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ANALYSIS OF CUTTING FORCES IN HYBRID TURNING AIDED BY GAS COMBUSTION HEATING OF WORKPIECE

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Abstract: The global industry development is also reflected in the development of special engineering materials. These materials usually have special properties at high temperatures, such are tensile high strength and hardness. Due to this special properties, this materials usually have low machinability. Consequently, it is necessary to develop technologies for machining of mentioned materials, such are hybrid cutting processes. In this paper, the alloy steel X210Cr12 was turned, whereby the workpiece was heated. Heating, as secondary process, was performed by gas combustion, directly in point next to the point of the cutting tool action. Cutting forces were measured in the two cases: without heating, and by heating of workpiece. Effects analysis and process modeling were performed using Taguchi's experiment design, by combining the cutting parameters of primary process. The analysis showed significant reduction in cutting forces, but also poorer quality of machined surface. Conclusions were made about the possibilities of using this hybrid machining process in material machining.
Keywords: hybrid turning, heating, machinability, alloy steel

INTRODUCTION

The increasing of using engineering materials with special properties (alloyed structural and tool steels, special titanium and nickel alloys, ceramics, glass, sintered hard metals, composites, and etc.) in industrial, has led to the neediness to develop of the advanced machining methods [1]. Due to chemical content and structure (crystalline or amorphous) of these types of materials, special properties are reflected in increased tensile strength and hardness, durability on high temperatures, chemical resistance, and etc. Machining of these materials is very difficult regard to mentioned properties. There are difficulties in achieving the machined surface quality and dimensional accuracy, due to high cutting forces, high cutting temperatures, intensive cutting tool wear, unacceptable chip shape, vibrations, and etc. Consequently, there are difficulties to achieve adequate economic, productivity and operate safety, and process sustainability at least.

The development of hybrid processes, as advanced machining processes, is one of the directions to successfully machining of materials with special properties [2, 3]. Hybrid process combines basically processes regard to improved machining efficiency (Figure 1). CIRP definition of hybrid processes is that hybrid process combines two or more machining process in new one, where advantage of each of them can be used synergistically [2].

There are two types of hybrid processes: aided and mixture. In aided, only one of the combined processes, noted as primary process, directly removes the material, while the other process, noted as secondary, only helps to remove the material by positively affecting the material removal mechanism. In mixture, all involved processes are directly involved in material removal. Hybrid process can involve thermal, mechanical or electrochemical secondary process.

In hybrid cutting processes aided by thermal process, the workpiece material softening due to its heating was used.

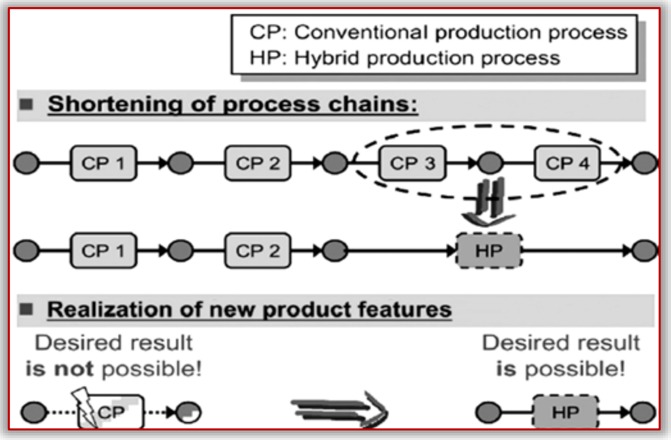

Figure 1. Principle of hybrid process introduction [2]

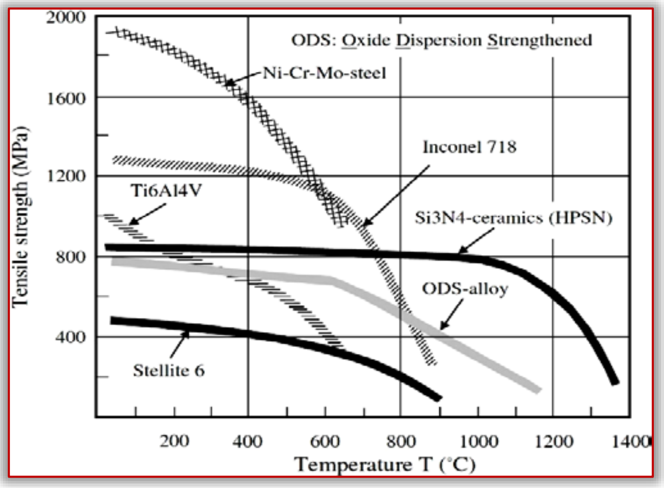

Figure 2. Tensile strength on different temperatures [3]

