Choice of the Optimal Parameters of the Ultra-Fine Grained Cooper Machining

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Abstract. This article is focused on the features of the structure of ultra-fine grained metals and the influence of the machining on its changes. The search for optimal parameters was carried out for machining of pure copper, obtained by the method of several plastic deformations. The objective function, which includes a new criterion of optimization, was proposed. Limitations of the function for turning ultra-fine grained copper were obtained from experimental data. As a criterion of optimality, a general combining criterion is proposed, which is based on the linear convolution, two particular criteria the productivity and size of the grain size of nano- and ultra-fine grained metals, each with its own weight coefficients. The optimization problem was solved by the penalty function method in the MATLAB software environment using the method of unconditional mini-mization of several variables. Optimal decisions on the selection of the cutting speed and feed during the rotation of ultra-fine grained copper with different initial grain sizes are obtained.

Keywords: Ultra-fine grained · Pure copper · Machining · Optimization MATLAB

1 Introduction

With newly developed materials being produced for their superior properties of high strength, high ductility, low weight, etc., a need for implementing them into practical use has arisen. Because of these features, many advanced materials show potential in engineering applications such as medical devices and aerospace structural components, but an adherent gap exists between the research and industrial fields to push these materials into usage. For newly produced materials which is shaped and formed into their final dimensions, further machining research is typically required [1].

The recent development of ultra-fine grained (UFG) or nanostructured materials, with strengths up to twice stronger has created greater interest in research fields than their coarse grained counterparts. Various methods of producing nanostructured materials are existed. Substantially large samples can be produced easily from bulk form with little internal porosity making SPD materials boasted the greatest potential for an industrial impact of all UFG materials [2, 3]. Because of this, all UFG materials,

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referred to this thesis, are considered as being constructed using SPD. The exceptional properties yielding from these materials can be attributed solely to their defect structures. Along with the extremely small grains in the range of 100–1000 nm, numerous dislocations and subgrains, which are existed throughout the microstructure, with the aid in blocking slip, thus, increase material strength. However, these defects in the polycrystalline structure exhibit high internal energy, and as a result, thermally induced grain growth or subsequent changes in defect structure may occur at considerably low temperatures. These changes will naturally indicate a loss of strength, and thus limit SPD materials to low temperature applications [4, 5].

Since heating UFG materials may change their microstructures, it may be difficult to find means of forming and shaping these materials into their final dimensions. Given that machining is a heat dissipating process, the thermal stability of nanostructured materials must be considered carefully to save their unique properties. The major motive for conducting machining research is to discover the interaction between the cutting tool and the workpiece material, so that the machining costs can be minimized while still optimizing part quality [6].

The effect of machining conditions on the change in grain size in metals with UFG structure has been observed in numerous studies [7–9].

Therefore, optimal cutting conditions will be able to ensure the preservation of the initial grain size in the manufacture of products from blanks with bulk nano and UFG structure. Studies, which determined such cutting conditions are an urgent task.

The problem of determining the optimum cutting conditions is given to a large attention in the scientific works [10–12]. The task of optimizing the cutting conditions has been studied quite fully to the present. This allows us to develop not only new mathematical models for calculating cutting modes, but also to implement them in the form of various control computer programs. Such programs are executed both in the form of separate applications, and in the form of modules of different CAM and TDM systems.

2 Optimization Model

2.1 Optimization Criterions

One of the generally accepted criteria of optimality for cutting modes is the productivity of processing Q - the volume of metal (allowance), taken from the workpiece per time unit. Varying parameters are the cutting speed (s) and the feed (f) [11].

$$Q = s \cdot f \to \max \text{ or } Q^{-1} = \frac{1}{s \cdot f} \to min, \tag{1}$$

where s – cutting speed, f – cutting feed.

The main difference and peculiarity of the processing of nanostructures is the appearance of a new optimization criterion is the grain size. This criterion is very important because it will minimize the effects of cutting conditions on the structure. And the grain size should tend to a minimum, as the smaller the grain size, the higher the physical and mechanical properties of the nanomaterial. However, it should not reach the boundary values, which are stipulated by the Hall-Petch equation [13].

This criterion for turning can be written in the following form [5]:

$$D = \sqrt{D_0^2 + A \cdot \frac{\pi \cdot d \cdot L}{s \cdot f}} \to min, \quad (2)$$

where L – length of the surface to be machined; d – the diameter of the workpiece to be machined; D_0 – initial grain size in UFG or NC metal; D – admissible critical grain size, at which high physical and mechanical properties of metal are preserved; A – a parameter that characterizes the intensity of grain growth, taking into account the properties of the material being processed.

