Journal of Engineering and Applied Sciences 11 (Special Issue 2): 3019-3023, 2016
ISSN: 1816-949X

Quality Assurance Issues of Hard-Processing Aluminum Alloy Parts Fabrication for Aircraft Construction and Engine-Building

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Abstract: The results of cutting tools material selection research, cutting tools geometric parameters and cutting conditions of half-finished materials made of dispersion-strengthened Composite Alloys (CAC) are presented. The influence of change in process parameters on the quality of parts being manufactured and recommendations for choosing the above-mentioned are given.

Key words: Aluminum alloys, superhard synthetic materials, workmanship, synthetic diamond cutters, cubic boron nitride cutters

INTRODUCTION

Modern aircraft construction is not possible without application of new materials; metal composites, structural ceramics, carbon-based composite materials of heat-resistant steels, titanium alloys, intermetallic alloys and powdered aluminum alloys. This is just a brief list of materials which design in the 21st century stimulated the development of rocket and aerospace engineering operating in extreme conditions. Constructing of modern aviation equipment is a complicated integrated process based on the latest achievements in the field of aerodynamics, thermodynamics, materials science, mechanical-engineering technology, strength theory, electronic engineering and computer science.

Huge research intensity of aircraft engine building is proven by the fact that only the US, England, France and Russia possessed a full designing cycle of competitive engines of different application prior to the beginning of the 21st century (Kablov, 2001). Heavier steel parts are replaced with the parts made of dispersion-strengthened Composite Alloys (CAC) (Vasilyev, 2013) during production of instruments and components case-shaped parts in the aircraft industry including engine building.

MATERIALS AND METHODS

Main text: CAC are fabricated from powders produced by spraying the alloy materials with predetermined compositions. CAC have a low linear expansion coefficient close to steel linear expansion coefficient and high modulus of elasticity. CAC alloys contain 25-30% of Si, 5-7% of Ni and aluminum is the rest of the above mentioned alloys. Linear expansion coefficient $\alpha = 14.5\ 10^{-6}$ 1/°C close to steel $\alpha = (11\div12)\ 10^{-6}$ 1/°C and far less than that of a pure aluminum ($\alpha = 10^{-6}$ 1/°C). CAC have a high strength and hardness ($\sigma_B \approx 260$ MPa and 1200 HB) and low plasticity (Komarov and Pleshakov, 2014; Kurganov *et al*., 2008).

The advantage of CAC is their fine-grained structure with a uniform-phase distribution and the absence of casting defects (sweating of ore, slag inclusions, etc.) (Pashentsev and Zhuravlev, 2007; Minaev, 2013). Analysis of drawings of special aluminum alloy (CAC-400) components manufactured at aviation industry enterprises showed that the surface roughness based on Ra parameter of the order of 0.2-0.4 μm and processing accuracy of diametrical sizes of the order of the 5, 6th accuracy degree where dimensional tolerances are of 8-15 μm, must be obtained during treatment of these parts.

The problems of special aluminum alloys parts fabrication are due to the fact that these alloys can not be processed via grinding operation. Therefore, it is recommended that a fine turning operation (Lyubomudrov, 1994) should be used for final operations. The preliminary experimental evaluation of determining the processing error value during fine turning operation showed that the processing error dominant components when turning the lot of parts were as follows: cutter dimensional wear, manufacturing system elastic

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deformations, thermal deformations of a cutter and a part. In order to determine the influence of these components on the accuracy of manufacturing the parts made of CAC, geometrical parameters and tool cutting part material should be chosen 1st. The requirements to geometric parameters and tool cutting part material are as follows:

- Tool material while processing CAC-400 should not undergo extreme heat, otherwise thermal deformations of the tool will not make it possible to ensure the required processing accuracy
- Good-quality finishing the cutting tool edge is needed for the reason that the cutting edge roughness greatly affects roughness of the surface to be obtained
- Providing the chemical inertness requirement to the material being treated, otherwise chemical reaction in the cutting area or the process of adhesive bonding the cutter with a workpiece material is possible
- Tool wear resistance is an important requirement for the reason that the intensive wear may greatly affect the accuracy of workpieces to be processed and production process stability

According to preliminary experiments conducted on the turning lathes of 16B16KA and FT-11 Models, the wear while processing CAC-400 with hard alloy T15K6 was about 40 μm per 10 km of the path which is unacceptable in terms of accuracy requirements. It is enough to apply a tool with the plates made of hard alloy T15K6 for rough machining the alloy CAC-400.

