CUTTING TEMPERATURE MEASUREMENT AND MATERIAL MACHINABILITY

by

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Cutting temperature is very important parameter of cutting process. Around 90% of heat generated during cutting process is transferred by sawdust, and the rest is transferred to the tool and work-piece. In this research cutting temperature was measured with artificial thermocouples and metal machinability from aspect of cutting temperature was analyzed. For investigation of material machinability during turning, artificial thermocouple was placed just below the cutting top of insert, and for drilling, thermocouples were placed through screw holes on the face surface. In this way simple, reliable, economic and accurate method for investigation of machinability during cutting is obtained.

Key words: *cutting temperature, drilling, turning, machinability, thermocouple*

Introduction

Metal cutting is a very common type of machining in a metal-cutting industry. It is realized in a very complex environment and until today not completely investigated. Complex geometry of cutting part of the tool and troubles with taking away the sawdust and introducing the cooler and lubricant cause complex temperature phenomena on the cutting part of the tool.

As a consequence of complex tribology phenomena on cutting tools, different types of tool wear occur, which are the basic cause or reduction of tool life. Definition of wear process can be based on direct indicators (changes on the tool or the work-piece) or indirect indicators (change of resistance and cutting temperature, change in surface topography and machining accuracy)

Many physical and chemical reactions that are developed during the cutting process are directly connected with the tool wear and with the cutting temperature. Well known rules of derivation and distribution of thermal energy during metal cutting significantly helps in solving many problems that occur during the cutting process and points to procedures for improving the cutting ability of tool, for optimal machining regime, as well as for improvement of quality and of accuracy.

This paper deals with application of appropriate temperature measurement method in areas close to the cutting zone and setting up of the reliable measuring chain in order to collect data that is necessary for investigation of material machinability. Developed model can also serve for development of adaptive methods of control for turning process, on the cutting temperature basis.

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Influence of the cutting temperature on machining effects

Heat phenomena occurring both in narrow and broad area of cutting zone, are directly related to the wear rate of tool, to the machinability of work-piece material, to the tool stability and to many other characteristics of the machining process. Almost all work of cutting forces is turned into the thermal energy, as experimental investigations show. Generated heat goes from the cutting zone into the chips, tool, work-piece and into the environment, causing decrease of hardness of tool's cutting elements, cutting wedge deformations, loss of tool cutting ability and its bluntness.

Generated heat distribution in work-piece, in tool and in chips, i.e. the temperature level at working elements of tool at processed surface and at chips depends on: work-piece material (its mechanical and chemical characteristics), cutting speed, feed rate, depth of cut, tool geometry, lubricants type and other relevant parameters.

Beside the influence on tool wear, heat generated in the cutting process has influence on: the machining process productiveness, processed surface quality, accuracy of machining and other output parameters of the machining process. Due to this, the investigation, measurement and knowledge of levels and distributions of the cutting temperature within the tool and work-piece are of the utmost importance. Optimum conditions, working regimes, quality, productiveness and economy of process and tool stability can be determined on basis of this knowledge.

Measuring of cutting temperature

The experimental works have been using many techniques to determine the temperature distribution in the cutting domain as new improvements in instrumentation have been developed. The nature of machining conditions, new cutting tools materials and products, such as small dimensions, high speeds and large temperature gradients, have been challenging the experimental works to develop certain instrumentation for accurate temperature measurement in the cutting domain. Among the widely applied techniques for temperature measurement followings can be listed: thermo-couple with tool–chip pair or embedded, infrared radiation, thermo-sensitive painting, metallographic with metal microstructure or microhardness variation, temper color and thermal camera. Each technique has its own advantages and limitations depending on the applied physical phenomena for measuring [19, 20, 21]. New attempts are in progress to enable accurate measurement of temperature field over the cutting domain. The experiments have been providing thermal map of the cutting zone and supportive data for all the analytical and numerical works [1, 2, 11].

