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PERFORMANCE OF ENVIRONMENTALLY FRIENDLY MACHINING USING COMPRESSED COLD AIR COOLING: FOCUSING ON PROCESS LEVEL ACTIVITIES AND IMPROVEMENTS

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ABSTRACT
Actual research and development in machining processes are focused on improvement of machining performances through higher productivity, tool life and surface quality. One approach to enhance machining performance is to apply cutting fluids during the cutting process. However, due to negative impact on machining process sustainability, researchers have been urged to search for some alternatives to minimize use of cutting fluids. Concept of environmentally friendly machining is offered as the solution of this problem. A suitable strategy of environmentally friendly machining needs to minimize or even eliminate usage of cutting fluids, minimize energy consumption and cutting tools. The way to sustainable machining process through environmentally friendly machining must start from the process level. It begins from the steps that must be taken to implement ecological machining methods in order to make these alternative technologies reliable, environmentally friendly and cost efficient. This paper focuses on an experimental investigation into the role of environmentally friendly machining on energy/power consumptions, tool life, and surface roughness, in the machining of steel 42CrMo4. A comparative study of milling experiments, under dry, compressed cold air cooling and wet cutting conditions was conducted using the same machining parameter set-up. The results of the conducted investigation have shown high efficiency of the developed compressed cold air technological system of environmentally friendly machining not only in comparison with dry machining, but also in comparison with traditional technologies using cutting fluids. Finally, capabilities and advantages of environmentally friendly machining using compressed cold air were reviewed and discussed.
Keywords: Environmentally friendly machining, Cutting environment, Vortex tube, Cutting energy, Tool life, Surface roughness

1. INTRODUCTION
Sustainable manufacturing is relatively less-known and significantly element of sustainable development, including three functional elements: sustainable products, processes, and systems [1]. The manufacturing process must exceed beyond their traditional requirements of functionality, cost, performance, and time-to-market, by considering also sustainability. The goal of the sustainable manufacturing from process point of view is to develop new technologies for transforming materials with objectives of reducing of energy consumption, avoiding use of non-renewable or toxic materials and avoiding generation of waste [2].
Machining processes make about 60% to 80% of the total manufacturing and represent the most often used metal processing in manufacturing [3]. During machining the choice of accompanying machining parameters depends on requirements such as geometry of workpiece, accuracy of dimensions and forms and quality of machined surface. Higher values of the cutting parameters offer the possibility to achieve higher productivity, but at the same time present a risk of deterioration surface quality and tool life. In traditional machining, cutting fluids (CFs) are commonly used during

the machining of metals. More attention directed to negative effects of CFs such as total cost of using CFs, as well as health and environmental issues, mandate manufacturing enterprises to drastically reduce coolant consumption and, if possible, eliminate it altogether [4].

2. ENVIRONMENTALLY FRIENDLY MACHINING

Modern trends tend to a shift to dry machining (DM) by which the conditions of environmental and social acceptability would be automatically fulfilled [5]. One of several ways of DM is compressed cold air cooling (CCAC) using vortex tube. As in this technique the cooling media is air, it could be defined as the cleanest and most environmentally friendly method of cooling in cutting operations.
The way to sustainable machining process through environmentally friendly machining must start from the process level. It begins from the steps that must be taken to implement ecological machining methods in order to make these alternative technologies reliable, environmentally friendly and cost efficient. Many elements and aspects of machining process have important implications on sustainability of the same, for this, the whole process and all aspects end elements involved have to be considered, Figure 1.