Application of a cutting tool equipped with the inserts made of superhard synthetic material (cubic boron nitride, synthetic diamond) (Vasin *et al*., 2001; Vereshchaka, 1993; Zubarev, 1988) produces the most acceptable results during fine turning the aluminum alloys and alloys produced via powder metallurgy processes. A series of experiments for lathe turning the workpieces made of CAC-400 alloy were conducted in order to select a tool material. Cubic boron nitride and synthetic diamond sharpened and finished in accordance with the presented recommendations (Zubarev, 1988) are used as an experimental material. The removable inserts made of cubic boron nitride and diamond are attached in a special holder with an adequate strength and rigidity providing. During the experiments, the workpieces made of CAC-400 alloy were turned at a cutting depth of 0.1 mm, feed of 0.01 mm/rev and the surface roughness per each part at 10 points as well as the cutter wear were measured after each part processing, plus the cutting tool relative wear was determined afterwards. The data of the experiments is presented in Table 1. It is apparent from the experimental results that the surface roughness of the treated surface relatively slightly depends on the processing speed which makes it possible to work in a large range of speeds.

Table 1: Surface roughness average value during processing of CAC-400 with cutters made of superhard synthetic materials depending on the cutting speed

Machining tool material	Rotation speed (rev. min^{-1})	Cutting speed (m min^{-1})	Surface roughness Ra (μm)
Cubic boron	250	96	0.28
	500	192	0.25
	1000	380	0.33
	2000	760	0.38
Synthetic diamond	250	96	0.26
	500	192	0.21
	1000	380	0.24
	2000	760	0.26

The time moment when the surface roughness sharply increases due to problem in the cutting edge form, should be taken for tool durability value when treating CAC-400 with cutters made of superhard synthetic materials. Tool durability based on this criterion is 50 km for diamond and 55 km of a cutting path at a cutting speed of 380 m min^{-1} for cubic boron nitride, respectively. Such durability makes it possible to treat almost any lot of workpieces made of CAC-400 without regrinding.

RESULTS AND DISCUSSION

The results of these experiments show that synthetic superhard materials (cubic boron nitride, synthetic diamond) may be successfully used for fine turning the parts made of CAC-400 material. The sharpening angles and the cutter wedge shape have a great influence on the quality of treatment. The following recommendations for choosing the sharpening angles of a cutting tool equipped with the inserts made of synthetic diamond while treating the aluminum alloys: γ = 0-50, $\alpha = \alpha 1$ = 12°, λ = 0, φ = 40°, φ 1 = 15-20°, length of transitional cutting edge (or a radius at the cutter tip)-0.1-0.6 mm are presented by Lyubomudrov and Makarova (2007).

The tool cutting part geometrical parameters for semifinish machining and final machining are characterized by a negative-rake angle of 1-6°, a back angle of 6-12° and a cutting-point angle of 90°. Finishing and polishing of the cutters front and rear surfaces provide improvement of their durability by 1.5-2 time as a result of reducing the intensity of adhesion phenomena within the contact area of the material being treated and chip scrap with the tool surfaces. Formation of chamfers with the width not exceeding 0.1 mm on the cutter rear face is also promising. The narrow chamfer significantly strengthens the cutting wedge near the top and moreover has a smoothing impact on the working surface. The experiments on sharpening of the workpiece made of alloy

Table 2: Time spent on finishing the cutters for fine turning the material CAC-400

Cutter material	Grinding and finishing time (min)	Cutting edge spherical radius (mm)
Hard alloy T15K6	30	5.0
Cubic boron nitride with a chamfer at the apex	120	1.5
Synthetic diamond with a chamfer at the apex	400	5.0

CAC-400 with the cutters made of cubic boron nitride and synthetic diamond sharpened together with a chamfer and a radius, respectively were conducted in order to determine the preference of using a chamfer or a radius at the apex. Grinding was carried out at the following angles: face angle of -8°, main clearance angle of 8°, major cutting edge angle of 40°, minor cutting edge angle of 45°, size of the radius at the apex r = 0.2 mm, chamfer size of about 0.4 mm. The time taken for various cutters grinding and finishing is presented in Table 2.

