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CUTTING ENERGY AND SURFACE TEMPERATURE ANALYSIS IN GAS COMBUSTION HEATING ASSISTED TURNING

Branislav Sredanovic[1], Jelena Marković[2], Saša Tešić[1], Stevo Borojević[1], Đorđe Čiča[1]

[1] University of Banja Luka, Faculty of Mechanical Engineering Banja Luka

[2]SIM Technik d.o.o. Kotor Varoš

Abstract.*Developments inthe mechanical engineering industryare accompanied by the development of new solutions in material machining technologies. One of the directions of this development is combining different processes,with regard to obtaining the required machining process performance. The machining performance rating is commonly based on energy consumption analysis, process productivity, and machining efficacy, at the least. In this paper, an analysis of the steel turning process assisted by gas combustion heating was performed.This combined machining process is widely available, on the one hand, but is unstable and causes negative changes in the workpiece surface layer, on the other. The cutting energy was analyzed, as well as the consumption of energy due to the heating of the workpiece. Based on the experimental data, statistical analysis was carried out, and mathematical models of process performance indicators were developed. By using the developed mathematical models, optimization was carried out in order to obtain the appropriate process parameters, which would result in the lowest heat input and the used energy.*

Key words:*Steel turning process, Gas combustion heating, Heatingof the workpiece, Cutting Energy, Performance indicators.*

1. INTRODUCTION

The process of cutting hard-to-machine materials, such as alloyed steels, super alloys, ceramic materials, etc.,implies a wide list of problems, includinghigh cutting forces, intensive cutting tool wear, vibrations, high temperatures in machining zones, unacceptable chip shape, poor machined surface integrity, environmental unacceptability of the machining process, etc. [1]. The cutting process performance analysis, modeling and optimization are the basis for achieving a controlled and highly efficient process [2].

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Corresponding author: Branislav Sredanović
University of Banja Luka, Faculty of Mechanical Engineering Banja Luka
E-mail: branislav.sredanovic@mf.unibl.org

In industry, new types of materials are used, and their machining must be accompanied by high process effectiveness and energy efficiency [3]. Demands for high process productivity and efficiency in the machining of a wide range of engineering materials condition the use of hybrid machining processes. In a hybrid process there isa combination of production or similar processes. The CIRP (fr. *Collège International pour la Recherche en Productique*) definition of hybrid processes is–a hybrid process combines two or more machining processes in a new one, where the advantages of each of them can be used synergistically [4]. These advantages refer to increasing efficiency, operational process safety and achieving high productivity and process economy [5]. In fact, advantages from each involved process are used, and this solves the problems related to using the other process.

There are two types of hybrid machining processes: aided or mixed hybrid processes. In aided hybrid processes, one process,calledthe primary process, directly removes the workpiece material. The other process, called the secondary process, helps in the workpiece material removal process by significantly affecting the removal mechanism. In mixture hybrid processes, all combined processes are directly involved in the material removal process. Currently, one of the most widely used hybrid machining processes is the process assisted by heating the workpiece. It is defined as a thermal aided process, where the workpiece material softening principle is used. However, this production principle has long been present in deforming technology (forging, drawing, rolling, etc.), non-conventional technology, but not in cutting technology. By increasing the workpiece material temperature, the tensile strength and hardness decrease (Fig. 1). It leads to lower mechanical loads on the machining system elements, less tool destruction. Workpiece heating is most often applied in hybrid processes where the primary process is turning. Other cutting methods, such as milling and drilling, have constructive limitations, due to combining the heat source action point and the cutting tool tip.

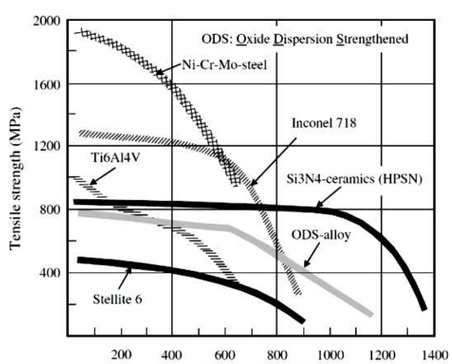

Fig. 1 Tensile strength reduction due to temperature

In practice, laser and plasma are most often used as a heat source [6, 7]. Also, another,secondary processcan be included in the cutting process[8]. The advantages of laser and plasma devicesare the possibility of high heat concentration in one place and achieving a high temperature of the workpiece [9]. On the other hand, these devices have complex constructions and must be portable. They are alsoexpensive, complicate to maintain, and consume a lot of energy [10]. Systems that use induction heating and gas combustion heating have a simpler construction. They are portable, available in wide production facilities, cheaper, and easier to maintain, but their disadvantage is a large dissipation of thermal energy.

