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Scheme for producing composite material based on structural aluminum alloy by the direct extrusion method

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Abstract: The work covers the development of a technology for producing a bimetallic rod from high-strength 7075 alloy with a cladding layer of 1100 aluminum, which is aimed at improving corrosion resistance while maintaining mechanical properties. A special feature of the proposed technology is the use of an additional front pure aluminum workpiece for the process of direct extrusion of a rod from 7075 alloy. The direct extrusion process for a composite workpiece was simulated with the DEFORM software package's finite element method. The influence of process temperature and speed on the formation of the cladding layer was analyzed. For this purpose, four problems were formulated with varying heating modes of workpieces and tools. It was found that it is possible to produce a thin cladding layer at a heating temperature of the base 7075 alloy equal to 360 °C and a cladding layer temperature equal to 20 °C, which ensures a uniform distribution of the coating along the length of the rod without signs of delamination. Stress-strain analysis during extrusion showed that a cold additional workpiece ensures continuity for cladding coating formation. However, heating above 300 °C leads to rupture from deformation localization. The developed approach can be used to reduce the cost of products by reducing the consumption of expensive 7075 alloy while simultaneously increasing corrosion resistance due to the use of pure aluminum cladding. Prospects for the development of further research are associated with the optimization of extrusion modes for various rod sizes.

Keywords: extrusion; finite element method; composite materials; 7075 aluminum alloy; cladding layer.

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INTRODUCTION

Modern requirements for increasing fuel efficiency, reducing the weight of structures and minimizing harmful carbon dioxide emissions justify the search for and development of promising lightweight materials and technologies for their processing. In this aspect, aluminum and aluminum alloys are of interest as promising structural materials, which is caused by the optimal combination of their physical and mechanical characteristics [1; 2]. However, to develop new types of products operating, for example, in extreme conditions, it is necessary to predict accurately their behavior at various stages of production (in particular, during metal forming).

The relevance of predicting properties at the stage of design of product manufacturing technologies is also caused by the continuing growth in metal prices. According to sources from the Fastmarkets database, the indicators of which are used in contracts, exchange trading and financial calculations, the cost of a cast ingot of 5000 and 6000 series alloys varies in the range of $ 2.5–4 per kg. For 7000 series alloys, the price is significantly higher, since these alloys belong to the class of high-strength and hard-to-deform. The 7075 alloy has high strength characteristics. Nevertheless, the aerospace industry's adoption of this metal is limited by poor corrosion resistance and fatigue life.

Manufacturers are interested in reducing costs, especially in the areas of production of goods from expensive metals, where even small savings per ton of material provide significant financial benefits. Primary aluminum with a minimum content of impurities is traditionally used as raw material to produce 6061, 6065 and 7075 alloys. In the current reality, there is a problem with the supply of this type of raw material due to the geopolitical situation in the world. This specifically concerns the introduction of new increased customs duty rates on goods. Manufacturers of metal products express concerns, since they will now have to pay a significantly higher amount for high-purity material. Custom tariffs are ultimately included in the cost of metal. This has a negative impact on all types of production whether the enterprise is a manufacturer of machining tools or sheet metal. For the case considered in this paper, the cost of the product includes both the manufacture of cast metal and the further production of extruded semi-finished product, which has a significant impact on the final cost of the product. Moreover, the dynamics of prices for aluminum products continues to grow. According to data for 2024, prices for 7075 alloy consistently exceed $ 20 per kg[1], which is dictated, among other things, by high demand in the aerospace sector. One solution aimed at improving productivity while maintaining product quality may be the use of composite workpieces, where functionally loaded areas contain expensive metals and the remaining parts are made of cheaper aluminum alloys or pure aluminum.

Although experimental methods remain the main research tool, numerical simulation provides significant advantages, including time and cost savings, as well as deeper analysis compared to experimental approaches [3]. This makes it important to study the properties of expensive alloys such as 7000 series alloys.

