Cooling systems based on cold compressed air: a review of the applications in machining processes

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Abstract

The present work collects a review and analysis of the cooling systems based on cold compressed air along with the main works about the application of such type of systems in machining processes. From the analysis of such works, it is possible to conclude that the cold compressed air system is a real environmentally friendly alternative to the traditional lubrication/cooling systems since it can: reduce the friction and the temperature in the cutting zone, improve the surface finish of the pieces, reduce the cutting forces, increase the tool life, facilitate the chip breaking and its evacuation, and reduce production costs. Among cold compressed air systems, it is possible to remark those that use a vortex tube due to its numerous advantages and good results.

Keywords: lubrication and cooling systems; cold compressed air; machining processes; vortex tube

1. Introduction

The friction and the temperature reached during the machining processes have been traditionally reduced by means of cutting fluids [1]. In addition, they have other advantages as, for example: to remove the chips from the tool rake, to limit chemical diffusion, to reduce the tool wear and to protect the surface of the machined pieces from corrosion.

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However, the use of cutting fluids involves some drawbacks such as their high costs, the risk to worker’s health and environmental concerns. These drawbacks make necessary to develop and to apply new lubrication/cooling systems as an alternative to the traditional methods.

Among these new lubrication/cooling systems (Figure 1), it is possible to name: dry machining, minimum quantity lubrication, cryogenic refrigeration, solid lubricants and gaseous refrigeration [2].

Fig. 1. Main lubrication/cooling systems as alternative to the traditional methods [2].

In this work, the gaseous refrigeration systems are analysed. Namely, the cooling systems based on cold compressed air. The main reason is the next one. Although these systems are not commonly used in manufacturing industry, commercial cold compressed air systems exist and they have become into a new and effective technique that allows: to reduce friction and heat in the cutting zone, to reduce the flank wear at high cutting speeds, to reduce the surface roughness and to increase the tool life during turning, milling and drilling processes carried out on hard-to-machining materials, as well as, to break the chip [3].

The present work collects a comparative review and analysis of the cooling system based on cold compressed air along with the main works about the application of such type of systems in machining processes [3-6].

2. Cooling systems based on cold compressed air

The cooling systems based on cold compressed air are included into the gaseous refrigerant group (Figure 1) and represent an alternative to the lubrication/cooling conventional systems. The main gases used in these systems are: air, water vapor, carbon dioxide, oxygen and nitrogen. Among them, the reduced cost and the low environmental impact that air and water vapor possess in relation to the others, make them particularly suitable to be used [4][7,8]. However, in assessing the penetration capability of the used gas in the area of contact between the tool and the workpiece, organic compounds, as ethanol or tetrachloromethane, have demonstrated to be very effective as well [9].

The properties of gaseous refrigerants as coolants, lubricants and chip eliminators are lower than those given by the oils and emulsions, considering that provide low cooling capacity and chip removal, and no lubricating ability [8-10]. To improve the cooling properties of gases can use different strategies, such as: compression, cooling or liquefaction [11].

Focusing attention on the use of air as a coolant, it can be found the next two alternatives: compressed air system and cold compressed air system. The compressed air system consists on using a compressor to compress the air that is dried and supplied through a nozzle in the cutting zone like it is shown in Figure 2 [5].
In cold compressed air systems, the air, once compressed, is cooled to decrease the temperature and to increase, in this way, its cooling capacity (Figure 3). This can be done by various means such as using liquid nitrogen, the vapor-compression refrigeration, the cooling by adiabatic expansion or cooling the air by a vortex tube. This technique achieves temperatures in the cutting zone much lower than those obtained by dry machining. This makes that: cutting forces, particularly the force along the feed, are, also, significantly lower; the chips and their thicknesses are smaller; and the tool life increases, due to the less wear that is produced on it [3][5,6].

Among cold compressed air systems, it is possible to remark the cooling of the air by means of a vortex tube. The vortex tube (Figure 4), also known as the Ranque-Hilsch vortex tube, is a mechanical device used in the industry for generating streams of hot and cold gas from a single source of compressed gas. This device is very efficient in the separation of air streams at different temperatures and it has been the focus of investigations since its development; specially, in the field of the machining processes [11-14]. Besides, the purchasing of a vortex tube system is around 500 €-1000 €; which means is very affordable for small-medium manufacturing companies.
The specific heat of the air is about a quarter part of the specific heat of water. So, the heat capacity of air is smaller than the heat capacity of water and, for this reason, water is able to absorb more heat in comparison with air. However, the air is shown as an efficient fluid for cooling at high working pressures because at these working conditions, its convection coefficient greatly increases. Due to this, the application of this device in machining processes as an alternative cooling system to the traditional flood systems is being investigated in the last years. These researches have provided, among other more specific conclusions, that the cooling system with cold compressed air significantly reduces the heat generated in the cutting zone when it is compared with a dry cutting process and slightly less when it is compared with the cooling by flood [4]; is able to extend the life of the cutting tool; and has a high environmental efficiency [11].