By increase of temperature, the workpiece material tensile strength and hardness decrease (Figure 2). It can be utilize with cutting by mechanical cutting tool, turning primarily, with aim to decrease cutting force and cutting tool wear. Other cutting processes (milling and drilling) have constructive limitations, in terms of heat source action point and cutting tool tip relative positioning and orientation.

As the heat source of secondary process in thermal assisted machining, can be used: laser, plasma, electrical induction, and gas combustion. Laser and plasma are more commonly used due to the ability to focus heat on a small area, and relatively higher temperatures [4-7]. In other hand, laser and plasma devices must be mobile. This types of heat sources often have a high cost, and very high maintenance costs. Devices for electrical induction and gas combustion are much cheaper, and more available in production facilities. Disadvantage of this heating methods are the great heat dissipation and lower temperature [8].

In this study, workpiece was heated by gas combustion. The effect of using this type of heating on the cutting forces was analysed. The standard turning process without heating and the hybrid process were compared, and the machinability indicators were analysed.

EXPERIMENTAL SETUP

Experimental research was performed by turning. Machining system was consist lathe Prvomajska assembled with equipment for gas combustion (Figure 3). In addition, the risk of fire and the possible effect of flame and heat on machine parts, measuring devices and operator were taken into account.

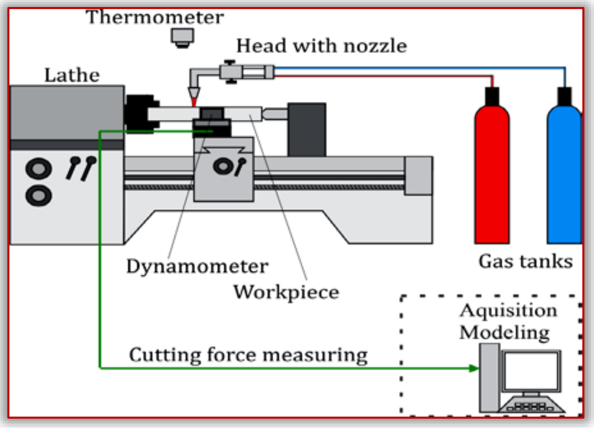

Figure 3. Schematic of machining system

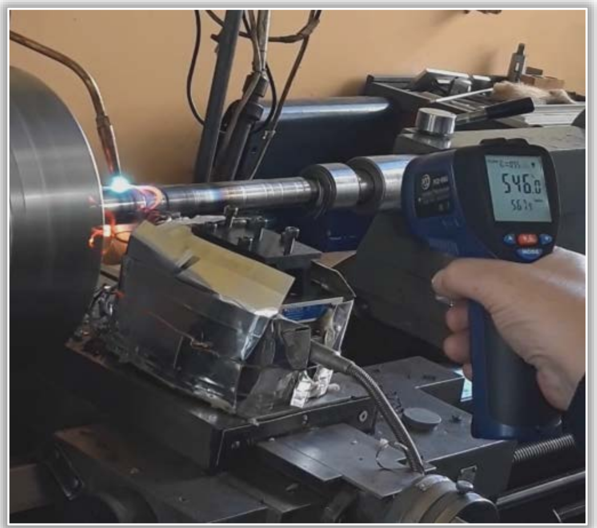

Figure 4. Experimental measuring

Equipment for gas combustion was consist operating head, with gas nozzle, and gas flow adjustment valves. Head is connected to the two gas tanks via two hoses. As burning mixture, acetylene and oxygen are stored in the tanks. Point of heating was placed in front of point of cutting tool, on non-machined surface (Figure 4). Horizontal distance was between mentioned two point was 15 mm. Gas head was placed above of workpiece surface, on vertical distance of 15 mm. Workpiece materials was tool alloy steels X210Cr12. Its tensile strength on room temperature is R_m = 600 MPa. Workpiece was cylinder rod, diameter 50 mm and length 450 mm. This steel contains a relative large percentage of chromium, so it is one of the harder to cutting materials, due to high cutting force, pressures and intensive cutting tool wear. Cutting tool insert was SNMG 12 04 08, grade GC4525, manufactured by Sandvik. Tool holder was PSDNN 2525 M12.

