forming", which may cause its considerable unevenness. Moreover, a thicker cladding layer (in this case aluminium) increases the mass of the finished product. By contrast, too thin a layer might not provide the appropriate corrosion protection.

The prepared new CAD model of the bimetallic stock was then forged in two operations (impressions) at a temperature lowered to 300°C, compared to Variant I. From the authors' studies [26-28] it has been found that applying an aluminium cladding layer on the magnesium core would lower the AZ31 alloy plastic working temperature to 300°C. In the case at hand, the cladding layer accumulates the imparted deformation, thus providing the capability to deform the magnesium core without compromising its integrity. Lowering the temperature to 300°C for Mg/Al materials reduces also the ratio of the flow stress of magnesium alloy AZ31 to aluminium AW-1050A, which makes the deformation of the magnesium core and the aluminium cladding layer more uniform (a reduced cladding layer "flow-down"), compared to deformation at 400°C. Because the forming process must be conducted without a flash or, at least, with a small flash of the cladding layer, this requires a modification to the pre-forming impression shape relative to the shape used in Variant I. For pre-forming, a new pre-forming (bending) impression was designed, which largely corresponds to the shape of the finished door handle. The preset deformation in this forging operation must be selected so that the thickness of the bimetallic stock after pre-forging is smaller than the width of the final impression. As a result of adopting the above assumptions, during forming in the final impression, upsetting will take place across the length of the bimetallic stock and the die will be filled with no flash.

Pre-forming was carried out in the impression shown in Figure 12, while the results of forging in this impression are illustrated in Figure 13.

From the analysis of the results of numerical computations of pre-forming impression forging it can be found that the Mg/Al bimetallic stock has been deformed correctly, in line with the adopted assumptions. No cladding layer discontinuities are observed to form on the lateral surfaces. The ends of the deformed core are not coated with the cladding layer. The numerical computation results have also confirmed the presumption that bevelling will limit the excessive flowing out of the material from the AZ31 core. At the same time, the reduction of the amount of the flash flowing out outside provides a greater capability to eliminate cladding layer discontinuities during forming in the final impression. To achieve the welding of the cladding layer at the ends and to obtain a continuous cladding layer, the stock length was selected so that it was slightly shorter than the length of the final impression groove. The interaction of the impression

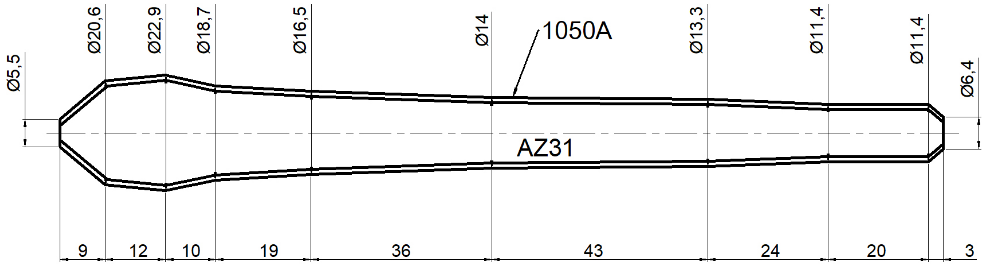

Fig. 11. Shape of the Mg/Al bimetallic stock to forging process of door handle (Variant II)