3. Experimental researches

Next, some of the major works found in the literature on machining processes that use cold compressed air are going to be described. They have been grouped by type of material used in the tests.

3.1. Stainless Steel

Su and his team conducted a comparative study of three cooling systems (dry machining, minimum quantity of lubricant and cold compressed air) in a process of high speed milling using stainless steel. They obtained, as main conclusion, that the cooling system cold compressed air was able to extend the tool life up 130% versus the dry machining and it was slightly better versus the system of minimum quantity lubricant (MQL). In addition, the cold compressed air considerably favors obtaining good surface roughness values [6].

3.2. Nickel-base alloys

Su and his collaborators, in a similar study to the described previously but using Inconel 718, concluded that cold compressed air system has a high cooling speed, a high answer speed and an excellent capacity of controlling temperature. Besides, tool life significantly improved versus dry machining or the MQL system. In particular, versus the dry machining until a 78% [6].

3.3. Cast iron

Sarma and his collaborators compared the results obtained turning cast iron workpieces under dry conditions and using cold compressed air. They observed that with this system, advantages were no found working at low cutting speeds (100 m/min) but, at high cutting speeds (exceeding 400 m/min) the tool wear was significantly reduced and the surface finish improved. In addition, the cutting forces were lower in all cases. Therefore, compressed air system without cooling seems to be a good alternative for machining high-speed, at least, for turning cast iron [5].

3.4. Aluminium alloy

Liu and his team made tests with workpieces made up of aluminium alloys and they observed that the cold compressed air system reduces until a 7% the temperature in the cutting zone compared to dry machining. In addition, cooling efficiency decreases with increasing cutting speed and feed, and increases with the airflow in the vortex tube. On the other hand, the tool life increases more when temperature diminishes than when the airflow increases. For this type of materials, the most effective cutting conditions seem to be a high cutting speed and a low feed [13].

3.5. Titanium alloy

Titanium alloys have low machinability, mainly, due to: a) their poor thermal properties hindering the dissipation
of heat generated in the machining process and turn into high temperatures in the cutting zone that accelerate the tool wear; b) an effective contact area, between the chip and the tool, very small makes mechanical loads are concentrated there and the tool life decreases; c) a low modulus of elasticity which results in a damaging vibration to the workpiece and the tool; d) high chemical reactivity at elevated temperatures with most materials used to manufacture cutting tools which causes a premature tool wear by diffusion; and e) the formation of the segmented chip that produces thermo-mechanical cyclic stresses that cause rapid deterioration of the tool.

For these reasons, in recent years, titanium has been the subject of multiple studies about tool materials [15-20], temperature distribution [21,22] and cooling systems [3].

Sun and his team used a flow of cryogenic cold compressed air system. They observed that with that system is possible: to reduce chip thickness; to change from regulate segmented chip to irregular segmented chip; to diminish tool wear; to reduce friction between tool and chip; to increase tool life; and to improve surface roughness [3].

4. Conclusions

The present paper shows the cold compressed air system as an alternative to the traditionally lubrication/cooling systems used in machining processes. Some of the most remarkable experimental works have been shown as examples of application. From the analysis of such works, it is possible to conclude that the cold compressed air system:

- Reduces the friction and the temperature in the cutting zone and, with this, improves the surface finish of the pieces and increases the productivity (because the number of parts that pass quality control is major).
- Reduces the cutting forces.
- Increases the tool life since the wear on the nose tool diminishes.
- Facilitates the chip breaking and its evacuation.
- Reduces production costs because air is easy to obtain and use. In addition, with this system, the decontamination of the cutting fluids is not necessary.

Among cold compressed air systems, it is possible to remark those that use a vortex tube due to they have, in addition to the advantages shown before, the following ones. They have an instant answer of cooling and a low cost. They are easy to install, do not need maintenance or electricity. Besides, they are systems more ecological, safer for the operators and provide better results in front of conventional cooling systems.