Taguchi L9 plan of experiment was used. In experiment plan was combined primary process parameters, cutting parameters of turning, as follow: depth of cut was a_p of 1, 2 and 3 mm; feed rate f_n was 0.082, 0.164, and 0.330 mm/rev; and cutting speed v_c was 35, 60, and 106 m/min. By Taguchi plan, there was nine combinations made by mentioned tree cutting parameters (Table 1). Same sets of parameter combinations was used in two types turning: turning without heating and turning with heating. Resultant cutting force component: cutting force F_c (N), feed force F_f (N) and passive force F_p (N) was measured for each combination. Kistler measuring chain was used for cutting force measuring. It consisted of Kistler dynamometer Kistler 9259A, amplifier, A/D converter PC card, and analysing PC software.

Table 1. Taguchi plan combinations

Exp no.	Depth of cut a_p (mm)	Cutting speed v_c (m/min)	Feed rate 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

Workpiece surface temperatures during research was checked by remote point laser thermometer. Workpiece non machined surface temperature was from 460°C to 560°C. It was depended on feed rate (feed per tooth and cutting speed), because this parameter affects the retention time on the observed workpiece surface area. But, temperatures are not modelled in this part of study.

RESULTS AND DISSCUSION

Results of cutting force measuring without and with heating of workpiece are shown on Figure 5. Can be concluded that cutting forces depends on cutting parameters. The highest value is obtained for a_p = 3 mm, f_n = 0.330 mm/rev and v_c = 35 m/min. Cutting forces in case of workpiece heating showed same tendency, but was lowest compare to forces without heating.

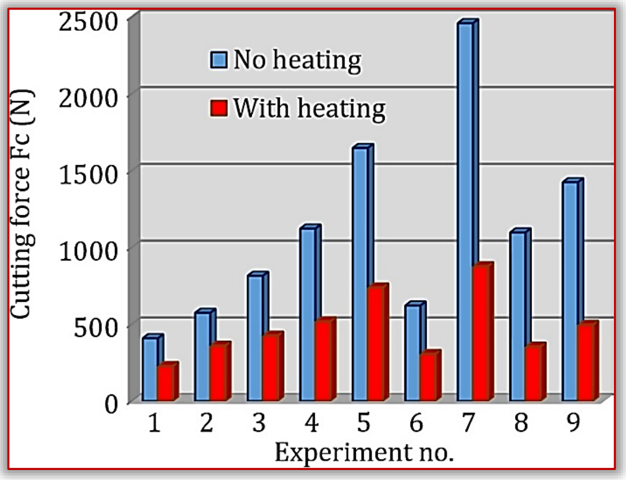

Figure 5. Cutting forces for two cases of turning

On Figure 6 and 7 are shown measured feed and passive forces for two cases of turning, without and with heating of workpiece. Based on combination and measured values, can be concluded that feed and passive force increase with increasing of cutting parameters. The higher values was obtained by using of higher values of depth of cut and feed rate, but the lowest value of cutting speed.