Recent studies of the corrosion behavior of 7075 aluminum alloy have revealed susceptibility to various aggressive environments: in NaCl solutions, intense intercrystalline corrosion is observed with the formation of surface roughness and grain embrittlement to a depth of 150 µm [4]. The corrosion rate is minimal at neutral pH due to the formation of a protective oxide layer, while acidic and alkaline environments accelerate the process [5]. Biological factors also have a significant impact. For example, the Aspergillus niger fungus increases the rate of uniform and localized corrosion by 3.7 and 22.4 times, respectively, compared to abiotic conditions [6]. The sulfate-reducing bacteria in seawater accelerate corrosion, completely destroying the protective film after 14 days [7]. These data demonstrate the complex interaction of environmental factors affecting the corrosion behavior of 7075 alloy and emphasize the need to develop specialized protection methods for different operating conditions.

The 7000 series alloys have high strength. This high strength makes them difficult to deform during metal forming [8]. Therefore, the traditional extrusion method is usually limited to a speed of 1–2 m/min due to the risk of surface defects [9]. In foreign practice, the development of new extrusion methods is very popular. For example, scientists from the Pacific Northwest National Laboratory (PNNL, USA) created the Shear Assisted Processing and Extrusion (ShAPE) technology, which allows achieving an extrusion speed of 12.2 m/min for 7075 alloy without the formation of surface ruptures, providing high mechanical properties after T6 heat treatment [10].

The 7075 alloy has a high sensitivity to various types of corrosion. Therefore, developing composite modifications for this material is highly relevant. For example, technologies for producing composites from aluminum alloys using rolling are known. This method is a more cost-effective alternative to applying protective coatings using chemical or galvanic methods. In [11; 12], a mathematical model of grain evolution and dislocation density during cold asymmetric rolling of pure aluminum (Al 99.5 %) and 7075 alloy under severe plastic deformation conditions was developed.

Research has shown that reinforcing 7075 alloy with ceramic particles such as SiC and Al_2O_3 significantly increases corrosion resistance in various environments [13]. The stir casting method has proven effectiveness for the production of metal matrix composites based on 7075 alloy with ceramic nanoparticles, providing a significant improvement in mechanical properties [14], which is especially important in view of the growing demand for lightweight materials in the aerospace industry.

In manufacturing practice, it is common to apply cladding with pure aluminum to reduce the likelihood of cracking and increase corrosion resistance. Several methods exist for applying cladding to aluminum alloys including combined hot rolling for sheet products; friction stir welding, particularly for aerospace alloys [15]; the rolling of aluminum powder onto a substrate [16]; and a technique where an aluminum alloy cylinder is compressed into a pure aluminum shell followed by swaging, rolling, and cold drawing [17]. In this case, the cladding process allows producing a composite with improved characteristics. For example, clad wire demonstrates higher electrical conductivity compared to the determined values while maintaining strength properties.

The objective of this study is to develop a method for producing a composite rod based on 7075 alloy with a cladding layer of 1100 aluminum by direct extrusion to ensure increased corrosion resistance.

METHODS

The feasibility of implementing a technology to produce a rod from 7075 alloy with a pure 1100 aluminum cladding was predicted via numerical simulation using the DEFORM-2D software package based on the finite element method.

A plastic type of deformable material was used. The number of grid elements for the main workpiece is 12,000; for the additional one – 1,700 (the grid size was selected taking into account the element size in accordance with the volume of the workpieces). Fig. 1 shows a CAD model of the original geometry in 3D visualization. The original diameter of the workpiece is 750 mm. The final diameter of the rod is 360 mm. The diameter of the container is 800 mm. The taper angle of the matrix extrusion die is 75°. The dimensions and other parameters were selected from the practice of one of the enterprises.

Fig. 2 shows the hardening curves of the materials for the considered temperature ranges.

The Siebel's friction index was set to 0.5 at the workpiece-die contact and 1 for the other contact pairs[2]. The extrusion speed was 4.27 mm/s. The parameter for accounting heat exchange between the workpieces materials

[1] *Aluminium reliant industries not spared from the impact of tariffs. Fastmarkets. URL: https://www.fastmarkets.com/insights/us-aluminium-tariffs-impact-prices/.*

[2] *Loginov Yu.N. Pressovanie kak metod intensivnoy deformatsii metallov i splavov [Pressing as a Method of Intensive Deformation of Metals and Alloys]. Ekaterinburg, UrFU Publ., 2016. 156 p.*

and the tool was included when solving the problems in DEFORM.

According to the data from the DEFORM materials library, the thermal conductivity for the materials under consideration was 180 W/(m·°C). The heat capacity of the material was 2.43 MJ/(m^3·°C).

