Cutting properties of aluminum matrix composites

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Abstract. Promising aluminum matrix composite experimental samples were obtained for the study of cutting properties. The peculiarities of the drilling process, as the most demanded and indicative process of machining, were assessed by the axial cutting force, torque, and chip shape. Studies of composite samples of various compositions with the initial matrix alloy made it possible to establish the basic laws of material behavior, to reveal the influence of reinforcing components, and to give recommendations on the drilling of the materials. Comparative analysis and comprehensive studies showed that the reinforcement of aluminum matrix composites affects the structure. The modifying effect of the reinforcement, expressed in the refinement of the grain structure, affects the hardness of the material. The strengthening effect of various reinforcements was accompanied by not so unambiguous behavior in the evaluation of machinability. With the introduction of SiC, the cutting force was decreased, but the conditions for chip removal deteriorated. When copper was added, cutting forces and torque were reduced by 2 times about the initial matrix alloy. The torque was further reduced when drilling a specimen with Cu-Al2O3 complex reinforcement. It can be argued that according to a comprehensive assessment of the cutting ability, the material with the addition of copper and nanoparticles of aluminum oxide shows the best characteristics.

1. Introduction

The combination of plastic aluminum matrices and high-modulus, high-strength reinforcements make aluminum matrix composites (AMCs) have a series of excellent performances, and hence AMCs are used in aerospace, automobile manufacturing, military equipment, optical component, precision instrument, and electronics [1-6].

Despite aluminum matrix composites have some obvious advantages over traditional materials, their application is also limited. The machining complexity is an important limiting factor. Mechanical processing of billet made from aluminum matrix composites using the existing equipment and available tools causes some difficulties, expressed in the rapid and significant wear of the cutting tool and large deviations in the accuracy and roughness of the processed surface [7-12].

Although AMCs components are designed to net-near shape, some subsequent mechanical processing is still necessary for giving AMCs the required size and shape with proper surface integrity. The machining of AKM differs from the machining of aluminum or aluminum alloys. For example, when drilling dispersion-strengthened aluminum matrix composites, the challenges arise not only of increased tool wear, but also significant drilling forces and the problem of ensuring the holes surface quality [13–18].

It can be used cutting tools made from different materials: high speed steel (HSS) [9, 11], uncoated and coated tungsten carbide (WC) [19], ceramics [20, 21], polycrystalline cubic boron nitride (PCBN) [22], polycrystalline diamond (PCD) [13, 22-24], single-crystal diamonds (SCD) [25], chemical vapor deposition (CVD) diamond [26-28]. Analysis of the work on the machinability of metal-matrix composite materials made it possible to choose an effective machining tool for the presented research object.
2. Experimental procedure

2.1. Materials

In the current research, promising metal matrix composites were chosen as the research object (Table 1).

| Specimens | Composition of the samples (wt.%) |
|-----------|----------------------------------|
| 1         | 1050                             |
| 2         | 1050 1%SiC (17µm)                |
| 3         | 1050 1%Cu (20µm)                 |
| 4         | 1050 1%Cu (20µm)+1%Al₂O₃ nanofibers |

2.2. Fabrication of composites

Experimental samples were fabricated by stir casting method in an argon atmosphere (figure 1) [33]. Pure argon was used as the carrier gas for injection of the reinforcements. After completion of the injection, the suspension was stirred, held, and cast into a metal mold. The fabricated billets (figure 2) were processed on a lathe 16K20 (n=2000 rpm/min, S₀=0.4 mm/rpm).

Figure 1. Schematic of the experimental set-up used in production of the composites [33]
2.3. Composite characterizations

Research samples were cut from the obtained billets. To study the microstructure, samples were prepared by grinding and polishing. Subsequent etching with Keller's reagent made it possible to reveal the grain structure. The microstructure of the composites and matrix alloy was characterized by optical microscope (Olympus GX51). The microhardness of the samples was measured on a DURASCAN 70 automatic microhardness tester with a load of 100 g.

2.4. Drilling experimental equipment setup and procedure

In this research, according to GOST 19265-73 high-speed steel R6M5 (table 2) drills with 3 mm in diameter (figure 3) were chosen to study the machinability. A dynamometric comparison method was used and the machinability was determined by the axial force and cutting torque measured when drilling on a vertical drilling machine. The process conditions for drilling composites are as follows: rotational speed $n = 1400$ rpm, feed $S_0 = 0.28$, 0.14 and 0.1 mm/rpm, hole of 3 mm in diameter $d$ and 15 mm in depth $h$, 10 holes on each billet. The dynamic parameters were measured with a Kistler dynamometer, built into the control and diagnostic complex, effectively functioning at the Department of Instrumental Engineering and Technology of the Bauman Moscow State Technical University [31-32]. In addition, a comparative analysis of machinability was carried out by comparing the chip shape obtained by drilling the experimental samples.

| Table 2. Chemical composition of high-speed steel R6M5 (wt.%) |
|-----------------|---|---|---|---|---|---|---|---|---|---|---|
| Composition     | Fe | W  | Mo | Cr | V  | C  | Si | Mn | Ni | Co | P  | S  |
| wt.%            | 80 | 5.5-6.5 | 4.8-5.3 | 3.8-4.4 | 1.7-2.1 | 0.82-0.9 | <0.5 | <0.5 | <0.4 | <0.5 | <0.03 | <0.025 |

3. Results and discussion

3.1. Microstructure analysis

Microstructural analysis of matrix samples AD0 and composites AD0 + 1% SiC, AD0 + 1% Cu, AD0 +
1% Cu + 1% Al2O3 showed that after the introduction of filler SiC or Cu, the grain structure is refined (figure 4). When Cu + Al2O3 nanofibers were added, the greatest refinement was shown: the grain size decreased by 25%. It is known that finer grain structure increases machinability.