The measurement of temperature in metal cutting processes has an extremely long history which is summarized in Figure 1, [19]. The voluminous body of publications is categorized by the metal cutting process and temperature measurement method.

Figure 1 shows that the number of measurement methods is increasing rapidly and that most methods were first introduced in processes having a single cutting edge, with the measurement device affixed to the tool. Some methods such as film thermography have been replaced entirely by more modern solid state sensors, while other methods, such as the thermocouple, have remained in continuous use for nearly a century.

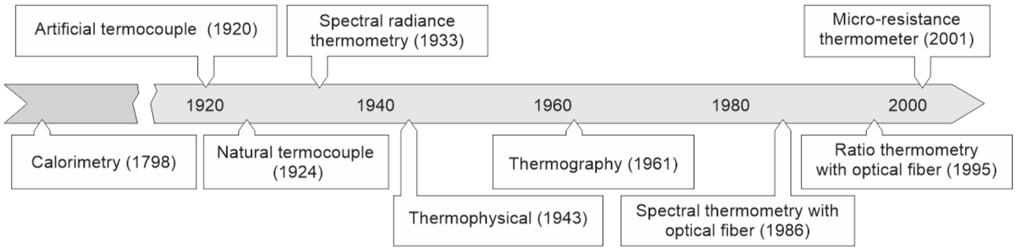

Figure 1. Historical evolution of temperature measurements in metal cutting processes

Natural or dinamic thermocouple. Temperature measurement using natural thermocouple (tool-work thermocouple) is based on the phenomenon that two metals in contact produce small voltage and change of this voltage is proportional to the change of temperature. If these two metals are tool and work-piece, after calibration the temperature on border surface between tool and work-piece can be measured. Basic limitations of this method are that tool and work-piece have to be isolated from the machine; coolers and lubricants cannot be used; if deposits are made method is inaccurate, calibration is necessary for every change in machining conditions; [1, 23, 26].

Artificial or embedded thermocouple. Previously formed thermocouples from special materials are inserted into places near cutting zone. It is accomplished by drilling a hole in the work-piece [5. 6, 14, 18, 29] or the tool [3, 4, 8, 9, 10, 12, 15, 22, 24, 28] in one or more spots at the same time or placing the top of thermocouple on the outer surface of tool. Measurement accuracy depends mostly on the distance of measuring point to the cutting zone.

Values of maximum cutting temperature measured with natural thermocouple are up to 600^{o}C [23, 26]. With application of artificial thermocouples placed in the work-piece, temperatures are about 45^{o}C for drilling of aluminium, [18], from 70^{o}C [29] to 300^{o}C [5] for milling and up to 500^{o}C for drilling [14].

Cutting temperatures with application of artificial thermocouples placed in specially drilled holes in cutting plates were up to 900^{o}C [24, 28]. Placing artificial thermocouples in special holes and grooves at drills, Figure 2, produced maximum measured temperatures of 230^{o}C, [32], up to 650^{o}C, [22], and for the mills 160^{o}C, [22].

Methods based on radiation, used for measuring temperature in one spot - *infrared pyrometer*, and for measuring temperature of a surface - *infrared thermography*. These methods are non-contact methods with a range of advantages over previously described contact methods. Basic disadvantage is the possibility for chips to cover the surface where temperature is measured or to damage measuring equipment. Also, it is difficult to know the exact value of emission coefficient of the surface which temperature is measured, [7, 10, 11, 13, 16, 17, 27, 30, 31, 33]. Measured values of temperature are from 320^{o}C, [17], to 900^{o}C, [27, 33], for scraping and up to 450^{o}C for milling, [16].

In order to investigate material machinability appropriate measuring systems for measuring temperature in points very close to cutting zone are located. Measurement of the cutting forces and temperature at lathe (by artificial thermocouple) is solved according to the measuring chain shown in Figure 2.