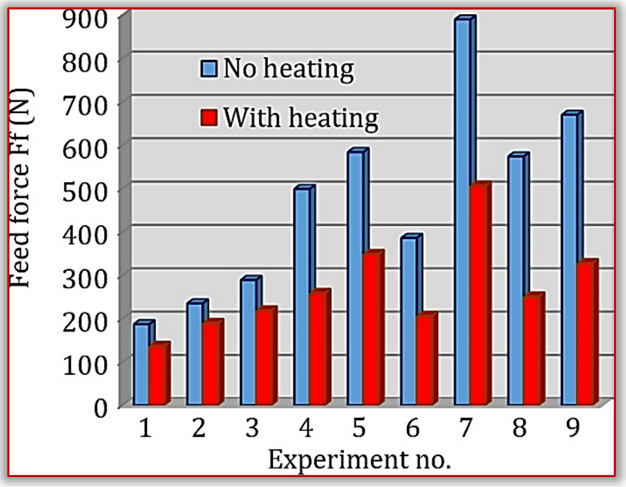

Figure 6. Feed forces for two cases of turning

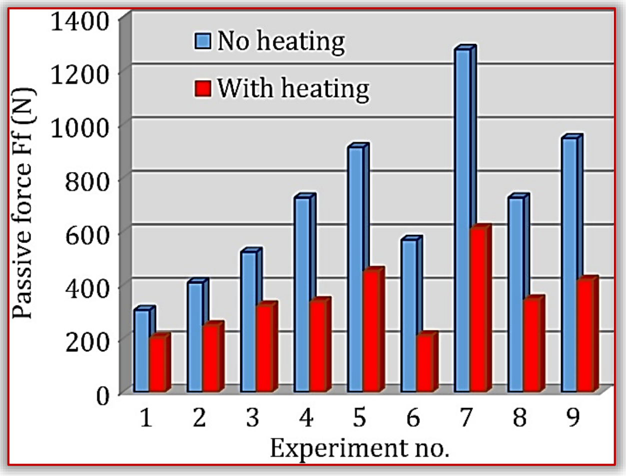

Figure 7. Passive forces for two cases of turning

Also, values of feed and passive forces in case of heating workpiece were lower in compare to the values obtained by turning without heating. On Figure 8, the percentage decrease in the value of the forces is shown. Minimum decreasing is obtained for feed forces on turning with cutting parameters a_p = 1 mm, f_n = 0.164 mm/rev and v_c = 60 m/min. Maximum value decreasing is obtained for cutting forces with cutting parameters a_p = 3 mm, f_n = 0.330 mm/rev and v_c = 35 m/min. However, the highest value of force was measured in this combination in case without heating. Higher percentages of reductions due workpiece heating were obtained in combinations with higher cutting parameter values. Higher percentages of were obtained for cutting forces in comparing with other two resultant cutting force components, also.

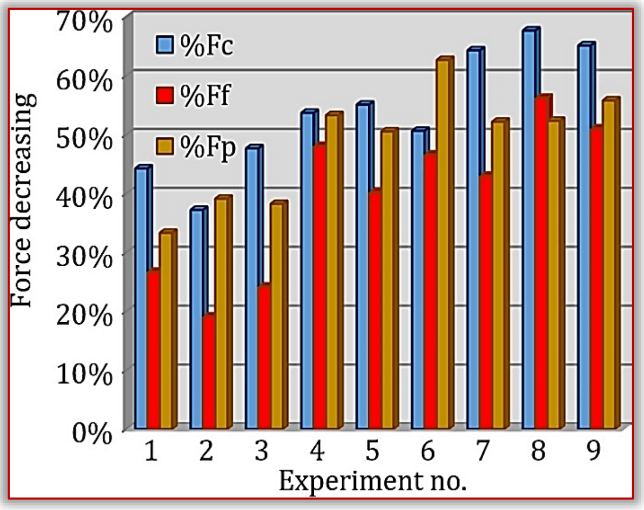

Figure 8. Percentages decreasing of cutting forces

Modelling and analysing of measured values was performed in DesigExpert 7.1 software. In modelling procedures, each cutting force components were analysed and modelled. Based on initial statistical parameters of F-value and P-value, for: model, each input parameters individually, and combination of input parameters, the software suggested the form of model function. Analyse of variance (ANOVA) was performed on each sets of measured values and adopted models.

In case of turning without workpiece heating, for cutting force model software suggested the linear model with all tree input parameters, but without their interactions:

$$F_c = -309.7 + 528.7 \cdot a_p - 5.0 \cdot v_c + 3751.2 \cdot f_n \qquad (1)$$

Based on values and model mean value $\bar{x}$ = 1131.78 and standard deviation SD = 128.03 was calculated. Signal to noise ratio was S/N = 23.3, and regression coefficient was R^2 = 0.98.

For feed and passive force, in case of turning without workpiece heating, software suggested the linear models with two input parameters depth of cut and feed rate, and without their interactions, follow as next:

$$F_f = -151 + 237.2 \cdot a_p + 812.4 \cdot f_n \qquad (2)$$

$$F_p = -142.8 + 286 \cdot a_p + 1468.1 \cdot f_n \qquad (3)$$

For feed force and passive force mean values are $\bar{x}$ = 479.3 and $\bar{x}$ = 711.1, respectively. Standard deviation is SD = 49.5 for feed force and SD = 76.8 for passive force. For feed force signal to noise ratio is S/N = 23.6, and regression coefficient R^2 = 0.96. For passive force S/N = 21.1, and R^2 = 0.95.