2. EXPERIMENTATION

The experimental setup included a turning tool machine Prvomajska, equipped with a standard gas combustion device (Fig. 2). The gas combustion device was assembled using two gas tanks (acetylene and oxygen), gas pipes, and an adjustable mixing combustion nozzle. The nozzle was placed 15 mm abovethe non-machined workpiece surface. The point of nozzle was 15 mm in front of the cutting tool position. The workpiece material was alloyed tool steel X210Cr12, with the tensile strength of R_m = 600 MPa, and very high hardness due to a high percentage of chromium. The workpiece was a cylinder rod, Ø50x450 mm. The tool holder was PSDNN 2525 M12, assembled with a cutting tool insert SNMG 12 04 08, graded as GC4525 by Sandvik.

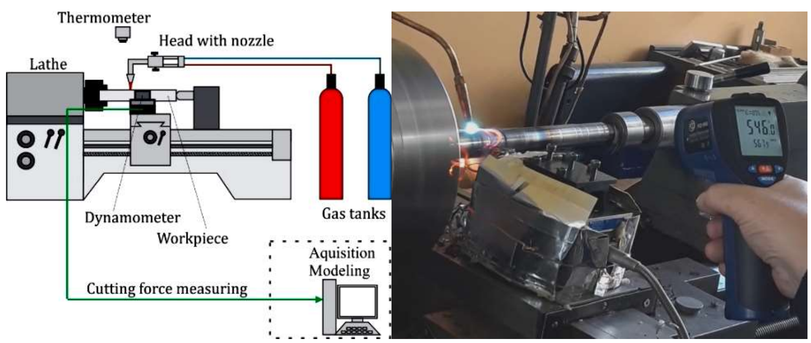

Fig. 2 Experimental setup

The Taguchi L9 experiment plan was used, aimed at the primary process (Table 1). Combinations of three turning process parameters, set on three different value levels, were used.The depth of cut was (ap) 1, 2 and 3 mm; feed rate (fn) 0.082, 0.164, and 0.330 mm/rev; and cutting speed (vc) 35, 60, and 106 m/min. Parameter level combinations were used in two cases: turning without heating and turning with heating. For each experimentation run the cutting length was 40 mm.

Table 1 Experimental plan

Exp.	a_p (mm)	v_c (m/min)	f_n (mm/rev)
1.	1.0	35	0.082
2.	1.0	60	0.164
3.	1.0	106	0.330
4.	2.0	35	0.164
5.	2.0	60	0.330
6.	2.0	106	0.082
7.	3.0	35	0.330
8.	3.0	60	0.082
9.	3.0	106	0.164

The Kistler measuring chain was used for cutting force component measuring. The Kistler chain was equipped with a Kistler 9259A dynamometer, an amplifier, an A/D convert PC card, and analyzing PC software. The resultant cutting force components were cutting force F_c (N), feed force F_f (N) and passive force F_p (N). Workpiece surface temperatures were measured by a remote point laser thermometer PCE-890U. Specific energy is a good indicator of energy efficiency of a production process. It is desirable to invest as less energy as possible to do as much work as possible. Specific cutting energy *SCE* (J/mm³) depends on cutting energy E_c (J) and removed workpiece material *MRV*, or cutting power P_c and material removal rate *MRR*:

$$SCE = \frac{E_c}{MRV} = \frac{P_c}{MRR} = \frac{F_c \cdot v_c}{a_p \cdot f_n \cdot v_c} \quad (1)$$

In addition to the mechanical energy in the cutting process, or cutting energy, that is invested in the workpiece material removal process, in this case, there is thermal energy that is spent on heating the workpiece also. It is assumed that the performed turning process on the heated area of the workpiece at least had the same machining length, workpiece properties, dimensions, and volume. Consequently, it can be assumed that the amount of invested thermal energy is proportional to the temperature of the heated workpiece surface. However, measuring surface temperature refers to how much energy is input into the cutting process.

3. Results and discussions

The diagram in Fig. 3 shows a comparison between the values of the specific cutting energy obtained during turning without heating the workpiece, and the values obtained during turning with heating the workpiece. The values in both cases change with the change of cutting parameters.

