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Metallurgical Methods of Improving the Machinability of Structural Steels for Faster Automated Production

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Abstract—The influence of nonmetallic inclusions on the machinability of steel is studied. Their influence on the cutting force is established. Generalized formulas are proposed for the tool life, cutting speed, and components of the cutting force.

Keywords: machinability, productivity, structural steel, nonmetallic inclusions
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In the Industry 4.0 framework, it is important to ensure the productivity of automated manufacturing. One approach is to increase the permissible cutting speed while maintaining the predicted tool life. The cutting parameters largely depend on the physicomechanical properties of the workpiece.

In the present work, we assess the influence of various factors—the physicomechanical properties of the metal and the conditions of smelting and refining—on the machinability.

The efficiency of automated equipment depends on high machining productivity with the required tool life and reliability. To that end, new tool materials and more efficient tools have been developed; hardening methods are employed; and the state of the tool is monitored in the course of machining [1, 2].

Tool life and productivity are largely determined by the machinability of the structural steel. By improving the smelting and refining technology and employing special additives, the machinability of the steel may be considerably improved, with little if any change in its physicomechanical properties [2]. For example, calcium-bearing steel of improved machinability may be produced by reduction with silicocalcium [3]. Because such steel offers benefits in comparison with sulfur-, lead-, and selenium-bearing steels of improved machinability, it is of great interest [4–7].

Various methods may be used to improve the machinability of structural steel. When machining calcium-bearing steel with anorthite (lime feldspar) inclusions, the quality of the machined surface is better and the cutting force is lower than for unmodified austenitic stainless steel, as shown in studying the influence of additives in [8]. Sn-alloyed steel in which MnS inclusions are formed on account of the presence of tin (and its compounds with MnS) as surfactants was developed in [9]. The resulting steel is characterized by excellent machinability and physicomechanical properties.

The influence of nonmetallic inclusions on the following characteristics has also been studied: the tool life, the cutting speed, the cutting force, the chip type, and the quality of the machined surface.

The machining conditions influence which aspect of machinability is determining. In all cases of cutting, maximum productivity and minimum cost are required [10]. These two factors depend on the permissible cutting speed, which is therefore the main criterion of machinability. In addition, the cutting speed largely determines the tool's wear rate and life.

In experiments, we use WNUM–120612 hexahedral cutting inserts (vertex angle 80°) with an aperture and chip-breaking channels of type 02114-120622 (State Standard GOST 19048–80) and GMUM–120408 rhomboidal inserts (vertex angle 80°) with two chip-breaking channels of type 05124-120408 (State Standard GOST 19059–80). The hexahedral inserts of type 02114 are widely used in manufacturing; the rhomboid inserts of type 05124 are used on CNC machine tools in automated production.

Workpieces of АЦ45 and АЦ40Х calcium-bearing steel are machined in comparison with workpieces of corresponding 45 and 40X steel. In each case, the basic and calcium-bearing steels are obtained from the same melt; they only differ in the method of reduction. These steels are chosen because they are widely used in manufacturing [7].

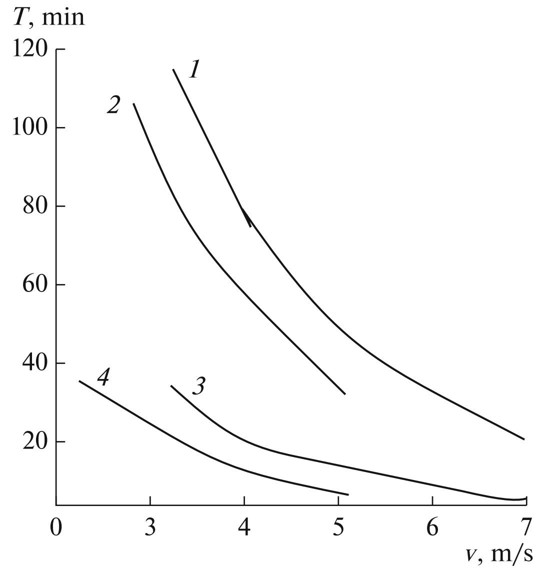

Fig. 1. Dependence of the tool life T on the cutting speed v in turning steel 45 (*3*, *4*) and АЦ45 calcium-bearing steel (*1*, *2*) by means of T15K6 hard-alloy inserts, when S = 0.1 mm/turn and t = 1 mm (*1*, *3*) and when S = 0.4 mm/turn and t = 3 mm (*2*, *4*).