Based on statistical analyse can be concluded that presented models are adequate. Model response for cutting force components in case of turning without workpiece heating are shown on Figure 9.

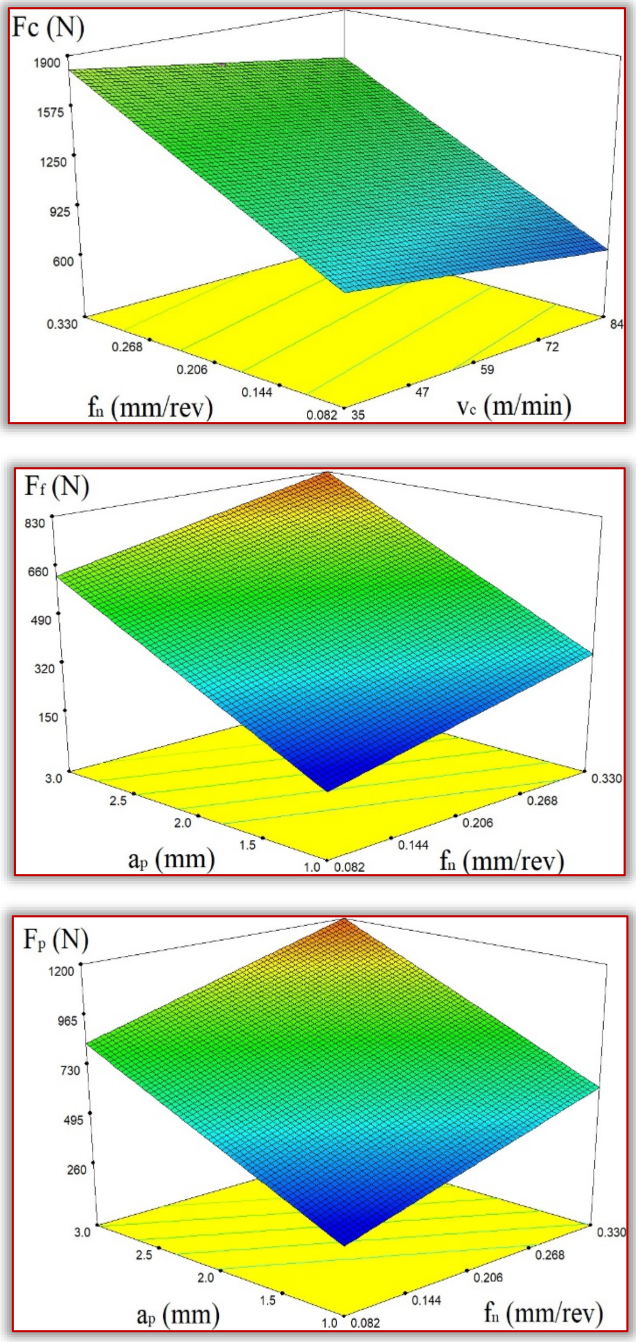

Figure 9. Model responses for turning without heating

For cutting and feed force in turning with workpiece heating, software suggested linear models with all tree input parameters, and their interactions. For passive force model, there was suggested linear model without parameter interaction. The mentioned models functions are listed below, while their responses are shown in Figure 10.

$$F_c=-72.5+78.3\cdot a_p+1.5\cdot v_c+2696.3\cdot f_n-17.6\cdot v_c\cdot f_n \qquad (4)$$

$$F_f=-60.2+69.3\cdot a_p+1.1\cdot v_c+1234.8\cdot f_n-8.91\cdot v_c\cdot f_n \qquad (5)$$

