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Plastometric Simulation of the Hot Rolling Process of Al/B_4C Powder Composite

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Abstract

The actual problem of nuclear machine building is mastering the manufacture of Al/B_4C powder composite cladded with layers of aluminum alloy in a rigid technological casing by a high-production method of rolling. Simulation tests of cylindrical samples were carried out using a uniaxial compression method on a cam plastometer with an evaluation of the influence of the strain on the density of the Al/B_4C powder compact with the aim of optimizing the rolling technology. The strain rate and strain correspond to the ones for the rolling process, and the compression process of samples was divided into three stages. The temperature of deformation and strain of the powder compound of aluminum and dispersed particles of boron carbide Al/B_4C were varied according to the experiment plan. The final density of the powder compound after each compression stage was accepted as an experimental variable as well as its cutting ability according to which the manufacturability of the obtained composite was evaluated. According to the simulation experiment results, the conditions of hot compaction of the Al/B_4C powder composite were evaluated and recommendations for temperature–deformation regimes were formulated.

Keywords: powder composite, plastometric tests, compression, hot rolling, Al/B_4C composite, densification, boron carbide

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1. Introduction

One of the actual problems of the nuclear machine building is the development of efficient technologies of the manufacturing composite materials with the neutron protection function as well as an increase in their operational characteristics and reliability. The most promising material in this field is an aluminum matrix composite with outer layers made from aluminum alloys and with an inner layer from compacted powder compound of aluminum and dispersed particles of boron carbide Al/B_4C, which is used for manufacturing transport and storage containers for transportation and storing spent nuclear fuel [1, 2]. Currently, when producing functional boron-aluminum composites, improved methods of casting and powder metallurgy mainly are used [3]: the technology of cryogenic grinding powders and their subsequent laser sintering [4], the method of infiltration of aluminum melt through the porous framework from boron carbide powder [5], the method of mechanochemical synthesis (mechanical alloying) with dynamic compaction on magnetic-pulse presses and subsequent deformation processing [6], the method of synthesis of boron carbide nanoparticles in the material melt directly «in-situ» [7] and others.

These methods are characterized by increased complexity, the need for highly engineered and specialized equipment and also low suitability for large-scale manufacturing and wide distribution of modern transport and storage containers from promising functional materials of new generation. This is explained by the fact that the geometrical dimensions of produced boron–aluminum composite blanks by known methods [3–7] are limited.

To obtain a processable material in the form of strips or sheets suitable for the production of transport and storage containers, boron-aluminum composite blanks made by casting and powder metallurgy methods require further deformation processing – by rolling or extrusion methods. However, this is difficult for materials with a high percentage of solid filler.

Thus, more preferable methods for producing functional composites based on aluminum and boron carbide Al/B_4C are technologies being developed based on hot rolling [8–10], which combine the processes of molding, consolidation, and sintering a powder compound of aluminum with boron–containing components. Profitability and productivity of such technology is significantly higher, which will allow organizing large-scale manufacturing sheet composite material. A number of papers [11–13] are devoted to the problems of formation of the structure and properties of the boron-aluminum composite under hot deformation.

However, issues related to the simulation of hot deformation of powder composites [14–16], as well as optimization of the technological regimes of their rolling remain poorly explored, therefore the problem of developing the technology of hot rolling Al/B_4C boron aluminum composite material is relevant. Relating to this, the goal of the present research work was to investigate the influence of the strain and temperature of deformation on the density of the Al/B_4C powder compact, as well as to evaluate the influence of these factors on the manufacturability of the obtained boron–aluminum composite.

2. Equipment and Research Method

The high-production technology of hot rolling aluminum powders and dispersed particles of boron carbide Al/B_4C in a closed technological casing developed in Institute of Engineering Science, Ural Branch of the Russian Academy of Sciences (IES RAS, UB) as the most promising method [10, 12] was chosen as the object of research. To evaluate the influence of the strain and temperature of deformation on the density of compact from a powder compound of aluminum and dispersed particles of boron carbide Al/B_4C, the test method of uniaxial compression on IES RAS (UB)'s automated plastometric complex [17] was used. To realize the stress-strain state, in a first approximation identical to the corresponding rolling method, samples with an Al/B_4C powder compound in a steel tubular container were proposed. The initial h_0 and final h_1 sample heights corresponded to the initial and final heights of rolled product of the implemented technology [12]. The diameter and wall thickness of the steel casing of the samples were selected taking into account the identical influence on the force parameters of the compression process and the deformation conditions of the powder compound. For the experiments, steel tubes with a diameter d_0 of 16 mm and a wall thickness of 1 mm were used, from which samples of height h_0 equal to 25 mm were cut. A prepared compound of B_4C (25% wt.) and PA-4 (75% wt.) powders with intermediate tamping was placed in the steel casing cavity to achieve a density of filled compound equal to 1.6-1.62 g/cm^3. The chemical composition of PA-4 included: 98.0% – Al; with impurities no more than: 0.35% – Fe, 0.4% – Si, 0.02% – Cu. Heating of the samples with the powder compound placed in them before deformation was carried out in an electric furnace up to a temperature of 500 and 620 °C respectively with a holding time at the setpoint temperatures of 50 minutes. The preparation conditions of the powder compound, the density of its laying into the casing and the heating regimes were completely identical to the corresponding parameters of the hot rolling process.