When installing the cutters with the chamfer at the apex on the machine by means of microscope, the chamfer was verified strictly parallel to the workpiece surface. Turning was conducted under the following conditions: cutting depth 0.1 mm, feed 0.01 mm rev^{-1}, cutting speed was varied and taken the values of 95, 190, 380 and 760 m min^{-1}. After processing with the profilometer has been completed, Ra parameter was measured over the workpiece surface at ten points and the surface roughness average value based on Ra parameter as well as variety of this parameter σ_{Ra} were identified. The experimental results are summarized in Table 3.

It is evident from Table data that the geometry with the chamfer at the apex gives better results than the one with the radius. The experiments for processing the parts made of CAC-400 with the cutter made of cubic boron nitride with different radii at the apex were additionally carried out in order to determine the radius influence. The data from these experiments are listed in Table 4. It is apparent from Table 4 that the optimum regarding roughness value is within the radius value at the apex of 0.2 mm but better results are obtained with the cutter having a chamfer at the apex therefore, they should be applied during treatment of alloy CAC-400.

The influence of the cutter dimensional wear on the processing accuracy: Such workpieces as a pin made of alloy CAC-400 were processed in order to determine the influence of cutting conditions on tool wear. Tool wear was determined after every cutting path kilometer. Relative wear per km of the path, initial wear and a root-mean-square deviation from theoretical line was determined based on the data obtained via least square method. The results of wear measurements during processing of CAC-400 alloy with the cutters made of composite and synthetic diamond showed that the cutter wear was slightly dependent on a cutting speed.

Table 3: Surface roughness during processing the alloy CAC-400 with a cutter made of synthetic superhard materials

Cutter type	Cutting speed (m min^{-1})	Surface roughness Ra (μm)	Roughness range, σ_{Ra} (μm)
Synthetic diamond with a radius at the apex	95	0.260	0.035
	190	0.210	0.021
	380	0.240	0.035
	760	0.260	0.035
Synthetic diamond with a chamfer at the apex	95	0.180	0.012
	190	0.150	0.009
	380	0.170	0.010
	760	0.220	0.023
Cubic boron nitride with a radius at the apex	95	0.280	0.020
	190	0.250	0.017
	380	0.330	0.011
	760	0.380	0.020
Cubic boron nitride with a chamfer at the apex	95	0.075	0.010
	190	0.069	0.008
	380	0.057	0.005
	760	0.141	0.017

Table 4: Surface roughness during processing the material CAC-400 with a cutter made of cubic boron nitride with a radius at the apex

Value of radius at the apex (mm)	Surface roughness Ra (μm)	Roughness, range σ_{Ra} (μm)
2	0.58	0.059
1	0.42	0.025
0.2	0.33	0.024
Cutting-off tool	0.54	0.024
Chamfer	0.14	0.017

Table 5: Change of surface roughness depending on cutter wear during processing the alloy CAC-400

Cutter material	Cutting speed (m min^{-1})	Roughness before jump Ra (μm)	Roughness after jump Ra (μm)
Cubic boron nitride	375	0.160	0.62
	600	0.078	0.43
Synthetic diamond	375	0.160	0.35
	600	0.180	0.35

For more detailed determination of the type of wear dependences on speed, cutting depth and feed, it is necessary to plan and set up an experiment for finding coefficients of power dependence of relative and initial dimensional wear on different factors. As it turned out, changing the tool dimensional wear affects a working surface roughness. The roughness changes slightly until reaching of a particular value by wear and sharply rises after reaching this value.

The type of dimensional wear does not change after this but a chamfer, clearly defined in microscope, appears on the rear edge. It is advisable to consider this moment of roughness sharp deterioration as a tool durability limit. Experimental researches have shown that a sharp deterioration of roughness occurs in case of a cutter dimensional wear of 9 μm as well as in case of cubic boron nitride and synthetic diamond. The tool made of synthetic diamond has a roughness jump less sharp than the tool made of cubic boron nitride. The values of this jump at different cutting speeds are listed in Table 5.

The influence of technological system elastic deformations on the processing accuracy: The major part of machining errors is related to changing of the cutting forces during the lot of workpieces machining. Different links of manufacturing system are shifted and deformed under the action of cutting forces. The result of such shifts and deformations is the change of cutting edge position relative to a part which leads to occurrence of part diametrical dimensions errors. Variation of cutting forces may greatly worsen the working surface roughness. Besides the cutting forces provide information on the cutting process the less they are the more efficient the cutting process is.