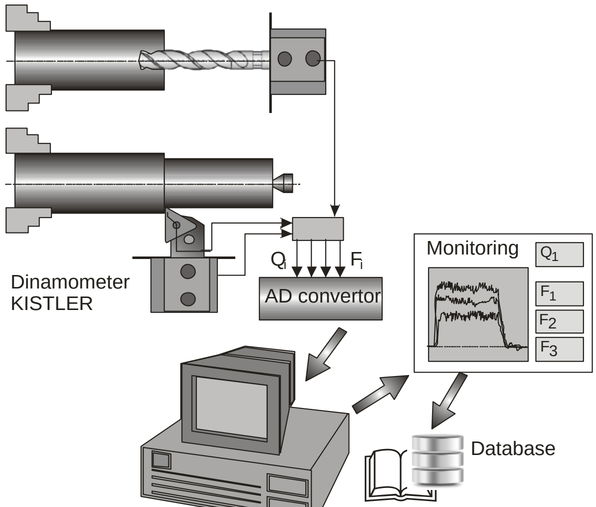

Figure 2. Measuring chain for measurement of the cutting forces and temperature

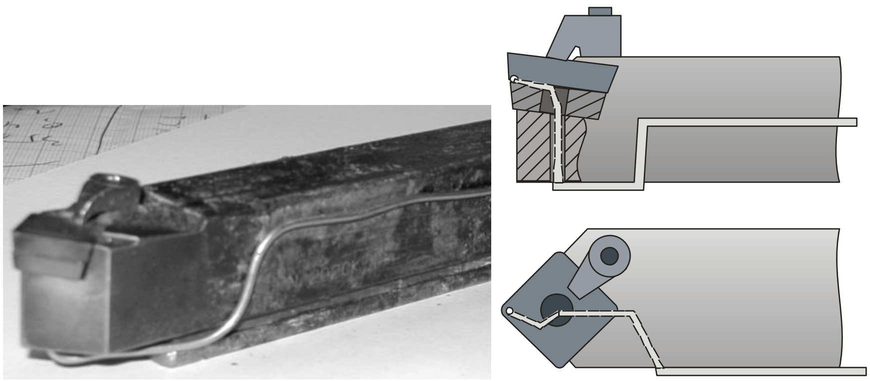

Figure 3. Position and measuring spot for artificial thermocouple at turning tools

For turning, specially formed artificial thermocouple was placed between shim and insert on the spot below cutting zone. Turning tool has had the holder mark CSDNR 2020K12 and changeable insert SPMX 12T3AP-75. For investigations the coated insert with TiN, TiAlN, TiZrN and ZrN were used. In Figure 3 position of the measuring point and method of thermocouple placement is presented, using the shim groove in which thermocouple was placed obtained by grinding.

For drilling using lathe, in order to measure the cutting temperature, two specially formed thermocouples were placed through screw holes with 2,5 mm diameter, on drill with 18 mm diameter, according to Figure 4. Relatively large tool diameter and small steps enabled similar conditions for drilling at lathe as with a drill. Special thermocouples were formed with thermo elements of type 2 AB AC 15 from series „Termocoax" made by „PHILIPS". Thermocouple elements were wires from NiCr(+) and Ni(-). Thermocouples were previously calibrated. During measurement, the dynamometer KISTLER-9441 (Figure 2) with appropriate amplifier was used for tool carrier.

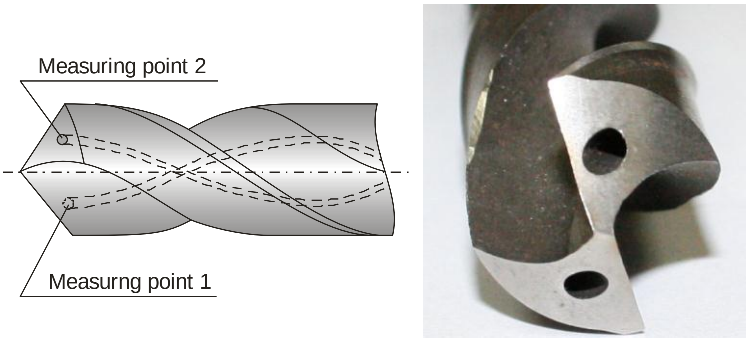

Figure 4. Position and measuring spot for artificial thermocouple at drills

Experiments were conducted with universal lathe, of 10 kW power, in the Laboratory for metal cutting, Faculty of Engineering Sciences, University of Kragujevac.