According to the MatWeb database, pure aluminum has the following thermodynamic parameters: specific heat of fusion is q_f=387 kJ/kg, specific heat capacity is c=900 J/(kg·°C), melting point is t_m=660 °C.

Each series of alloys is characterized by certain ranges of thermodynamic properties, which is caused by the inconsistency of the chemical composition even within a single grade. For example, 1000 series alloys contain over 99 % aluminum. However, trace impurities cause their phase diagrams to demonstrate both liquidus and solidus lines. This can lead to a melting point decrease compared to pure aluminum. The lowest melting point values are characteristic of 7000 series alloys, which is explained by the presence of low-melting zinc in their composition.

Table 1 shows the average values of specific heat capacity c_m and melting point t_m to simplify engineering analysis [18]. In addition, the parameter Δ (%) characterizing the deviation of the average melting point of the alloy from the melting point of aluminum of the 1000 series was determined. The greatest discrepancy (up to 13 %) is observed in 7000 series alloys. This indicator allows estimating the potential error when determining energy costs if the parameters of pure aluminum are taken as a basis, and the alloy is actually processed.

Considering the specific thermodynamic properties of aluminum alloys of different series is critical for accurate simulation of technological processes and minimizing errors in engineering analysis.

The successful implementation of a cladding technology for extruded rod requires an additional front workpiece made of pure aluminum and the correct selection of process boundary conditions. In particular, the selection of temperature conditions is difficult, since pure aluminum obviously has greater plasticity than 7075 alloy.

Several variations of temperature conditions for the process were selected (Table 2). The choice of temperature conditions for 7075 alloy was carried out in accordance with the recommendations from the manual[3], which notes that the optimal temperature range is 360–430 °C.

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RESULTS

During the simulation for temperature modes No. 1–3 (Table 2), unsuccessful results were obtained. When the product leaves the drawing cylinder of the matrix extrusion die parallel land, the cladding material is torn off from the main workpiece. For modes No. 1 and 3, a similar effect of cladding delamination is observed.

At temperature mode No. 2, the cladding material is intensively heated in the deformation zone – more than 100 °C from the initial temperature of 300 °C. The heating rate of the additional workpiece material does not allow achieving the desired result. At the same time, it is unreasonable to reduce the heating temperature of the tools, since 7075 alloy is difficult to deform and such a solution will obviously lead to a negative result.

Based on the results shown in Fig. 3 and 4, it was decided to attempt extruding without heating the additional workpiece (Table 2, option No. 4). For this temperature mode option, it was possible to obtain a rod with a thin uniform cladding layer. In this case, the material of the additional workpiece does not peel off.

As can be seen from Fig. 5, the cladding layer of pure aluminum is applied to the rod throughout the extrusion process. At the steady state stage of the extrusion process, the thickness of the cladding layer is 5 mm, which is 1.38 % of the diameter of the resulting product. The flow rate of the cladding metal is restrained by high friction forces at the container contact. This phenomenon is characteristic of the direct extrusion process and illustrated in Fig. 6.

It is evident from Fig. 7 that in the absence of heating of the additional workpiece, heat transfer occurs with moderate intensity. The flow stresses of the additional workpiece material are slightly lower (Fig. 2 b) than those of the base metal (Fig. 2 a), which prevents the separation from the main workpiece during extrusion.

Based on the distribution of the strain rate (Fig. 8), it can be concluded that the highest value of the strain rate is characteristic of the zone adjacent to the matrix extrusion die parallel land. The strain rate reaches the value of ξ=0.5 s^{-1}.

DISCUSSION

The result of the composite rod extrusion process, shown in Fig. 3, was obtained for the first three variants of the problem statement (Table 2, No. 1–3). For variant No. 2, the maximum possible extrusion temperature of 7075 alloy was selected 470 °C. This choice was caused by the existence of works that described the process of extruding rods from 7075 alloy at a heating temperature of 450 °C and higher [19]. When choosing this temperature mode, the possible chilling of the main workpiece metal during the extrusion process was considered. The heating temperature of the additional workpiece made of 1100 alloy was set to 300 °C in order to try to create conditions for more intense deformation of 7075 alloy.

As a result of the analysis, the optimal process parameters were identified: the heating temperature of the base 7075 alloy is 360 °C, the temperature of the cladding layer is 20 °C, and the heating temperature of the tools is 430 °C (Table 2, No. 4).