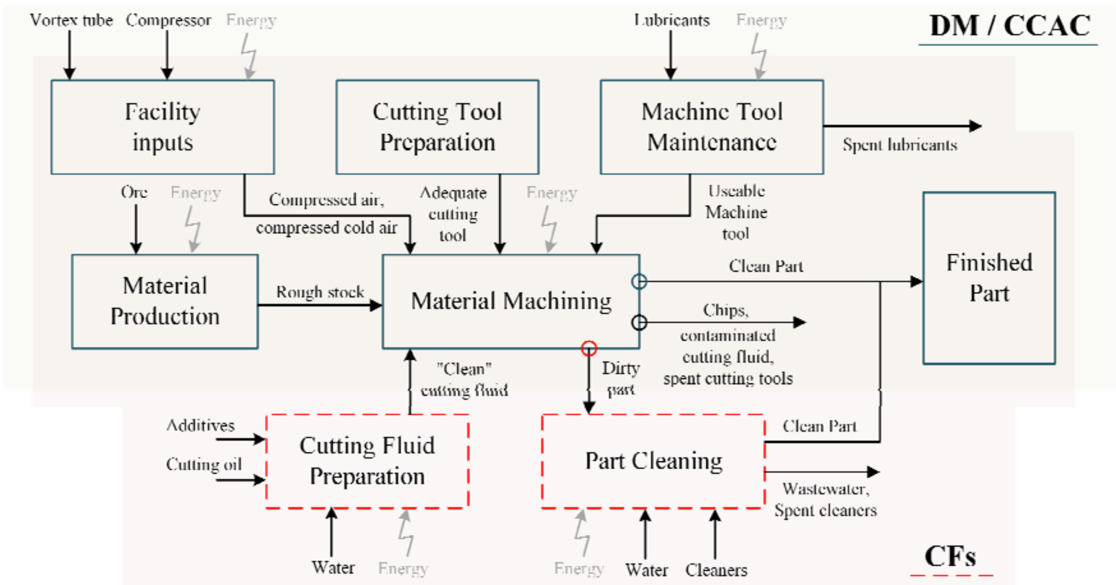

Figure 1. Comprehensive system view of process level activities for different machining conditions

A proper strategy of environmentally friendly machining needs to minimize energy, cutting fluid, and cutting tools [6]

2.1. Cost-effectiveness of machining in different cutting environments

Machining industry in a globalized and turbulent competitive environment faces rising economic cost pressures. Many optimization potentials concerning efficiency improvements of value adding production processes have already been raised in the past. Thus, cost reductions by optimizations of non-direct value adding processes in production are getting focused in recent times [9]. For example, the percentage of manufacturing sector of the total consumption of electricity in Germany of 519 TWh was about 47%. Studies have shown that around 12,5% of manufacturing sector consumption is caused by the installed metal cutting machine tools. In the field of metal cutting, up to 60% of the energy consumption is needed for the supply and reprocessing of CFs. Such a high percentage presents a serious problem due to the continuing trend of growth in energy prices. For this reason it is very important to determine the real energy/power consumptions of different types of cooling/lubricating techniques. Respectively, any increase in energy consumption for some cooling/lubricating technique has to be justified with some certainly improvement of machining process, such as longer tool life, lower workpiece surface roughness, etc.
Before experimental investigation detailed energy consumption of used equipment for different machining conditions was made, Figure 2. Energy consumption measurement while machining in the

presence of CFs confirmed theoretical research about machine tool power consumption, in this case even 140% higher than the same in DM and in fact CCAC. The higher compressor energy consumption of CCAC is evident due to need for supply of compressed air for operating Vortex tube.