Measurement errors are reduced to minimum because all measurements were conducted with one tool without moving or replacement of thermocouple or cutting plate. After each measurement a break was taken so the temperature of tool, work-piece and thermocouple environment can be restored to start value of the environment, 20^{o}C.

Measuring results

Experimental investigations for turning were conducted in following conditions

- Cutting speed: v = 70÷150 m/min,
- Feed rate f = 0.14; 0.2 and 0.25 mm/rev,
- Depth of cut a = 0.5 and 0.7 mm.
- Work-piece material:
  - DIN 25CrMo4 steel in the quenched and tempered state of 273-300 HB hardness (semi-lining),
  - DIN 34CrMo4 steel in the quenched and tempered state of 230-280 HB hardness (axle shaft),
  - DIN 18CrNi8 steel isothermally annealed of 120 HB hardness (forging),
- Type of coating: TiN, TiAl, TiZrN, ZrN.

Experimental investigations for drilling were conducted in following conditions

- Cutting speed: v = 15,8 ÷ 25,4 m/min
- Feed rate: f = 0,05 mm/rev
- Hole depth: L = 18 mm, (L=D)
- Work-piece material:
  - DIN 9SMn28, annealed, 148 HB,
  - DIN 22CrMoS3-5, annealed, 166 HB,
  - DIN 36CrNiMo4, annealed, 190 HB.

Some of the results obtained are given in Figures 5, 6 and 7. Influence of the work-piece material on the temperature measurement is presented in Figure 5 and 7, and the influence of the tool with coating type is presented in Figure 6.

Figure 8 shows the influence of the tool with coating type and cutting speed on the temperature in the case of turning and Fig. 9 shows the influence of the materials work-pieces type and cutting speed on the temperature in the case of drilling.