The difference in the heating temperatures of the workpieces creates an optimal balance of the plasticity

[3] *Loginov Yu.N. Pressovanie kak metod intensivnoy deformatsii metallov i splavov [Pressing as a Method of Intensive Deformation of Metals and Alloys]. Ekaterinburg, UrFU Publ., 2016. 156 p.*

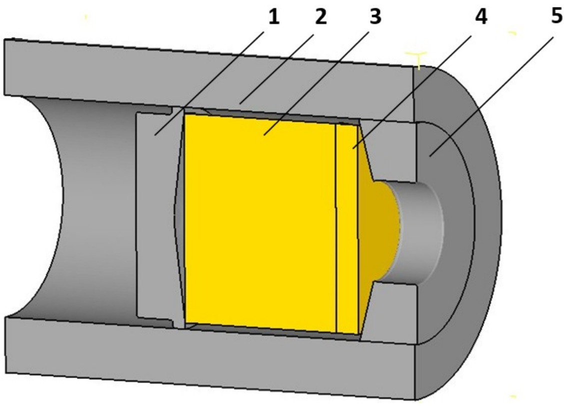
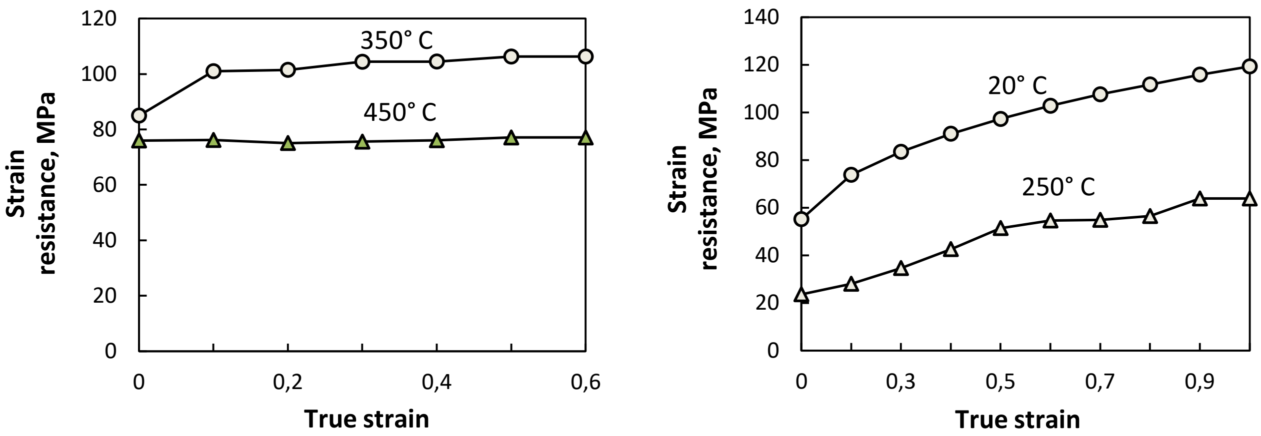


Fig. 1. *Assembly for setting the task in 3D visualization: 1 – pressing disk; 2 – container; 3 – main workpiece; 4 – additional workpiece; 5 – matrix extrusion die*
Рис. 1. *Сборка для постановки задачи в 3D-визуализации: 1 – пресс-шайба; 2 – контейнер; 3 – основная заготовка; 4 – дополнительная заготовка; 5 – матрица*



a *b*

Fig. 2. *Hardening curves for materials at a strain rate of ξ=0.1 c^{-1}:*
***a** – for 7075 alloy; **b** – for 1100 aluminum*
Рис. 2. *Кривые упрочнения для материалов при скорости деформации ξ=0,1 с$^{-1}$:*
***a** – для сплава 7075; **b** – для алюминия 1100*

Table 1. *Thermal properties of aluminum alloys by series [Reference: 18, p. 68]*
Таблица 1. *Теплотехнические свойства сплавов алюминия по сериям [Привод. по: 18, с. 68]*

Alloy series	System	c, J/(kg·deg)	c_m, J/(kg·deg)	t_m, °C	t_{mm}, °C	Δ, %
1000	Al	900–904	902	643–660	652	0
7000	Al–Zn–Mg	856–960	858	476–657	567	−13

Table 2. *Temperature modes for setting problems*
Таблица 2. *Температурные режимы для постановки задач*