Expressions (1) and (2) are optimization criteria for the problem under consideration.

2.2 Technical Limitations

Technical limitations of the machining are represented in the form of a system of inequalities (Table 1).

Table 1. Technical limitations for tuning [14].

Restrictions	Mathematical expressions
Kinematic	$\begin{cases} f - f_{min} \geq 0 \\ f_{max} - f \geq 0 \end{cases} \begin{cases} s - s_{min} \geq 0 \\ s_{max} - s \geq 0 \end{cases}$
Roughness	$R_{amax} - C_{Ra} \cdot s^{xRa} \cdot f^{yRa} \geq 0$
Microhardness	$C_{Hv} \cdot s^{xHv} \cdot f^{yHv} - H_{vmin} \geq 0$
Power machine	$N_{max} - \frac{F_c \cdot s}{60 \cdot 1000} \geq 0$
Cutting temperature	$T_{max} - C_t \cdot s^{xT} \cdot f^{yT} \cdot d^{zT} \geq 0$

2.3 Method of Optimization

Optimization can be single-purpose, an extremum of one objective function is defined, and a multi-criteria (multi-objective) search for an extremum for a combination of several optimization criteria.

The problem under consideration is a multicriteria optimization problem. To solve it, the linear convolution method was chosen. Using this method, individual criteria were combined, the productivity $Q^{-1}(s, f)$ and grain size $D(s, f)$ into one [14]:

$$J\left(Q^{-1}, D\right) = k_1 \cdot f\left(Q^{-1}\right) + k_2 \cdot f(D), \quad (3)$$

where, Q^{-1} – a particular performance criterion; D – a particular criterion grain size; k_1 – the weighting coefficient of the grain size criterion; k_2 – the weight coefficient of the performance criterion.

This method allows us to reduce the problem of multicriteria optimization to the problem of one-criterion optimization, the solution of which depends on the selected weight coefficients of the partial criteria.

The method of penalty functions was chosen to solve the optimization problem. Using the penalty function, the initial problem of conditional minimization is transformed into a sequence of unconditional minimization tasks [14]. The idea of transforming a constrained problem in this way seems the best, mainly in connection with the existence of effective and reliable methods of unconditional minimization. To apply this method, the following objective function was formulated:

$$F = k_1 \cdot Q^{-1} + k_2 \cdot D + R \cdot \sum_{i}^{i=8} q_i^2, \tag{4}$$

where R – penalty parameter; q_{i} – the i-th technical constraint.

In practical calculation, a penalty was used such as the square of the cut [10]:

$$\begin{aligned} &\Omega = R \cdot \sum_{i}^{i=8} \langle q(x) \rangle^2 \\ &\langle q(x) \rangle = \begin{cases} q(x), & if, q(x) \leq 0 \\ 0, & if, q(x) \geq 0 \end{cases}, \end{aligned} \tag{5}$$

If $q(x) \geq 0$, then the vector of variable variables x belongs to an admissible set, and otherwise does not belong. In this case, the objective function is “punished” by a penalty, i.e., decreases, so long as the point x does not enter the admissible set, and the objective function does not begin to increase again.

The penalty of the type of the cut-off square is very convenient, in particular, the function is defined and continuous throughout the range of values. Calculations are carried out with some given positive P. After solving the next subtask, the penalty R is increased and the search for the next more accurate solution is performed until the specified accuracy is achieved.

3 Realization of Optimization Model in MATLAB

The material for research was selected from technically pure copper C10100 (standard ASTM B359, USA), 2.0040 (standard WNr. Germany). Chemical composition: Cu + Ag min 99.93%. UFG structure is obtained by the method of overall forging [15]. The study of changes in the quality of the surface layer (microhardness and roughness) was carried out during the turning process with varying processing conditions: cutting speed from 30 to 100 m/min, feed from 0.1 to 1.2 mm/rev. T11302 (standard UNS, USA), 1.3343 (standard WNr, Germany) were used as instrumental material.

Table 2. Limitations obtained by processing experimental data.

Restriction criterion	Mathematical expressions
Roughness	$R_{a\,max} - 7.5 \cdot s^{0.04} \cdot f^{0.6} \geq 0$
Microhardness	$1374 \cdot s^{-0.3} \cdot f^{-0.15} - H_{v\,min} \geq 0$
Cutting temperature	$T_{max} - 183 \cdot s^{0.5} \cdot f^{0.2} \cdot d^{0.1} \geq 0$

Using the experimental data which is given in [9, 15, 16], the obtained analytical dependencies were reduced to the canonical form for specifying the main limitations of the model (see Table 1). The final form for the constraints obtained on the basis of the experimental data is given in Table 2.