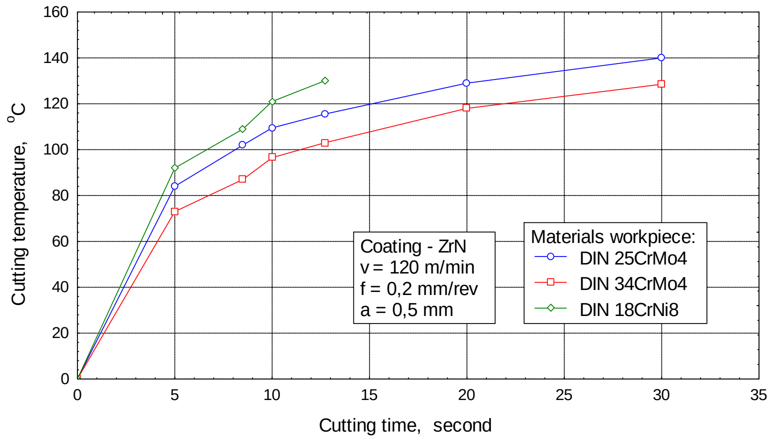

Figure 5. Influence of the work-piece material type on the temperature - turning

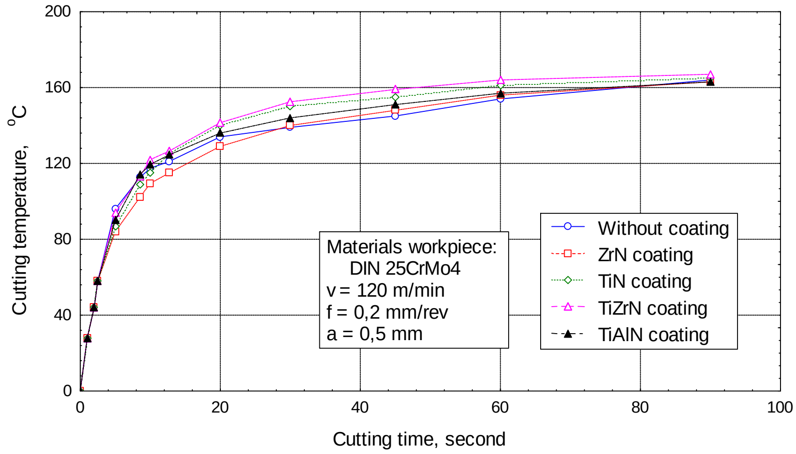

Figure 6. Influence of the tool with coating type on the temperature– turning

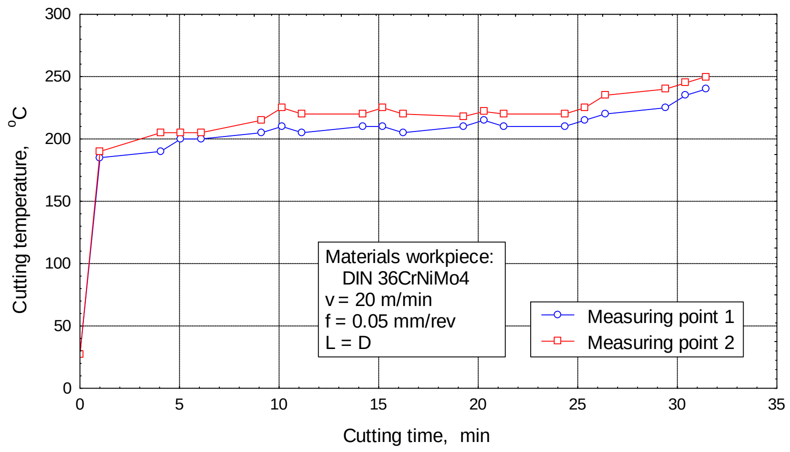

Figure 7. Variation of the temperature measured during the processing time - drilling

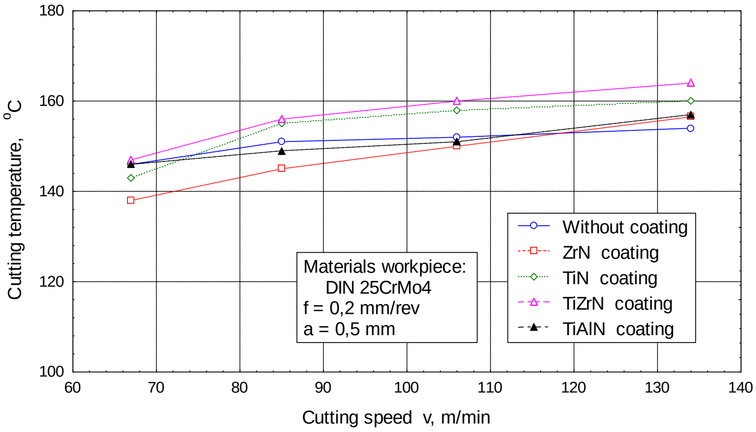

Figure 8. Influence of the tool with coating type and cutting speed on the temperature - turning

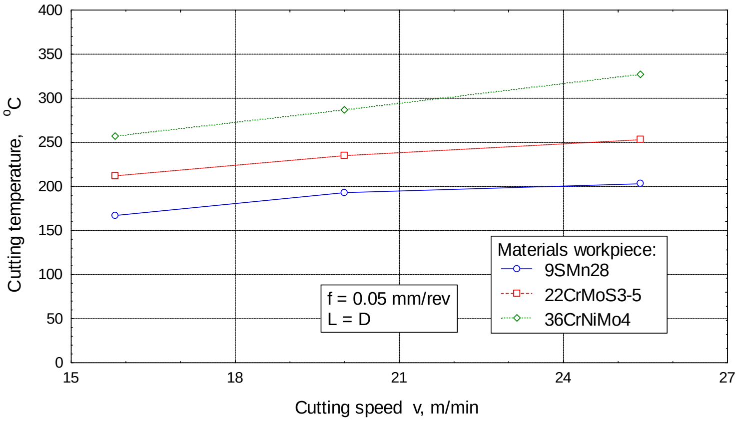

Figure 9. Influence of the materials work-pieces type and cutting speed on the temperature - drilling