The following experiments were conducted to research the changes of cutting forces values during fine turning the thin alloy CAC-400. The rings of CAC-400 were turned with the cutters made of cubic boron nitride and synthetic diamond in different cutting modes. The experiment was conducted at the following cutting conditions: cutting depth 0.1 mm, feed took the values of 0.01 and 0.02 mm rev^{-1}, cutting speed was 100, 200, 400, 800 m min^{-1} sequentially, diameter of the workpiece to be processed was 120 mm. Treatment was carried out with sharpened, freshly-sharpened and finished cutters. The cutting ends were sharpened at the angles: $\gamma = -10°$, $\alpha = 7°$, $\varphi = 45°$, $\varphi_1 = 15°$, the chamfer at the apex was about 0.4 mm, cubic boron nitride had a cutting edge rounding-off radius of about 1.5 μm and synthetic diamond had a cutting edge rounding-off radius of about 4 μm. The results are listed in Table 6 and 7.

It is apparent from Table 6 and 7 that the cutting force component P_Y which has the strongest influence on the machining accuracy and roughness has low values in the following cases: it does not exceed 7 N when processing with a cutter made of cubic boron nitride at a cutting depth of 0.1 mm. It reaches the minimum values at cutting speeds of 400 m min^{-1}, so it is advisable to conduct this processing at the speeds of 400-600 m min^{-1} during machining the alloy CAC-400 with the cutters made of cubic boron nitride and synthetic diamond.

Table 6: Cutting force components during turning the alloy CAC-400 with a cutter made of cubic boron nitride

Feed (mm rev^{-1})	Cutting speed (m min^{-1})	Cutting force P_Z	P_Y
0.02	100	11.0	4
0.02	200	10.0	3
0.02	400	6.5	2
0.02	800	5.0	3
0.01	100	10.0	7
0.01	200	9.0	3
0.01	400	8.0	2
0.01	800	7.2	5

Table 7: Cutting force components during turning the alloy CAC-400 via a cutter made of synthetic diamond

Feed (mm rev^{-1})	Cutting speed (m min^{-1})	Cutting force P_Z	P_Y
0.02	100	08.5	6.0
0.02	200	08.5	6.0
0.02	400	09.4	3.5
0.02	800	10.2	3.5
0.01	100	06.4	4.5
0.01	200	08.5	4.5
0.01	400	07.2	4.5
0.01	800	08.5	3.5

The influence of technological system thermal deformations on the processing accuracy: Thermal deformations of cutting tool, part and machine heavily affect the accuracy of workpieces machining. Machine thermal deformations are included in a slide position error in cross direction and are low in absolute magnitude.

Thermal deformation of a part significantly affects the accuracy of its shape and may exceed the part shape tolerance in certain cutting modes but these errors are not too large in case of aluminum parts fine turning. The cutting tool thermal elongation has the greatest influence on the processing accuracy. Many researchers suggest (Anukhin and Makarova, 2014) that the tool tip temperature indicates the machining process accuracy to the fullest extent, so the most appropriate is to monitor the tool tip during shaping process. However, the lack of such systems in operation leads to indirect operation of this component, for example by calculating the tool thermal deformation through changing its temperature in the cutting area or using the formula available from experiments which leads to significant errors of such method. Nevertheless, the tool thermal deformation errors during fine turning are significant in some cases, they reach >60% of total processing error value and it is necessary to know and consider their value.

Special device developed at the department “mechanical-engineering technology” of Peter the Great Petersburg Polytechnic University was used to determine the influence of process parameters change on the value and type of tool thermal deformations change. The following experiments were conducted to determine the influence of cutting modes on the cutter thermal elongation: fine turning of workpiece made of CAC-400 was fulfilled with cutters of cubic boron nitride at various values of cutting depth, cutting speed and feed. Cylindrical workpiece of 120 mm in diameter and 700 mm in length was applied. Cutting was carried out for thirty minutes in all cases and tool temperature elongation was being registered with a recorder during whole cutting process. Experiments shown that the cutter maximum thermal elongation depended on feed almost linearly and the dependence on the cutting depth was a power function.