No.	Heating temperature of the main workpiece (AL7075), °C	Heating temperature of the additional workpiece (AL1100), °C	Heating temperature of tools, °C
1	450	430	360
2	470	300	430
3	430	430	430
4	360	20	430

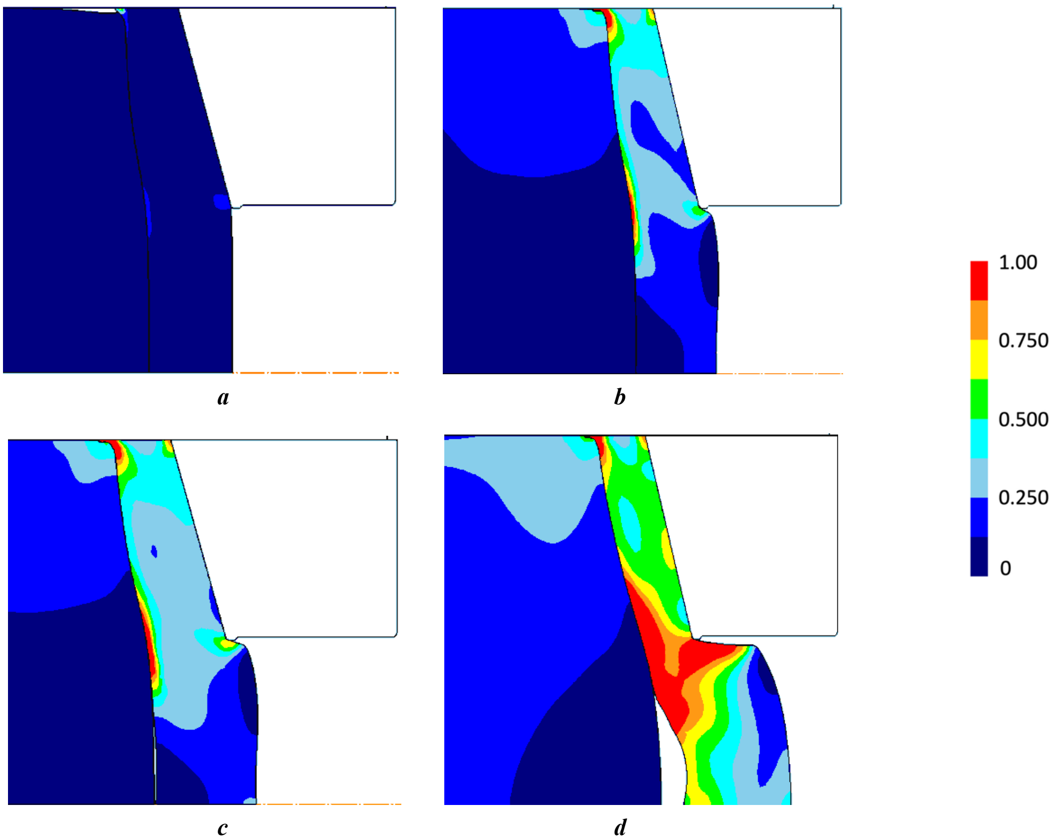


Fig. 3. *The course of the extrusion process with the display of effective strain color levels for temperature mode No. 2:* ***a*** *– the stage of pressing out;* ***b*** *– the beginning of extrusion;* ***c*** *– the beginning of cladding peeling off;* ***d*** *– the development of the process of cladding peeling off*
Рис. 3. *Ход процесса прессования с отображением цветовых уровней эффективной деформации для температурного режима № 2:* ***a*** *– стадия распрессовки;* ***b*** *– начало прессования;* ***c*** *– начало отслоения плакировки;* ***d*** *– развитие хода отслоения плакировки*

of the components, which is a critically important factor. Heating the tool to 430 °C maintains the plasticity of the 7075 alloy. However, if the 1100 alloy heats up, it sticks to the tool. Therefore, a suitable result is only achieved by combining a cold 1100 alloy with a hot 7075 alloy.

An additional advantage of the proposed technology may be the possibility of using process waste in the form of scraps as a front workpiece, which increases the resource efficiency of production. A promising direction for further research is the optimization of the technology for rods of different diameters. This material’s combination of high strength and corrosion resistance meets a critical requirement for structural materials in the aerospace industry.