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References

[1] E.M. Rubio, M. Villeta, D. Carou, A. Saá, Comparative analysis of sustainable cooling systems in intermittent turning of magnesium pieces, Int. J. Precis. Eng. Man. 15(5)(2014), 929-940.
[2] D. Carou, E.M Rubio, J.P. Davim, A note on the use of the minimum quantity lubrication (MQL) system in turning, Ind. Lubr. Trib. 67(3) (2015), 256-261.
[3] S. Sun, M. Brandt, M.S. Dargusch, Machining Ti-6Al-4V alloy with cryogenic compressed air cooling, Int. J. Mach. Tool Manu. 50 (2010), 933-942.
[4] V.S. Sharma, M. Dogra, N.M. Suri, Cooling techniques for improved productivity in turning, Int. J. Mach. Tool Manu. 49 (2009), 435–453.
[5] D.K. Sarma, U.S. Dixit, A comparison of dry and air-cooled turning of grey cast iron with mixed oxide ceramic tool, J. Mater. Process. Tech. 190 (2007), 160-172.
[6] Y. Su, N. He, L. Li, A. Iqbal, M.H. Xiao, S. Xu, B.G. Qui, Refrigerated cooling air cutting of difficult-to-cut materials, Int. J. Mach. Tool Manu. 47 (2007), 927-933.
[7] O. Çakır, M. Kıyak, E. Altan, Comparison of gases applications to wet and dry cuttings in turning, J. Mater. Process. Tech. 153–154 (2004), 35-41.
[8] D. Carou, Estudio experimental para determinar la influencia de la refrigeración/lubricación en la rugosidad superficial en el torneado intermitente a baja velocidad de piezas de magnesio, Tesis Doctoral, UNED, Madrid, 2013
[9] W.Y.H. Liew, I.M. Hutchings, J.A. Williams, Friction and lubrication effects in the machining of aluminium alloys, Tribol. Lett. 5(1998), 117–122.
[10] K. Weinert, I. Inasaki, J.W. Sutherland, T. Wakabayashi, Dry machining and minimum quantity lubrication, CIRP Ann.-Manuf. Techn. 53(2) (2004), 511-537.
[11] A. Shokrani, V. Dhokia, S.T. Newman, Environmentally conscious machining of difficult-to-machine materials with regard to cutting fluids, Int. J. Mach. Tool Manu. 57 (2012), 83–101.
[12] M. Selek, S. Tasdemir, K. Dincer, S. Baskaya, Experimental examination of the cooling performance of Ranque-Hilsch vortex tube on the cutting tool nose point of the turret lathe through infrared thermography method, Int. J. Ref. 34(3) (2011), 807-815.
[13] L. Liu, K. Chou, On temperatures and tool wear in machining hypereutectic Al–Si alloys with vortex-tube cooling, Int. J. Mach. Tool Manu. 47 (2007), 635-645.
[14] B. Yalcın, A.E. Ozgur, M. Koru, The effects of various cooling strategies on surface roughness and tool wear during soft materials milling, Mater Design 30 (2009), 896–899.
[15] C.H. Che-haron, A. Jawaid, The effect of machining on surface integrity of titanium alloy Ti-6% Al-4% V, J. Mater. Process. Tech. 166(1-2) (2006), 188-192.
[16] C.H. Che-haron, Tool life and surface integrity in turning titanium alloy, J. Mater. Process. Tech. 118(1-3) (2001), 231-237.
[17] E.O. Ezugwu, Key improvements in the machining of difficult-to-cut aerospace superalloys, Int. J. Mach. Tool Manu. 45 (12-13) (2005), 1353–1367.
[18] E.O. Ezugwu, Z.M. Wang, Titanium alloys and their machinability-a review, J. Mater. Process. Tech. 68(3) (1997), 262-274.
[19] E.O. Ezugwu, R.B. Da Silva, J. Bonney, A.R. Machado, Evaluation of the performance of CBN tools when turning Ti–6Al–4V alloy with high pressure coolant supplies, Int. J. Mach. Tool Manu. 45(9) (2005), 1009–1014.
[20] H. Safari, S. Sharif, S. Izmana, H. Jafaria, D. Kurniawan, Cutting force and surface roughness characterization in cryogenic high-speed end milling of Ti–6Al–4V ELI, Mater. Manuf. Process. 29(3) (2014), 350-356.
[21] M. Cotterell, G. Byrne, Characterisation of chip formation during orthogonal cutting of titanium alloy Ti-6Al-4V. CIRP Ann.-Manuf. Techn. 1(2) (2008), 81-85.
[22] M. Cotterell, G. Byrne, Dynamics of chip formation during orthogonal cutting of titanium alloy Ti-6A-4V. CIRP Ann.-Manuf. Techn. 57(1) (2008), 93-96.