CONCLUSION

The conducted researches on processing a special aluminum alloy make it possible to draw the following conclusions. It is recommended to use cutters equipped with cutting plates made of superhard synthetic materials, specifically, made of cubic boron nitride and synthetic diamond for fine turning the alloy CAC-400. The use of hard alloys is inadvisable because of the poor quality of treated surface and the intensive dimensional wear. The results of chip formation research shown that chip type had an expressed shift nature in this case, the chip type, when increasing the cutting speed, varies from the elementary connected line to the ribbon-like line. Chip shrinkage coefficient during processing the alloy CAC-400 by cutter made of cubic boron nitride is about <20% in case of treatment with the cutter made of synthetic diamond.

It is recommended to apply the following angles of sharpening the cutters made of cubic boron nitride and synthetic diamond: γ = -10°, α = 8°, φ = 40°, φ_1 = 15° chamfers at the cutter apex of 0.4-0.6 mm with finishing the working surfaces via diamond paste and maintaining of the roughness of edges based on parameter Ra $\leq$0.1 μm in order to obtain roughness of the treated surface based on parameter Ra within the range of 0.2-0.4 μm. The results of grinding and finishing of the cutters with a standard grinding machine show that the time of grinding and finishing of the cutter made of cubic boron nitride is 120 min that is 3 time less than the time taken for grinding and finishing of the diamond cutter.

When turning the alloy CAC-400, the durability of cutters made of cubic boron nitride is 50 km when an allowable cutting dimensional wear is of 9 μm, resistance of cutters made of synthetic diamond is 45 km of a cutting path. Thermal elongation of the cutter when machining the cubic boron nitride is about 1.8 time less than during machining with synthetic diamond. The resulting empirical equation makes it possible to calculate the cutter thermal elongation at any time of machining. Cutting force components P_Y and P_Z during machining with a cutter made of synthetic diamond within the range of cutting speeds from 200-800 m min^{-1} slightly vary and equal to P_Y = 4 N, D_Z = 7 N at a cutting depth of 0.1 mm, feed of 0.01 mm rev^{-1} and there is a clearly expressed minimum at a speed of 400 m min^{-1} during machining with a cutter made of cubic boron nitride.

REFERENCES

Anukhin, V.I., and T.A. Makarova, 2014. Turning processing error compensation during process automation. Proceedings of the International Research and Practice Conference on Science and Technology: Step to the Future, March 3-4, 2014, Argo S.R.O. Publisher, Prague, Czech Republic, pp: 30-39.

Kablov, E.N., 2001. Cast blades of gas turbine engines alloys, technology covers. Moscow Institute of Steel and Alloys, Moscow, Russia.

Komarov, V.A. and V.V. Pleshakov, 2014. Processing of parts made of aluminum alloys without coolant-cutting fluid. Bull. Moscow State Univ. Instrum. Eng. Inf., 55: 29-33.

Kurganov, S.V., Y.U.A. Kurganova, T.A. Chernyshova and L.I. Kobeleva, 2008. Mechanical working of casting blocks made of dispersion-reinforced composite materials based on aluminum alloys. Eng. Mag. Appendix, 12: 26-29.

Lyubomudrov, S.A. and T.A. Makarova, 2007. Quality assurance of processing special aluminum alloys during fine turning. Qual. Manage. Prob. Res. Experience, 5: 86-97.

Lyubomudrov, S.A., 1994. Ensuring the accuracy of machining the cylindrical work pieces made of powder aluminum alloys via assigning rational control cycles. Ph.D Thesis, Saint Petersburg State University, Saint-Petersburg, Russia.

Minaev, A.A., 2013. Innovative analysis of cast metal-containing composites development. Foundryman Russia, 1: 40-43.

Pashentsev, A.B. and A.N. Zhuravlev, 2007. Combined machining of parts made of aluminum alloys. Mach. Tools, 3: 40-40.

Vasilyev, A.V., 2013. Research of mechanical properties of dispersion-strengthened composite alloys. Tech. Technol. Prob. Serv., 13: 24-29.

Vasin, S.A., A.S. Vereshchaka and V.S. Kushner, 2001. Materials Cutting; Thermo Mechanical Approach to the Interrelationship System while Cutting: Textbook for Technical Universities. Bauman Moscow State Technical University, Moscow, Russia,.

Vereshchaka, A.S., 1993. The Efficiency of a Cutting Tool with a Wear-Resistant Coating. Mashinostroenie Publishers, Moscow, Russia,.

Zubarev, Y.U.M., 1988. Progressive Cutting Tool Based on Cubic Boron Nitride. LDNTP Publisher, Saint Petersburg, Russia,.