We compare the cutting forces in one-pass turning of two pairs of basic and calcium-bearing steel disks attached coaxially to the same shaft, so that the basic steel disks are at the edges.

Two methods are used to derive formulas for the tool life: a single-factor experiment and a statistical approach.

(1) Single-factor experiment. In Fig. 1, we show the dependence of the tool life T on the cutting speed v in turning steel 45 and АЦ45 calcium-bearing steel by means of T15K6 hard-alloy inserts (05114-080408). The limiting wear (the maximum wear at the cutter's rear surface) is selected as 0.6–0.7 mm.

Analysis of the results shows that the cutter life in machining АЦ45 steel is 2–5 times greater (depending on the cutting speed) than in machining steel 45. Accordingly, the cutting speed may be increased by 20–60%.

(2) Statistical approach. In this case, we may write the following formula

$$T = \frac{C}{v^n S^q t^p}, \quad (1)$$

where C is a constant; v and t are the cutting speed and depth; S is the supply; and n, q, and p are exponents.

To obtain the regression equation, we use a complete factorial experiment of 2^3 type. To assess the experimental accuracy, we employ four experiments at the additional central point of the experiment design.

Table 1 presents the initial data and the corresponding coded factors in the experiments.

The regression equation is

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_2 + b_{23}x_1x_2 + b_{123}x_1x_2x_3,$$

where y is the logarithm of the life; the constant b_0 determines the constant C in Eq. (1); the constants b_i determine the exponents in Eq. (1); x_i are dimensionless coded variables corresponding to v, S, and t.

By determining the constants and exponents, the life may be calculated as a function of the uncoded cutting parameters; their values are presented in Table 2.

In production, as a rule, one cutting parameter is determined in order to ensure the specified tool life. Most often, we determine the permissible cutting speed

$$v = \frac{C_v}{T^m S^a t^b} = \left(\frac{C}{TS^q t^p}\right)^m, \quad (2)$$

where $m = \frac{1}{n}$; $a = \frac{q}{n}$; $b = \frac{p}{n}$; $C_v = C^m$.

The accuracy is estimated by analysis of the experimental data. With a confidence level of 0.95, the error in calculating the tool life is no more than 15%. Fisher testing of these expressions indicates their high reliability.

Since Eq. (2) is obtained by means of Eq. (1), this approach may also be used to determine the cutting speed, on the basis of the data in Table 2.

Experiments beyond the scope of the design have shown that the formulas for the tool life and cutting speed may be used within the following intervals: v = 2.5–5 m/s; S = 0.15–0.5 mm/turn; and t = 0.5–4 mm.

We compare the conditions of tool operation with different cutting parameters by means of the coefficients

$$K_{li} = \frac{T_2}{T_1} = \left(\frac{C_2}{C_1}\right) v^{(n_1-n_2)} S^{(q_1-q_1)} t^{(p_1-p_2)};$$

$$K_{sp} = \frac{v_2}{v_1} = \left(\frac{Cv_2}{Cv_1}\right) T^{(m_1-m_2)} S^{(a_1-a_2)} t^{(b_1-b_2)},$$

Table 1

Level	v, m/s	$\bar{X}_1 = \ln v$	S, mm/turn	$\bar{X}_2 = \ln S$	h, mm	$\bar{X}_3 = \ln t$
−1	3.54	1.26	0.20	−1.61	1.00	0
0	4.17	1.43	0.28	−1.26	1.70	0.55
+1	4.95	1.60	0.40	0	3.00	1.10
Range	0.17		0.35		0.55	

where K_{li} characterizes the increase in tool life (the factor by which it is greater for workpieces of calcium-bearing steel than for the basic steel, in fixed conditions); and K_{sp} characterizes the increase in cutting speed (the factor by which it is greater for workpieces of calcium-bearing steel than for the basic steel, with the same tool life). Subscripts 1 and 2 correspond to the machining of the basic and calcium-bearing steels, respectively.

We may write

$$K_{li} = K_{li1}K_{li2},$$

where K_{li1} takes account of the influence of the cutting depth and the supply at fixed cutting speed, while K_{li2} takes account of the influence of the cutting speed at fixed t and S.