$$F_p=-52.3+100.2\cdot a_p-0.9\cdot v_c+828.9\cdot f_n \qquad (6)$$

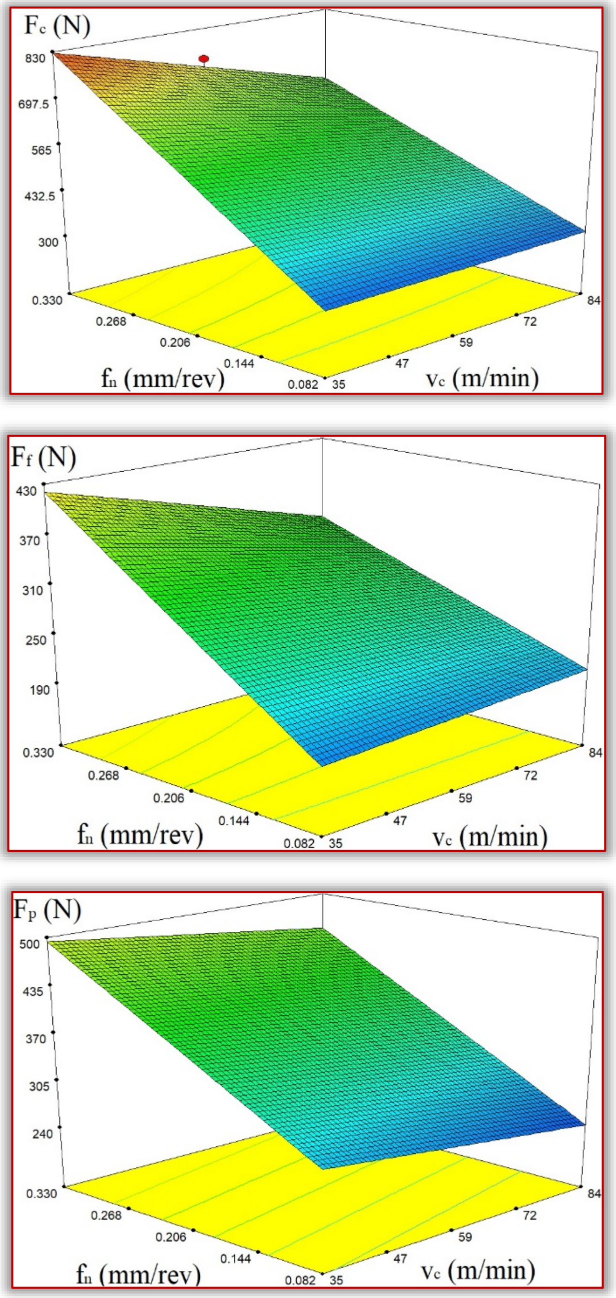

Figure 10. Model responses for turning with heating

Based on experimental obtained values and model responses, statistical parameters calculation is performed. For cutting force with workpiece heating data, mean value is $\bar{x}$ = 479.2, and standard deviation is SD = 37.8. Signal to noise ratio was S/N = 23.9, and regression coefficient was R^2 = 0.98.

For feed force with workpiece heating data, mean value is $\bar{x}$ = 271.8, and standard deviation is SD = 21.9. Signal to noise ratio was S/N = 22.5, and regression coefficient was R^2 = 0.98.

For passive force with workpiece heating data, mean value is $\bar{x}$ = 350.7, standard deviation is SD = 23.5, signal to noise ratio is S/N = 25.9, and regression coefficient is R^2 = 0.97. Based on calculated statistical parameters, there was concluded that previous presented linear models are adequate.

Based on analysed data and model responses can be concluded that depth of cut and feed rate have high influence on cutting force components. As the values of these two parameters increase the values of the forces increase. Cutting speed has relative lower influence on cutting force component. Influence of cutting speed is often neglected in cutting force components models. In most cases, with increasing cutting speed, there is a decrease in cutting forces components. In the case of turning assisted by heating the workpiece, the cutting speed has a greater impact, especially in its interaction with the feed rate. The reason for this can be time and position of the heating flame action point. With higher speeds and steps, the workpiece heats up less.

CONCLUSIONS

From other research in this field, can be concluded that hard-to-machining materials are machined by lasers and plasma assisting, but these devices can be expensive and difficult to maintenance. However, laser and plasma have many advantages. In other hand, gas combustion heating devices are much cheaper and available.

Presented research in this paper shows possibility of reducing the cutting forces component in turning, by assisting with gas combustion heating of non-machined workpiece surface. The analysis is showed a significant difference in the values of the cutting forces components. Also, the models have shown that it is possible to adequately describe process and cutting forces. The value of the cutting forces components is significantly reduced. The reduction averages about 50%.

Additionally, the effect of heat on the machined surface was observed. There was poor machined surface, with visible burnt places. These facts could be investigated in future research, where the penetration of heat through the workpiece would be studied. Future research will directed on optimizing the heater head construction regard flame focusing. Examinations of the influence of its position relative to the cutting edge will be performed. Also, an analysis of the processing of different materials will be carried out, using different methods of workpiece heating.

Note:
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