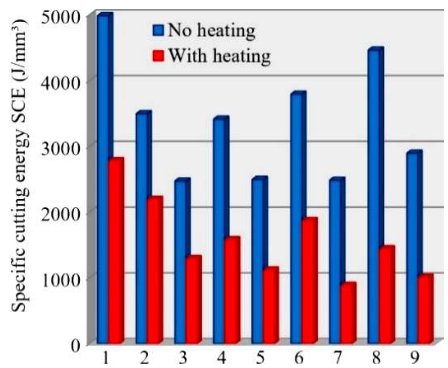

Fig. 3 Specific cutting energy values

However, with an increase in cutting force, cutting power and cutting energy consumption also increase. It can be noted that the specific cutting energy decreases with an increase in depth of cut, feed and cutting speed. In the case of heating the workpiece, the specific energy is lower compared to turning without heating. The reason for this is the lower value of the main cutting force component. The smallest reduction percentage in specific cutting energy of 37% was obtained when using a depth of cut of 1.0 mm, a cutting speed of 60 m/min and a feed of 0.164 mm/rev. The highest reduction percentage in specific cutting energy of 68% was obtained when using a depth of cut of 3.0 mm, a cutting speed of 60 m/min and a feed of 0.082 mm/rev.

Fig. 4 shows a diagram of temperature values for different combinations of process parameters. Significant changes in the temperature value of the workpiece surface are noticeable.The highest value of the measured surface temperature was obtained during turning with the combination containing the lowest values of the cutting parameters. On the other hand, the lowest values are obtained when using the combination containing the highest values of the process parameters. By analyzing the values, it was determined that the workpiece surface heats up more if the heat source stays in one zone on the workpiece for a relatively shorter time. A lower workpiece temperature results in a lower percentage of main cutting force reduction, and thus a lower reduction percentage in specific cutting energy.

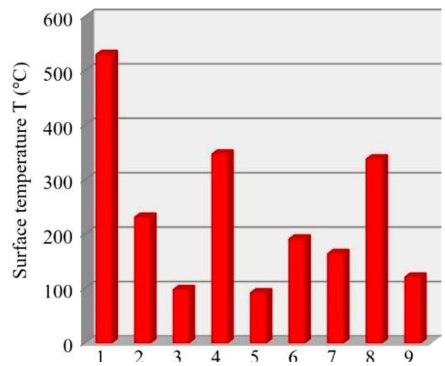

Fig. 4 Workpiece surface temperature values

For the mathematical description, modeling and statistical analysis of experimentally obtained data, the least squares method (LSM) and analysis of variance (ANOVA) were used. For this purpose, polynomial mathematical dependences of specific cutting energy and workpiece temperature values were assumed, in which the input factors (i.e. cutting parameters) participated as variables. The assumption was based on the significance of the input factors. Essentially, cutting parameters and their mutual combinations were used as factors. In this case, only the value of the specific cutting energy during turning with workpiece heating was considered.

Based on the significance of the input factors, a linear model with parameter interaction was assumed as the appropriate mathematical model for *SCE* (J/mm³):

$$SCE = 3998 - 861 \cdot a_p - 7528 \cdot f_n + 1943 \cdot a_p \cdot f_n \tag{2}$$

Based on these values, the model mean value $\bar{x}$ = 1575.87 and standard deviation *SD* = 125.67 were calculated. The signal to noise ratio was *S/N* = 21.8, and the regression coefficient was R^2= 0.97. Depth of cut and feed had an equal significance, while cutting speed did not influence specific cutting energy. It must be mentioned that there was no influence of the cutting speed when taking the analytical equation into consideration also. In the previous analytical equation for *SCE*, the influence of the cutting speed can be canceled out. The response of the specific cutting energy model is shown in Fig. 5. Based on the response of the model, it can be observed that more significant changes in the value of specific cutting energy are obtained in combinations with lower values of process parameters. This indicates that it is acceptable to use higher values of cutting parameters for the purpose of higher energy efficiency.