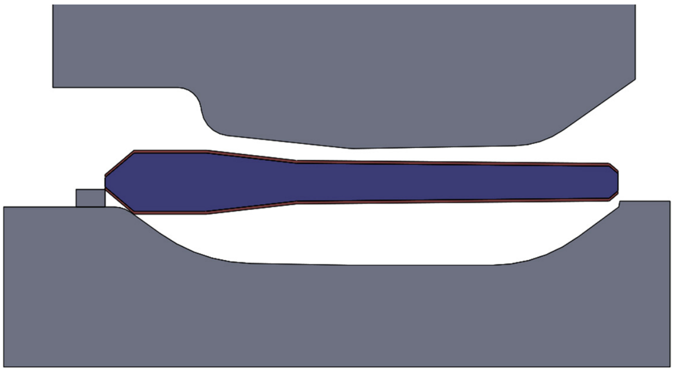

Fig. 12. The shape of tools for pre-forming the Mg/Al bimetallic stock

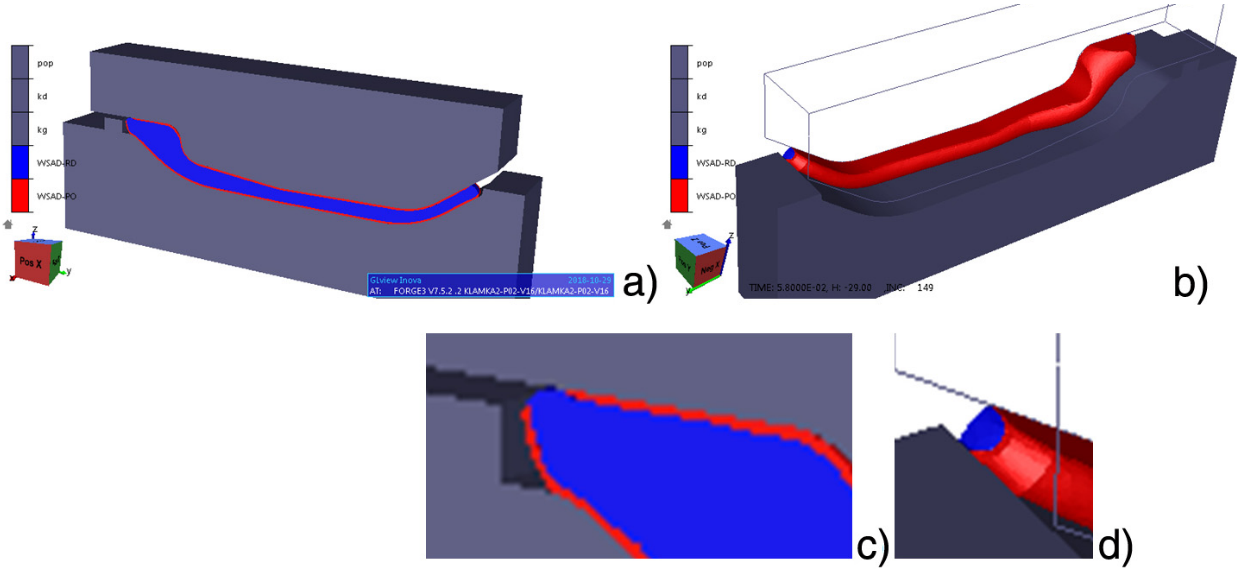

Fig. 13. The results of numerical modelling of the process of die forging in the pre-forming impression: a, b) general view; c, d) view of bevelled stock parts after pre-forming

during forging causes the elongation of the pre-deformed bimetal and also kneading of the cladding layer, whereby the aluminium coating will move towards the die division line, thus closing up the cladding layer (Fig. 14). The second forging operation is carried out in the final impression, after rotating the bimetal by an angle of 90° (Fig. 15).

Applying the new shape of the pre-forming impression and the new stock shape, and lowering the forging temperature eliminated the flash in the final impression. As a result, a continuous cladding layer was obtained on the entire finished product perimeter. A slight overfilling of the final impression was obtained at the bimetallic door handle ends, as well as in a region designed for mounting the door handle axle. In that region, a 0.5 mm cladding layer overfill occurred due to the cladding layer "flowing down" the magnesium core. Nevertheless, this did not result in a break in cladding layer integrity. Small regions can be observed at the door handle ends, which have not been coated (closed up) by the cladding layer due to the formation of too big a magnesium core flash (see arrows in Fig. 15), resulting from an excessively large material volume in those regions. Exposed surfaces are small and occur in locations less prone to mechanical damage. Thus, an additional paint coat in those areas should suffice as an added corrosion protection.

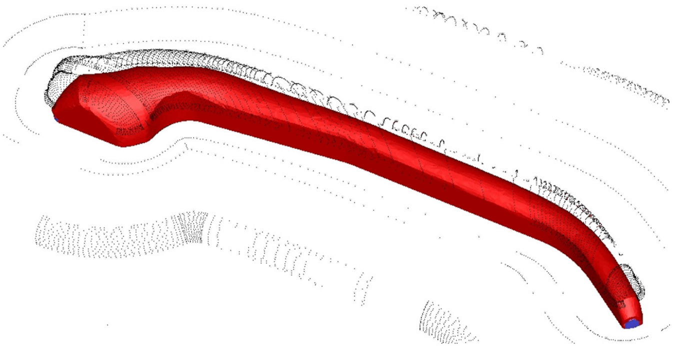

Fig. 14. The position of the deformed bimetal in the final impression

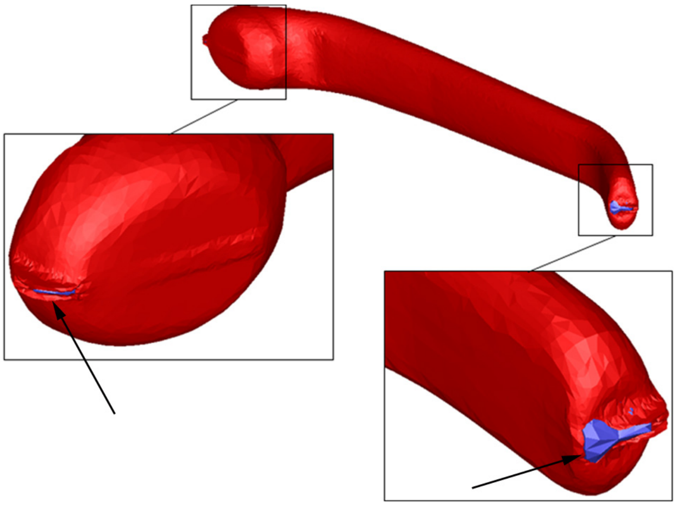

Fig. 15. A view of the Mg/Al bimetallic forging after the process of die forging in the final impression