To verify the obtained results, other works related to this topic were considered. In [20], a scheme for extrusion a rod

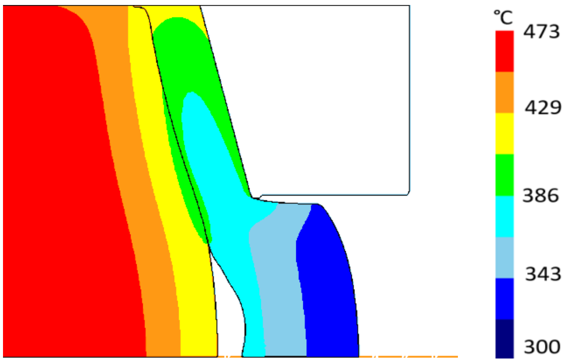


Fig. 4. Temperature field at the stage of additional workpiece peeling off for the extrusion option No. 2, °C
Рис. 4. Температурное поле на этапе отслоения дополнительной заготовки для варианта прессования № 2, °C

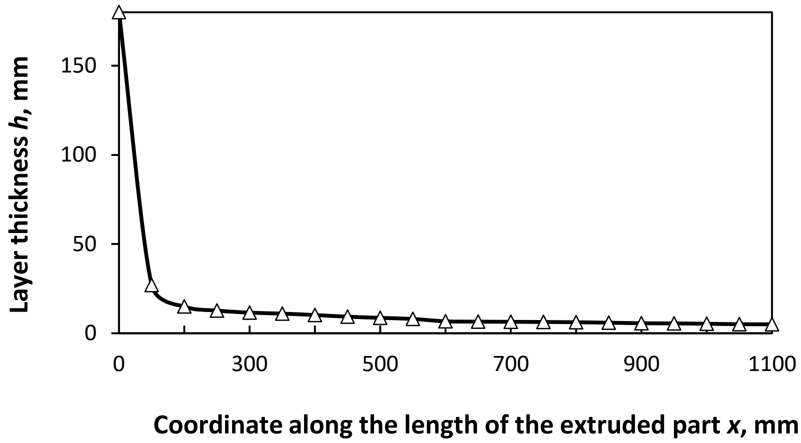


Fig. 5. Graph of the dependence of the cladding layer thickness h on the coordinate along the length of the extruded part of the product x
Рис. 5. График зависимости толщины плакирующего слоя h от координаты по длине отпрессованной части изделия x

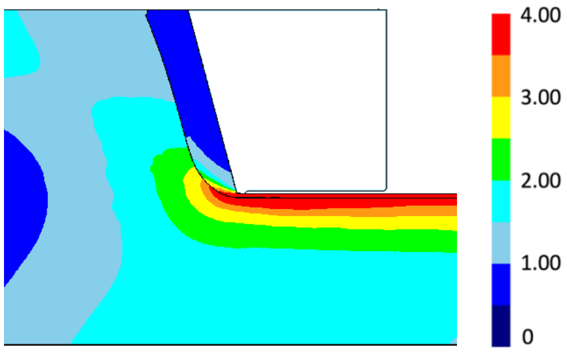


Fig. 6. The effective strain color levels for the temperature mode No. 4
Рис. 6. Цветовые уровни эффективной деформации для температурного режима № 4