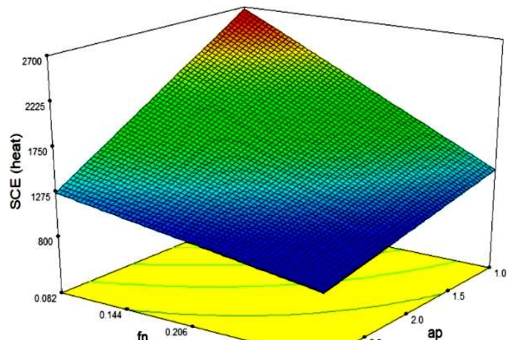

Fig. 5 Specific cutting energy model response

The workpiece surface temperature value was modeled using a modified quadratic model with an interaction of parameters. The factors of the workpiece temperature model were defined based on their significance to the model output value changes. The model of temperature *T* (°C) is defined as:

$$T = 914 - 5.829 \cdot v_c - 3344 \cdot f_n + 1943 \cdot v_c \cdot f_n + 3271 \cdot v_c \cdot {f_n}^2 \quad (3)$$

Based on this model, there were the calculated mean value $\bar{x} = 235.78$ and standard deviation SD = 40.72. The signal to noise ratio was S/N= 13.6, and the regression coefficient wasR^2= 0.96. Feed had the highest influence on workpiece temperature. The next factor in terms of significance was cutting speed. There was no influence of depth of cut. The response of the workpiece temperature model is shown in Fig. 6.Based on the diagram, it can be concluded that lower values of temperature are obtained at higher values of cutting speed and feed. This coincides with the conclusions reached previously. And for this machining performance indicator, larger temperature changes are obtained with combinations with lower values of process parameters.

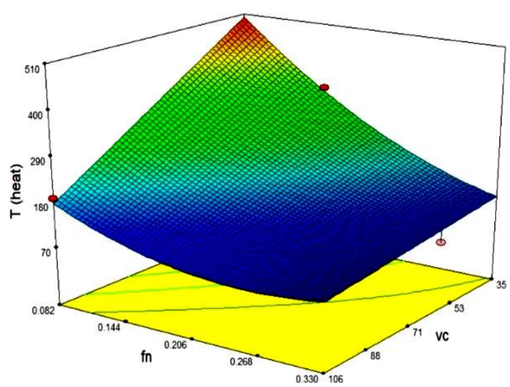

Fig. 6 Workpiece temperature model response

3.1 Turning process optimization

In order to establish an efficient cutting process, the presented process of turning with gas combustion heating of the workpiece was optimized. The optimization was performed on the basis of the developed output performance value models for turning processing with workpiece heating. The goal of the optimization was to reach a situation, where the minimum value of energy was invested to remove as much material as possible from the workpiece. Also, the minimum heat intake in the process of heating the material of the workpiece was set as an optimization goal. This goal was set in order to avoid the effect of heat on the workpiece surface.

Based on the previously defined optimization goals, the minimization of specific cutting energy and minimization of workpiece surface temperature values were set as the optimization goal functions. The space between the domains of the input cutting parameters was searched using an optimization algorithm. Table 2 showsthe mathematical frame for optimization.The standard gradient method and algorithm were used in the optimization procedure.

Table 2 Optimization frame

Name	Goal	Lower	Upper	Lower weight	Upper weight
ap (mm)	in range	1	3	1	1
vc (m/min	in range	35	106	1	1
fn (mm/rev)	in range	0.082	0.33	1	1
SEC	minmize	887	2780	1	1
T	minmize	92	540	1	1

In the optimization algorithm, for each input and output cutting parameter and each process performance indicator, the same importance degrees were given. The optimal parameters were determined as: depth of cut of 3.0 mm, cutting speed of 98 m/min, and feed of 0.311 mm/rev. According to the obtained optimal cutting parameter values, the initial assumptions and theoretical conclusions can be confirmed. It can be concluded that this method can be used for rough processing, with higher values of process parameters, whereby high productivity and a high level of energy utilization are obtained.

4. CONCLUSION

This paper presents a study of the use of the workpiece heating process, for the purpose of easier and more efficient turning of high-alloy tool steel. Unlike more efficient and expensive heat sources such as laser and plasma, a cheaper one was used here - heating by gas combustion. The experimental analysis included turning with heating and without heating. Based on the Taguchi experimental plan, the temperature values of the workpiece were determined, and the specific energy was obtained. Statistical analysis ANOVA was performed, and models with included significant factors were developed by the last square method. Changes were described and significant parameters were determined. Finally, mathematical optimization was performed, with the goal of minimizing the energy input (mechanical and thermal energy), whereby the cutting parameters were obtained.

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