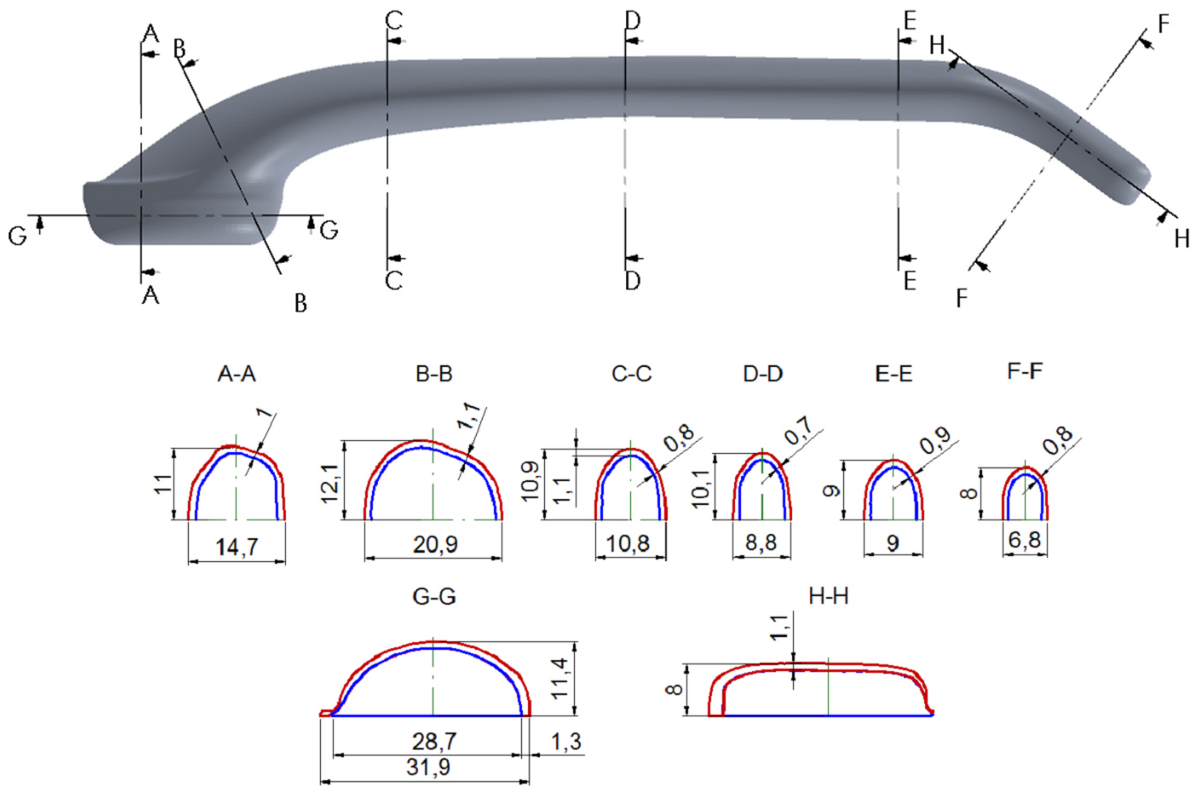

Fig. 16. Cladding layer thickness in respective cross-sections of the Mg/Al bimetallic door handle; ½ symmetric half of the door handle

Within the theoretical studies, change in cladding layer thickness in selected cross-sections, as shown in Fig. 16, was also examined.

The data illustrated in Fig. 16 shows that cladding layer thickness was varying in individual cross-sections, ranging from 0.7 mm to 1.1 mm. The varying cladding layer thickness is the result of the cladding layer "flowing down" the magnesium core, which is due to different deformation magnitudes occurring in individual door handle regions, both in the first and the second forging operations. In locations, where there is a direct interaction between impression surfaces, the cladding layer becomes thinner, while in free deformation regions, a cladding layer thickening occurs. The rotation of the bimetallic preform prior to the second forging operation changes the behaviour of cladding layer thickness distribution. Therefore, a cladding layer thickness greater than in the bimetallic stock was obtained. Cross-sections G-G and H-H shown in Fig. 16 are indicative of the occurrence of a cladding layer and core flash and the formation of a discontinuity in the cladding layer, which is caused by exceeding the limiting deformation value. In those regions, no cladding layer welding will take place.

By comparing the obtained cladding layer thickness distributions for Variant I (Fig. 9) and Variant II – the modified technology (Fig. 16), it can be found that the change of the preforming impression shape and the bimetallic preform shape, as well as the change of process parameters (forging temperature) have all resulted in a more uniform cladding layer thickness distribution and practically eliminated the possibility of discontinuities occurring in the Al layer.

4. Summary

From the theoretical studies and experimental tests carried out it has been found that the application of the currently used technology (Variant I) does not assure that a finished door handle characterized by a continuous cladding layer will be produced. Within this study, using computer simulations, a novel method of bimetallic door handle die forging (Variant II) has been developed, which limits the amount of the flash formed and assures the integrity of the cladding layer. In the case at hand, an important feature of the modified die forging process method is the precise selection of the bimetallic stock shape which will ensure the correct fill of the die, while eliminating the formation of the flash. The cladding layer discontinuities occurred at the door handle ends are possible to be eliminated; however, further experimental studies are needed to be carried out to this end.

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