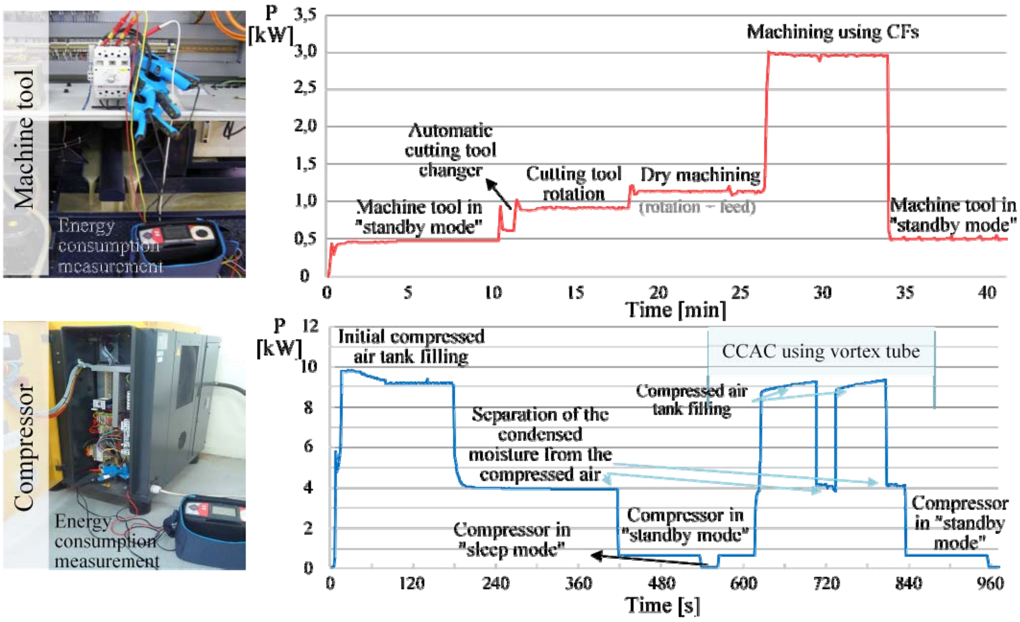

Figure 2. Energy consumption diagram of machine tool SPINNER VC 560 and KAESER SX6 T compressor (preparation and delivery of compressed air) in different machining conditions and phases

3. EXPERIMENTAL SETUP

Experimental investigations were carried out at the Machine tool laboratory (Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split). The type of machine used for the milling test was machining center VC 560 manufactured by Spinner, with added Vortec cooling system Cold Air Gun 610BSP. Cold air gun consumes 425 l/min (at 6,9 bar) of air. The temperature of compressed cold air was -2°C. Test sample used in experiment were made of steel 42CrMo4 with dimensions 110x150x30 mm. The end milling experiments, 30 for each cutting condition (DM, CCAC, and CFs), were executed by a tool CoroMill 390 with three TiN coated inserts, produced by Sandvik. Average surface roughness Ra of machined workpieces was measured by a Surftest SJ-301, produced by Mitutoyo.

4. ANALYSIS OF RESULTS AND CONCLUSIONS

Analysis of results has shown that regarding surface roughness, the best results were achieved with application of CCAC, reaching a minimum value of average surface roughness, and also minimum median value, Figure 3.

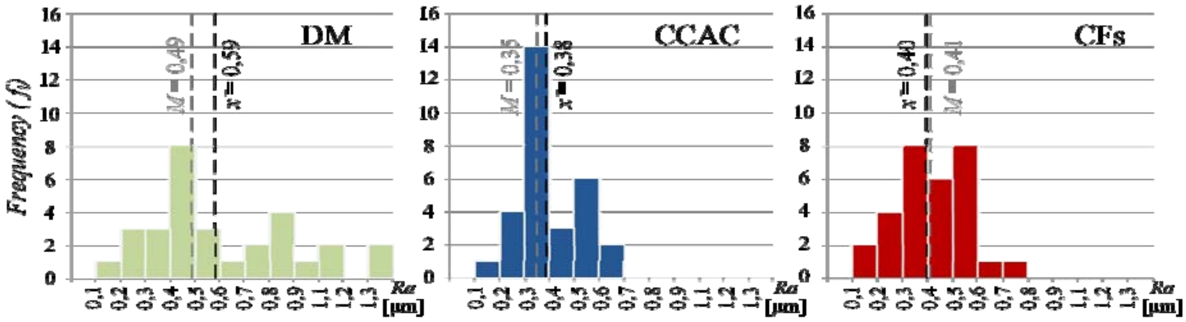

Figure 3. Frequency of the measured values of surface roughness in different cutting conditions

The relationship between the tool wear and volume of the removed material under different machining conditions is shown in Figure 4. It can be seen that changes in tool wear such as crater wear on rake face (e.g. Experiment 2, CFs), and excessive flank wear (e.g. Experiment 4, DM) are less likely to occur during machining in condition of CCAC.