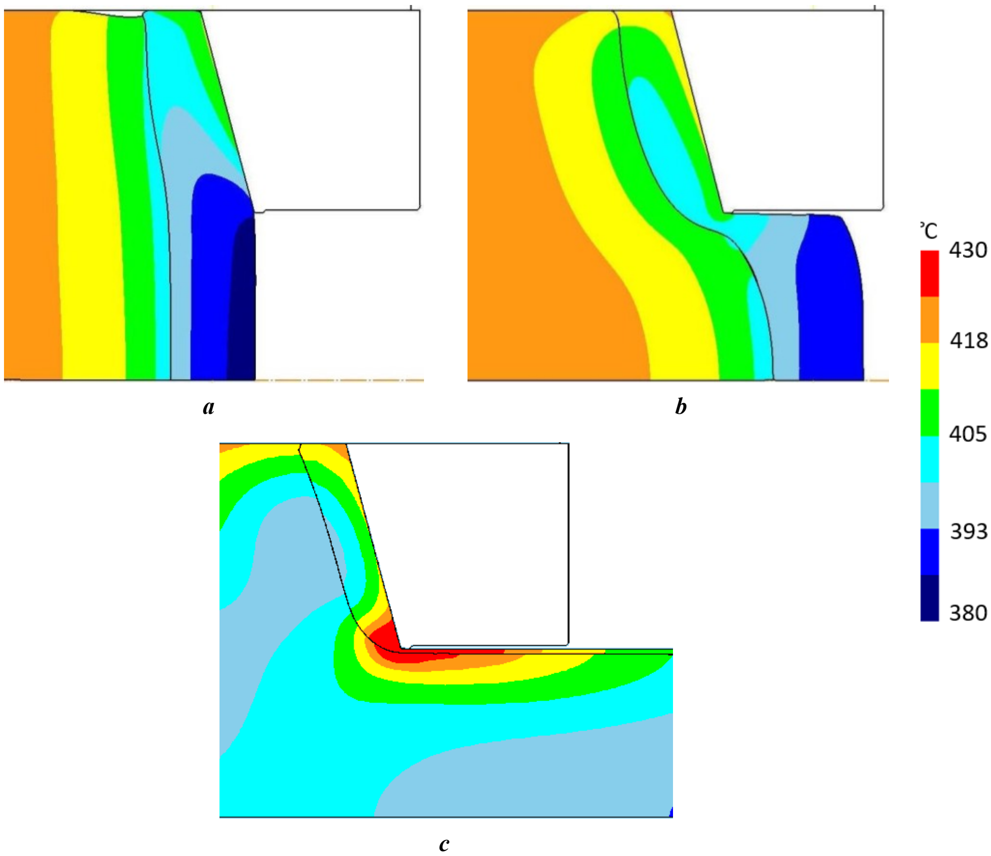


Fig. 7. Temperature field during the extrusion process, °C:
a – pressing out stage; *b* – beginning of extrusion; *c* – steady state stage
Рис. 7. Температурное поле по ходу процесса прессования, °C:
a – стадия распрессовки; *b* – начало прессования; *c* – стационарная стадия

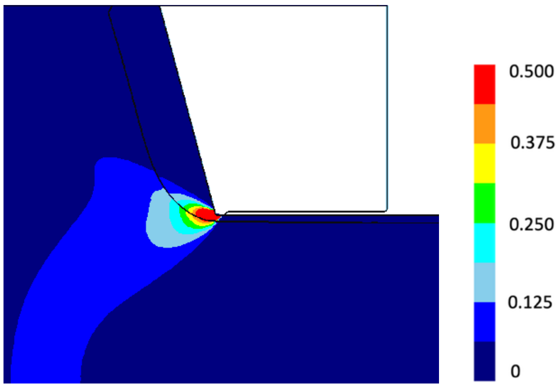


Fig. 8. Color levels of effective strain rate for the temperature mode No. 4, ξ, c^{-1}
Рис. 8. Цветовые уровни эффективной скорости деформации для температурного режима № 4, ξ, c^{-1}

made of a 6000 series aluminum alloy using an additional rear workpiece made of a less expensive alloy in order to reduce the loss of the base metal was considered. Three temperature modes for implementing the extrusion process were studied. It was found that the optimal mode is the one without heating the pressing disk and the additional workpiece. This confirms the result obtained in the course of the current study, where it was found that it is possible to implement the technology of extruding a composite rod without heating the additional workpiece.

The implementation of the analogous composite rod production technology in [21] utilized a hot extrusion process wherein both workpieces were heated to a temperature of 380 °C. The technology proposed in this work implies the possibility of using process waste in

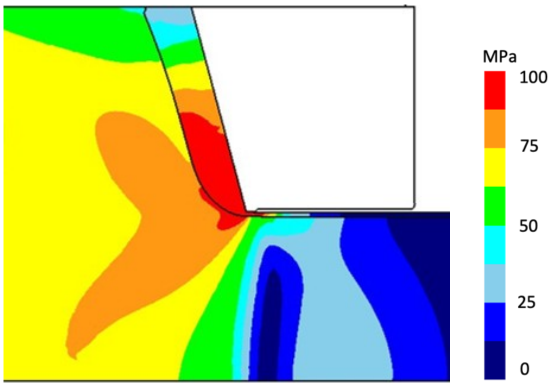


Fig. 9. *Color levels of effective stresses for the temperature mode No. 4, $\sigma_{effective}$, MPa*
Рис. 9. *Цветовые уровни эффективных напряжений для температурного режима № 4, $\sigma_{effective}$, МПа*

the form of extrusion discard as an additional front workpiece, which is intended to reduce losses of the base metal.