Simulation tests were carried out at the strain rate ξ close to the one at the deformation zone during rolling and equal to 0.57 s^{-1} approximately. During the compression process, the strain rate ξ was constant, which was ensured by the technical feature of the used testing machine – the cam plastometer.

In order to prevent possible cooling of the samples during the process of taking them out from the furnace and compression, samples were heated in the steel containers. To reduce heat transfer, the space between the wall of the container and the sample was filled with kaolin wool. In accordance with the experiment plan, the samples were compressed in three stages with the strain for each upsetting $\epsilon = \frac{h_0 - h_1}{h_0} \cdot 100\% = 30\%$, where h_0 and h_1 are the initial and final height of the sample respectively.

After compression and cooling of the samples to room temperature, the steel shell was opened to extract the obtained compact. The obtained compacts of the powder compound were machined to evaluate the manufacturability of the obtained boron-aluminum composite and determine its density.

3. Results of Investigation and Its Discussion

The actual strain and compression forces for three samples after one, two, and three upsetting stage are presented in Tables 1. From the table it can be seen that the compression force in each subsequent stage is approximately doubled.

Table 1: The results of simulation tests by compression of samples with a compound of powders at temperatures equal to 500 °C and 620 °C.

No. of sample	Weight of backfilling, g	Initial density of the compound of powders, g/cm^3	Strain ε, %			Compression force, kg			Average pressure per unit of area, kg/ mm^2	Final density, g/cm^3
			first upsetting	second upsetting	third upsetting	first upsetting	second upsetting	third upsetting		
Tests at a temperature of 500 °C										
1	6.42	1.67	33.2	-	-	1038	-	-	3.14	-
2	6.44	1.67	30.0	33.1 (Σ=53.2)	-	1038	2096	-	5.65	2.2
3	6.42	1.67	28.4	35.1 (Σ=53.6)	32.7 (Σ=68.8)	1038	2095	5711	12.02	2.32
4	without powder					986			-	-
Tests at a temperature of 620 °C										
1	6.14	1.6	31.2	-	-	650	-	-	2.0	2.07
2	6.24	1.62	34.4	25.0 (Σ=50.8)	-	650	1480	-	4.3	2.2
3	6.14	1.6	29.0	29.2 (Σ=49.6)	34.9 (Σ=67.2)	650	1480	3140	7.4	2.32
4	without powder					615		-	-	-

The correctness of the selected geometric dimensions of the samples was determined by the contribution of the deformation force of the steel casing without powder (table 1 – sample 4) during its compression to the total average pressure per unit of area of the samples with the Al/B_4C powder compound. Comparing the forces observed at the deformation temperature of 500 °C during the first compression of the samples with the Al/B_4C powder compound (sample 1) and without powder compound (empty steel casing – sample 4), it was concluded that the Al/B_4C powder compound was compacted in the absence of plastic deformation of the powder particles during the first compression. Identical results were obtained from the tests at the temperature of 620 °C.

Applying the results to the optimization of the rolling process of powder compound, it is necessary to note the following. When the strain is less than 30 % in the first rolling pass, the required density of the powder compound for the sintering process during subsequent heating is not ensured, and if the strain is more than 30 %, the strip will not be captured by rolls at the rolling mill.

Thus, a rational strain ε was selected for the first hot rolling pass taking into account the pressure per unit of area under compression of the container with the Al/B_4C powder compound and without it.

The results of measurements of the powder compound density are also presented in table 1. After three stages of upsetting at both deformation temperatures of 500 and 620 °C, the same final density of the composites is observed – 2.32 g/cm^3. The results of technological experiments by test machining showed that the samples compressed at the temperature of 620 °C after two and three upsetting stages retain their integrity when machined on the turning lathe, which may indicate satisfactory quality of the obtained compact.

At the same time, the sample obtained at the temperature of 500 °C after two upsetting stages crumbles when machined. However, after three upsetting stages at the same temperature, the sample is machined with the chip removal, which indicates satisfactory quality of the obtained compact. It should be noted that for both temperature regimes after the first upsetting stage, the quality of the compacted powder compound is low, since the sample does not retain its shape and has the appearance of a sponge. Despite the same density obtained at identical strain, but at different temperatures of deformation, the quality of the obtained compacts is significantly higher at the deformation temperature of 620 °C.

4. Summary

The method of testing cylindrical samples on IES RAS (UB)'s plastometric complex with the aim of optimizing the process of hot rolling of a compacted powder compound of aluminum and dispersed particles of boron carbide Al/B_4C in a rigid technological casing was proposed in the paper. The influence of the strain and temperature of deformation on the density of the Al/B_4C powder compact was evaluated. It was established that at identical strains, but at different temperatures, the quality of the obtained Al/B_4C powder compacts is significantly higher at the deformation temperature of 620 °C. The results of simulation experiments made it possible to evaluate the compaction conditions of the Al/B_4C powder composite and formulate recommendations on temperature–deformation regimes.

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