For the correct application of the imposed constraints, it is necessary, that the corresponding constraint parameter (*Ra*, *Hv*, *Tmax*) does not exceed the maximum or minimum values to maintain the high physico-mechanical and operational properties of the corresponding workpiece material.

The parameter which is limited (*Ra*, *Hv*, *Tmax*) corresponding to the imposed restrictions should not exceed the maximum or minimum values for preserving the original grain size. This allows us to apply the imposed restrictions correctly.

Thus, we have received the main components of the optimization problem - these are particular criteria for optimality (productivity and grain size), a general criterion for optimality and a system of constraints.

Table 3. Initial data for the search for optimal processing conditions.

Designation	Name	Parameter values
L	Length of the surface to be machined (m)	0.1
d	Diameter of the workpiece (m)	0.01
A	The index, which takes into account the properties of the processed material (m/min)	2.5×10^{-12}
D_0	Initial grain size (nm)	100
s_{min}	Minimum speed (m/min)	30
s_{max}	Maximum speed (m/min)	160
f_{min}	Minimum feed (mm/rev)	0.1
f_{max}	Maximum feed (mm/rev)	0.24
d	Depth of cut (mm)	0.5
Nmax	Cutting power (kW)	12
Ramax	Allowable maximum roughness value (µm)	3.2
Hvmin	Allowable minimum value of microhardness (MPa)	600
Dmax	Maximum permissible grain diameter (µm)	1
Tmax	Permissible maximum cutting temperature (K)	623

The numerical solution of the problem was carried out in the MATLAB software environment using the method of unconditional minimization of the function of several variables *fminsearch*.

The values given in Table 3 were accepted as input data for the calculation.

The general view of the target function for implementation in MATLAB is:

$$F(s,f) = k_1 \cdot s \cdot f + k_2 \cdot \sqrt{D_0^2 + A \cdot \frac{\pi \cdot d \cdot L}{s \cdot f}} + P_{en} \tag{6}$$

$$\begin{aligned} P_{en} = R \cdot \Big(& (f_{max} - f)^2 + (f - f_{min})^2 + \cdot (s_{max} - s)^2 + (s - s_{min})^2 \\ & + \left(7.5 \cdot s^{0.04} \cdot f^{0.6} - R_{a\,max}\right)^2 + \left(1374 \cdot s^{-0.3} \cdot f^{-0.15} - H_{v\,min}\right)^2 + \\ & + \left(\frac{F_{c \cdot s}}{60 \cdot 1000} - N_{max}\right)^2 + \left(183 \cdot s^{0.5} \cdot f^{0.2} \cdot d^{0.1} - T_{max}\right)^2 \Big) \end{aligned} \tag{7}$$

where *Pen* – the penalty term.

When solving a multicriteria problem, the problem of normalization and scaling arises - bringing the criteria to a single scale and dimensionless is formed.

The most frequent usage is the replacement of the absolute values of their criteria dimensionless relative values:

$$\overline{F_k(x)} = \frac{F_k(x)}{F_k^*}, F_k^* = \max_{x \in D} F_{k(x)} \tag{8}$$

Thus, after normalization, the original function will have the following form:

$$F(s,f) = k_1 \cdot \frac{s_{max} \cdot f_{max}}{s \cdot f} + k_2 \cdot \frac{\sqrt{D_0^2 + A \cdot \frac{\pi \cdot d \cdot L}{s \cdot f}}}{D_{max}} + P_{en} \tag{9}$$

$$\begin{aligned} P_{en} = R \cdot \Bigg(& \left(1 - \frac{f}{f_{max}}\right)^2 + \left(\frac{f}{f_{max}} - \frac{f_{min}}{f_{max}}\right)^2 + \cdot \left(1 - \frac{f}{s_{max}}\right)^2 + \left(\frac{s}{s_{max}} - \frac{s_{min}}{s_{max}}\right)^2 \\ & + \left(\frac{7.5 \cdot s^{0.04} \cdot f^{0.6}}{R_{a\,max}} - 1\right)^2 + \left(\frac{1374 \cdot s^{-0.3} \cdot f^{-0.15}}{H_{v\,min}} - 1\right)^2 + \left(\frac{F_{c \cdot s}}{60 \cdot 1000 \cdot N_{max}} - 1\right)^2 \\ & + \left(\frac{183 \cdot s^{0.5} \cdot f^{0.2} \cdot d^{0.1}}{T_{max}} - 1\right)^2 \Bigg) \end{aligned} \tag{10}$$

4 Results and Discussion

As a starting point for the optimization process, we selected: s = 65 m/min; f = 1.2 mm/rev. As the initial value of the penalty, R = 10 is taken. The weights for the derived results are k_1 = 0.7 (for the grain size of the structure) and k_2 = 0.3 (for productivity).