The feasibility of the technology was assessed through numerical simulation of the direct and inverted extrusion processes for a large-sized rod. The model incorporated a softer aluminum alloy as an additional workpiece. Using the tracing point function, a comparative study of the flow rates of the materials of the main and additional workpieces during plastic deformation was performed. For both extrusion options, graphical dependencies of the cladding layer thickness on the length of the rod extruded part were constructed. It was found that the direct extrusion method is preferable for solving the problem of producing a bimetallic rod. Experimental modeling of the extrusion process on model materials was carried out. As a result, a bimetallic rod with a thin cladding layer was produced.

At the same time, a defect of local delamination of the additional workpiece material after exiting the matrix extrusion die parallel land was detected. In the study conducted within this work, the effect of peeling of the cladding layer material is not observed.

The study's key task was to develop resource-saving recommendations for setting experimental conditions. This was essential because running the experiment on the targeted industrial equipment would have been prohibitively expensive.

The verification of the obtained data is substantiated in the literature. For example, the reference manual[4] presents hardening curves for pure aluminum for various types of tests. The values of effective stresses vary in the range of 50–100 MPa depending on the state of the material for which the curves are given. In the course of solving the problem in DEFORM, the distribution of effective stresses shown in Fig. 9 was obtained.

As can be seen from the figure, no abnormal growth of stresses in the deformation zone is observed, therefore, it can be concluded that the extrapolation of stress values for the materials under consideration (Fig. 2) in the course of solving the problem occurs correctly.

[4] *Burkin S.P., Babaylov N.A., Ovsyannikov B.V. Soprotivlenie deformatsii splavov Al i Mg [Resistance of deformation of Al and Mg alloys]. Ekaterinburg, UrFU Publ, 2010. 344 p.*

CONCLUSIONS

The study allowed predicting the possibility of implementing the developed technology for producing bimetallic rods from high-strength 7075 alloy with a cladding layer of 1100 aluminum by direct extrusion using an additional front workpiece. The optimal extrusion temperature mode was identified, which makes it possible to produce a rod with a thin uniform cladding layer, amounting to 1.38 % of the diameter of the final rod. For this mode, the heating temperature of 7075 alloy is 360 °C, and the temperature of pure aluminum is 20 °C.

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Схема получения композиционного материала на основе конструкционного алюминиевого сплава методом прямого прессования

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Аннотация: Исследование посвящено разработке технологии получения биметаллического прутка из высокопрочного сплава 7075 с плакирующим слоем из алюминия 1100, которая направлена на улучшение коррозионной стойкости при сохранении механических свойств. Особенностью предложенной технологии является применение дополнительной передней заготовки из чистого алюминия для процесса прямого прессования прутка из сплава

7075. Проведено численное моделирование процесса прямого прессования композитной заготовки в программном комплексе DEFORM с использованием метода конечных элементов. Проведен анализ влияния температурно-скоростных условий процесса на формирование плакирующего слоя. Для этого была выполнена постановка четырех задач с варьированием режимов нагрева заготовок и инструментов. Установлено, что получить тонкий плакирующий слой удается при температуре нагрева основного сплава 7075, равной 360 °C, и температуре плакирующего слоя, равной 20 °C, что обеспечивает равномерное распределение покрытия по длине прутка без признаков расслоения. Анализ напряженно-деформированного состояния материалов в ходе прессования показал, что вариант использования дополнительной заготовки в холодном состоянии позволяет сохранять достаточную сплошность для формирования непрерывного плакирующего покрытия, в то время как нагрев до 300 °C и выше приводит к его разрыву из-за локализации деформации. Разработанный подход может быть использован для снижения себестоимости изделий за счет уменьшения расхода дорогостоящего сплава 7075 при одновременном повышении коррозионной стойкости за счет применения плакировки из чистого алюминия. Перспективы развития дальнейших исследований связаны с оптимизацией режимов прессования для различных типоразмеров прутков.

Ключевые слова: прессование; метод конечных элементов; композиционные материалы; алюминиевый сплав 7075; плакирующий слой.

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