Analysis of the results shows that K_{li} and K_{sp} increase with increase in the permissible cutting speed or specified tool life, and hence the replacement of the basic steel by calcium-bearing steel becomes more expedient. In turning calcium-bearing steel, the tool life is such that the permissible wear may be decreased, where necessary. In combination with intake monitoring, that significantly increases the stability of the cutting properties and decreases waste associated with chipping of the tool. In automated manufacturing, these factors are of great importance.

Another key variable is the cutting force, which determines the energy consumption in machining, the life of machine-tool components, the tool wear, and the machinability of the workpiece.

In this case, we use a complete factorial experiment.

Table 2

Steel	C	n	q	p
45	98.45	3.70	2.25	0.82
АЦ45	78433	$5.3 + 1.68\ln S$	$1.04\ln t - 2.09$	1.76

The mathematical model of the cutting force takes the form

$$P_i = C_{pi}t^{x_{pi}}S^{y_{pi}},$$

where C_{pi} are constants for the alloy–coating system; x_{pi} and y_{pi} are exponents.

In all the experiments, the cutting speed remains constant: $v = 2.5$ m/s.

We assume variation of the cutting force and supply within the following intervals: $t = 0.5$–3.5 mm; and $S = 0.15$–0.50 mm/turn. Analysis of the results shows that the combined influence of these factors is slight. The confidence interval is 0.05, and the computational error P_i is no more than 15%. Comparison of the results obtained by the single-factor experiment and the statistical approach indicate that the formulas obtained may be used within the following intervals: $t = 0.6$–4 mm; $S = 0.15$–0.6 mm/turn; and $v = 2$–5 m/s.

Analysis of the data in Table 3 shows that, in turning calcium-bearing steel, the cutting force is less than for the basic steel: P_x declines by 40%; P_y by 20%; and P_z by 15%. This effect increases with increase in the cut layer and when wear-resistant cuttings are employed.

Table 3

Material		P_x			P_y			P_z		
tool (alloy)	workpiece (steel)	constants and exponents								
		C_p	x	y	C_p	x	y	C_p	x	y
T15K6 (R)	45	53	1.57	0.58	62	0.46	0.80	220	1.06	0.91
	АЦ45	45	1.54	0.64	45	0.68	0.69	193	1.06	0.89
T15K6 + TiN	45	52	1.19	0.57	78	0.33	0.93	200	1.00	0.81
	АЦ45	30	1.42	0.40	58	0.50	0.84	195	0.98	0.84
T15K6 + NiC	45	48	1.26	0.75	65	0.52	0.79	171	1.09	0.77
	АЦ45	18	1.95	0.27	47	0.72	0.64	137	1.25	0.66
MS 2210	45	51	1.52	0.51	33	1.01	0.41	178	1.13	0.74
	АЦ45	29	2.03	0.35	49	0.58	0.74	157	1.22	0.76
T15K6 (H)	45	40	1.18	0.39	60	0.63	0.50	156	1.05	0.58
	АЦ45	38	1.11	0.38	66	0.53	0.63	173	0.95	0.66
KNT 16	45	36	1.36	0.15	76	0.40	0.36	147	1.13	0.50
	АЦ45	34	1.27	0.15	81	0.35	0.45	151	1.07	0.52

Here R and H denote rhomboidal and hexahedral inserts, respectively.

To compare the energy consumption in turning for workpieces of basic and calcium-bearing steels, other conditions being equal, we use the coefficient

$$K_e = \frac{E_1}{E_2}.$$

Here E_1 and E_2 denote the energy consumed in turning the basic and calcium-bearing steels, respectively, and may be calculated from the formula

$$E = \frac{N_e yT}{Q}, \quad (3)$$

where $N_e = P_z v$ is the mean effective cutting power over the cutter life; $Q = Tvab$ is the volume of material removed within the cutter life; and we know that $a \approx S$ and $b \approx t$ for the cutters employed. Thus, we may write

$$E = \frac{P_z}{St}.$$

Hence, in fixed cutting conditions

$$K_e = \frac{P_{z1}}{P_{z2}} = \frac{C_{Pz1}}{C_{Pz2}} t^{(XP_{z1} - XP_{z2})} S^{(YP_{z1} - YP_{z2})}.$$

Thus, the productivity of machining may be increased by using structural steels of improved machinability, including calcium-bearing steel.

If the optimal parameters are used in turning calcium-bearing steel by means of hard-alloy cutters, the hard-alloy consumption may be decreased by a factor of 3–5 and the machining cost by a factor of seven, while the productivity may be quadrupled.

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