Table 4. The change in the optimum solution near the optimum for the machining of cooper with an initial grain size of 100 nm.

Penalty function R	Cutting speed s (m/min)	Feed rate f (m/rev)	Productivity Q (m^2/min)	Grain size D (nm)	min F (s, f)
10000	30.0000	0.0001	0.0042	1830	0.0050

Table 5. The change in the optimum solution near the optimum for the machining of cooper with an initial grain size of 300 nm.

Penalty function R	Cutting speed s (m/min)	Feed rate f (m/rev)	Productivity Q (m^2/min)	Grain size D (nm)	min F (s, f)
10000	30.0000	0.0001	0.0045	1900	0.0030

Tables 4 and 5 show the results of the calculation of the optimum parameters of the cutting process for UFG copper with different grain sizes of the structure.

The developed program, as a result, derives the optimal solution for the selected objective functions when constraints are satisfied. Increasing the penalty allows you to obtain results with increasing accuracy. When the value of changeable variables (cutting speed and feed) on the two subsequent fine values coincide to the first decimal place, the optimal solution is considered to be received.

The results which is given in Tables 4 and 5 show us that during processing of nano (initial grain size of the billet 100 nm) and UFG (initial grain size of the blank 300 nm), the copper cutting speed does not exceed 30 m/min with a feed of 0.1 mm/rev. At the same time, the grain size of the billet is increased to more than 1 μm, which will lead to a decrease in the physical and mechanical properties and the operational properties acquired when the billet is produced by intensive plastic deformation.

The obtained values of cutting conditions for UFG copper significantly lower than recommended for coarse-grained copper [17].

The developed program allows to vary the significance of particular objective functions (coefficients k_1 and k_2), thus, in advance it is possible to determine the degree

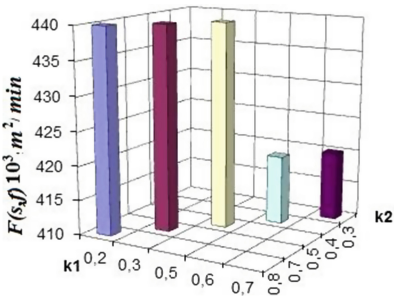

Fig. 1. Dependence of the objective functions on the values of the weight coefficients for copper with an initial grain size of 100 nm.

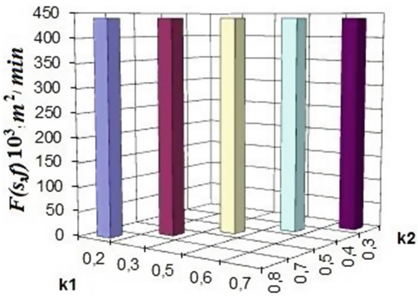

Fig. 2. Dependence of the objective functions on the values of the weight coefficients for copper with an initial grain size of 300 nm.

of the necessity to maintain a certain grain size of the workpiece or the level of productivity for each product individually.

Graphs of the dependence of the objective function on the values of the weight coefficients for nano- and UFG copper with an initial grain size of 100 nm and 300 nm are presented in Figs. 1 and 2.

The graphs (see Figs. 1 and 2) show the values of the objective functions when the weights are changing. Due to the fact that optimal conditions were not found for processing without cutting fluid, the developed program received the least value of the grain size after machining at a practically constant speed and feed, so it has no significant changes.

5 Conclusions

The work has explored and mastered the possibilities of solving optimization tasks in the MATLAB software environment. The method *fminsearch* was chosen as the crucial. A subroutine for the MATLAB software environment has been developed, which makes it possible to search for optimal parameters for machining in the manufacture of products from workpiece with a nano- or UFG structure. The proposed objective function allows us to counter the intensity of grain growth, which is very important when processing this group of materials.

As a result of solving the task, the following values of the cutting and feeding speeds were obtained. For copper with the initial grain size of the workpiece both 100 nm and 300 nm, optimal values for machining were not obtained. Since copper has a high thermal conductivity, the machining without coolant gives a lower productivity and does not allow preserving the original grain size.

Thus, the proposed optimization model works correctly and is consistent with the experiments. For copper, it is necessary to perform a series of investigations of machining with coolant and the use of diamond tools to reduce the amount of heat accumulated in the workpiece.

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