Machinability index

Without entering the problems of origination and development of the wear process, it can be assumed that by knowing values of the cutting temperature and its dependence from machining conditions and with other relevant parameters, machinability index for certain material can be determined with satisfying accuracy, [1, 3, 4, 32]. Machinability index (or coefficient) is determined from the following equation

$$I_o = \frac{\theta_{ref}}{\theta_i} \cdot 100\%$$

where: θ_{ref} - temperature of the referent material (etalon), θ_i - temperature of the investigated material.

For determining of the machinability index for the work-piece material, results obtained during machining of various materials with cutting bits with various coatings were sorted. With referent material being the material of the semi-lining, the machinability index is easy obtained by the previously defined equation. The machinability index for materials and tools investigated is given in Figure 10 and Figure 11 after 20 seconds machining.

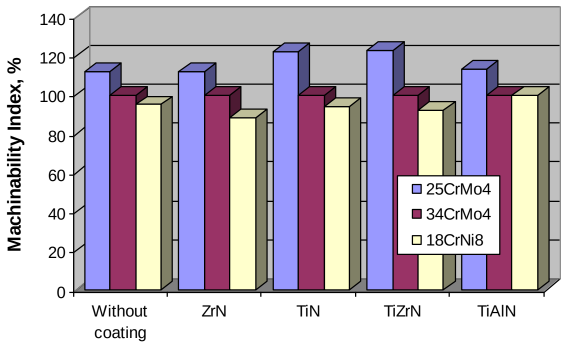

Figure 10. Machinability index for materials and tool – turning (v=120 m/min, f=0,2 mm/rev, a=0,5 mm)

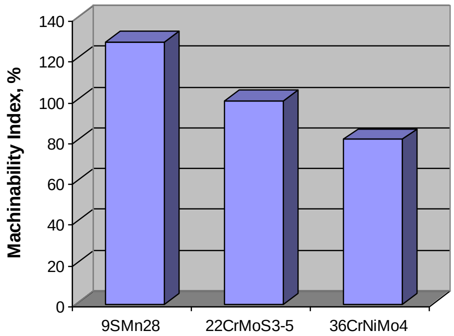

Figure 11. Machinability index for materials – drilling (v=20 m/min, f=0,05 mm/rev, L=D)

Conclusions

Investigation presented in this paper is the part of extensive research with aim to develop method of cutting temperature measurement using artificial thermocouples and to form a data base of material machinability from aspect of cutting temperature.

Based on the results following conclusions can be made:

- Methods developed for measuring cutting temperature during turning using thermocouple placed on the surface of shim just below insert and method for measuring cutting temperature during drilling on lathe using thermocouple placed through special screw holes in cutting zone are simple, accurate, reliable, economic and sensitive.
- These methods enable investigation of influence of technological parameters (machining regime, tool material, cutting geometry etc.) on cutting temperature.
- Using developed method machinability of work-piece materials can be compared,
- Although results show that it is necessary to do extensive research to make general conclusions, obtained measurements confirm previous conclusions about dependence between machining regime and temperature.
- Results enable appropriate choice of coating on insert for every of investigated operations (work-piece material), from aspect of cutting temperature.
- Investigations are preliminary and present solid ground for further development of adaptive process management models.
- Application of developed method for temperature measurement created the conditions for development of the model for adaptive process management.
- Further investigations of cutting process from friction coefficient aspect of work-pieces material and cutting tool, cutting temperature, cutting force, tool wear etc., should enable explanation of measured differences in cutting temperatures and differences in material machinability.

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