![Figure 4. Microstructure of experimental samples:](image)

(a) AD0; (b) AD0+1% SiC; (c) AD0+1% Cu; (d) AD0+1% Cu+1% Al2O3 (200x)

3.2. Microhardness

In comparison with the microhardness of the matrix material AD0, the microhardness of the AD0 + 1% SiC sample increased by 8%, and AD0 + 1% Cu + 1% Al2O3 - by 18% (figure 5).

![Figure 5. Microhardness of experimental samples](image)

3.3. Axial force and cutting torque

The typical axial force and cutting torque are shown in figure 6.
It was found that, in comparison with the matrix material, samples with silicon carbide SiC wear out the tool more intensively, so after drilling the fifth hole, the drill was not suitable for work.

The measuring results of the dynamic parameters in the drilling process of the sample are shown in table 3. The averaged axial forces and torques are shown in figure 7.

| Numble of holes | AD0   | AD0+Cu | AD0+SiC | AD0+Cu+Al2O3 |
|-----------------|-------|--------|---------|--------------|
|                 | $T$, H | $F$, N | $T$, H  | $F$, N       |
| 1               | 0.77  | 350.1  | 0.42    | 184.4        |
| 2               | 0.94  | 407.9  | 0.39    | 179.2        |
| 3               | 0.76  | 367.5  | 0.42    | 179.4        |
| 4               | 0.65  | 319.9  | 0.46    | 189.2        |
| 5               | 0.77  | 370.1  | 0.37    | 178.1        |
| 6               | --    | --     | 0.48    | 183.7        |
| 7               | --    | --     | 0.42    | 178.1        |
| 8               | --    | --     | --      | --           |
| 9               | --    | --     | --      | --           |
| 10              | --    | --     | --      | --           |

The analysis of the results showed that the highest axial cutting force and torque occur when machining the matrix alloy. With the addition of copper and silicon carbide, the cutting forces are
significantly reduced. It is convenient to imagine the decrease in axial force and cutting moment fractions of the force and moment when cutting commercially pure aluminum (table 4). It can be seen that the greatest decrease in torque (by 60%) is observed with the addition of 1% Cu + 1% Al$_2$O$_3$, and the axial force (50%) - with the addition of 1% Cu and 1% Cu + 1% Al$_2$O$_3$.

Table 4. The ratio of the axial cutting force and torque when drilling samples AD0 with different fillers to the force and torque when drilling AD0

|       | AD0+1%SiC | AD0+1%Cu | AD0+1%Cu+1%Al$_2$O$_3$ |
|-------|-----------|----------|------------------------|
| $F$   | 0.78      | 0.50     | 0.50                   |
| $T$   | 0.65      | 0.54     | 0.40                   |

During the processing of technically pure aluminum (AD0) chips adhere to the front surface of the drill due to their high plasticity (figure 8a). When alloyed with copper powders, chips stick to the front surface of the drill much less, which contributes to its quick removal from the tool. When drilling samples from AD0 + 1% SiC, drill breakages occurred, apparently due to chip stacking in the drill flute, or the drill hitting highly hard SiC particles (figure 8b). When drilling samples from AD0 + 1% Cu + 1% nano Al$_2$O$_3$, the chips are long, not crushed, they were not driven into the chuck (figure 8c).

Figure 8. Chip shape when drilling: a. AD0; b. AD0 + 1% SiC; c. AD0 + 1% Cu + 1% Al$_2$O$_3$.

4. Conclusions
Thus, comparative analysis and comprehensive studies of machinability by drilling of aluminum matrix composites demonstrated that introducing a small amount of reinforcement into aluminum significantly affects the machinability. The modifying effect of the reinforcement, expressed in the refinement of the grain structure, affects the change in the hardness of the material. The strengthening effect of various reinforcements is accompanied by different behavior in the evaluation of machinability. With the introduction of silicon carbide, although there is a decrease in the axial force and cutting torque compare to the initial matrix alloy, the chips adhesion to the drill front surface and its stacking in the drill groove significantly reduce the machinability. When copper is introduced into the aluminum matrix, a significant (up to 50%) decrease in axial force and torque occurs, but the greatest decrease in torque (60%) is observed when 1% Cu + 1% Al$_2$O$_3$ is added. The best machinability indicators, expressed by the smallest cutting force and drilling torque, were shown by a specimen with a complex reinforcement Cu-Al$_2$O$_3$. 
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