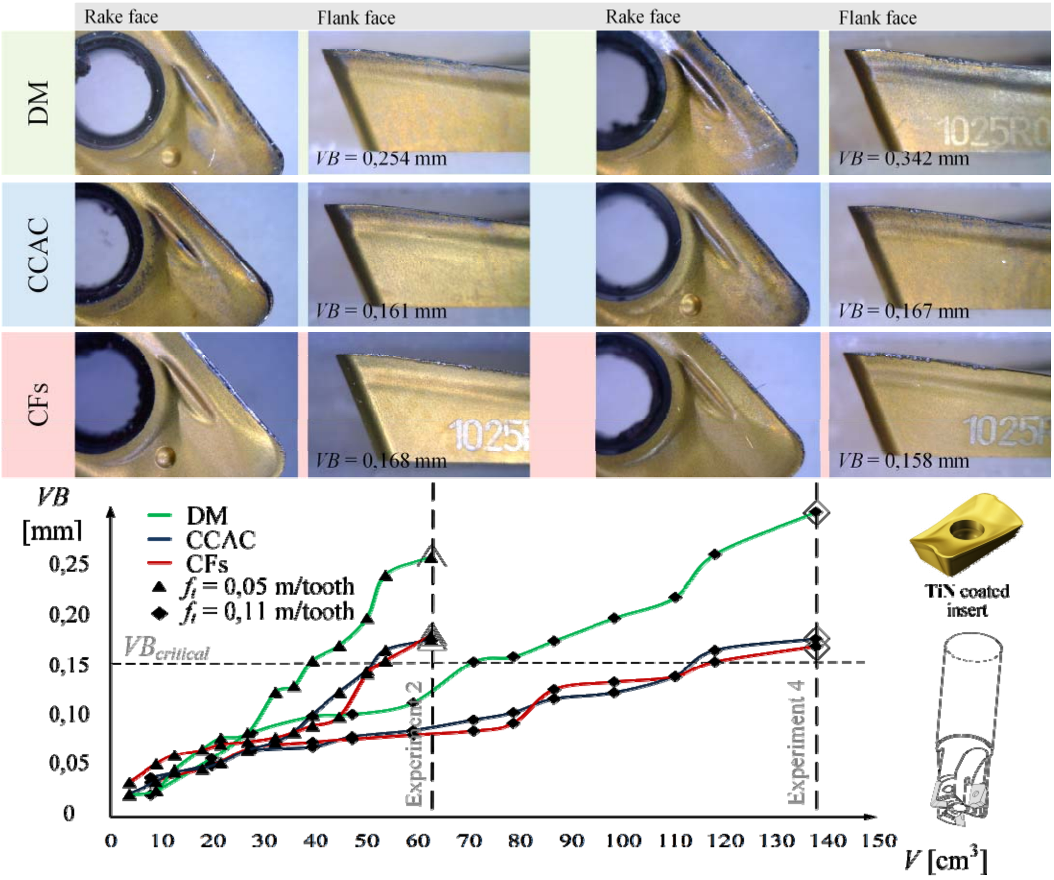

Figure 4. Tool wear progression with volume of the removed material for different machining environments (v_c = 150 m/min, a_p = 5 mm, a_e = 1 mm, $t_{machining}$ = 35 min)

The results of the conducted research have shown high efficiency of the CCAC system in contest of environmentally friendly machining not only in comparison with DM, but also in comparison with traditional machining using CFs. Despite higher energy consumption, the advantages of CCAC are multiple, especially observed from process level activities and improvements, such as:

- longer tool life, and consequently lover surface roughness,
- non-existence of any harmful effect on humans and the environment,
- easier recycling of a chip which is not polluted by CFs,
- avoidance of degreasing of workpiece upon finishing of machining.

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