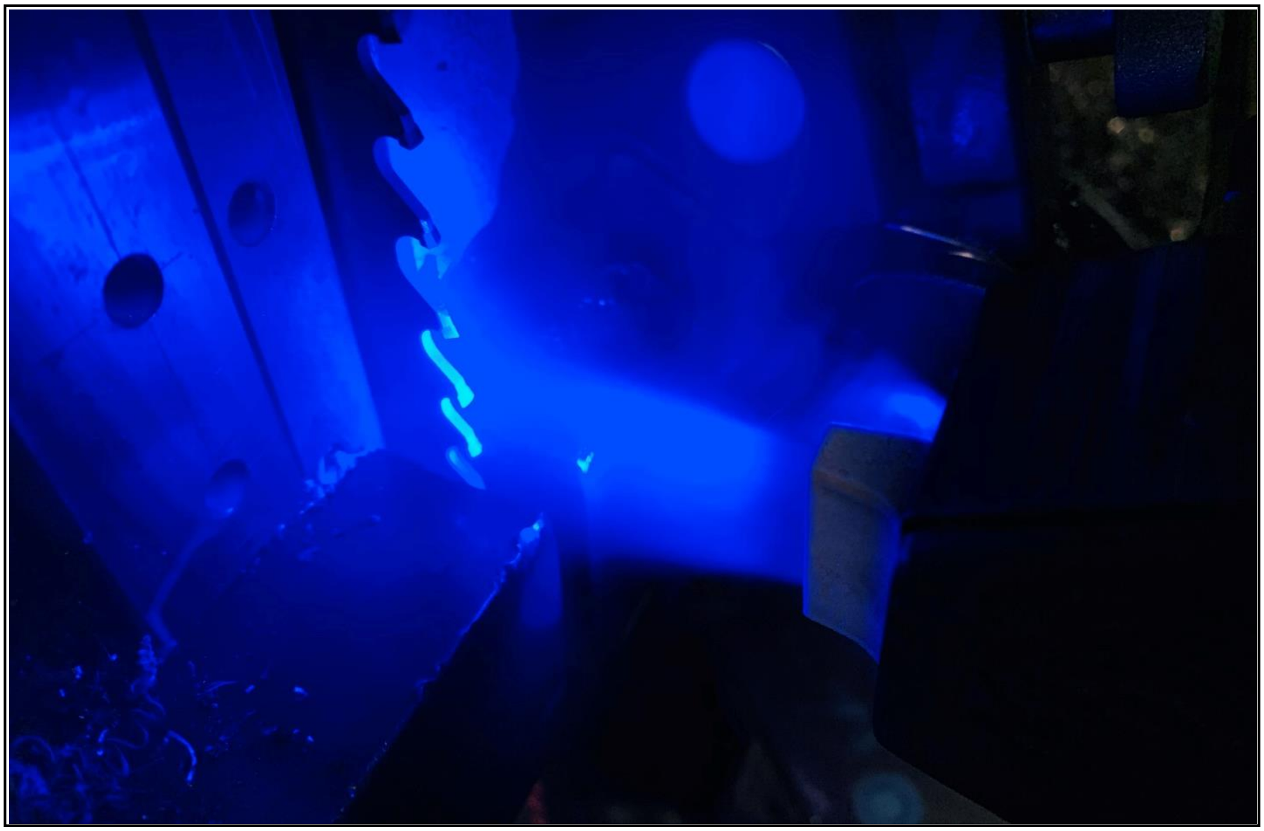
# $CO_2$ - Minimum Quantity Cooling Lubricant for Titanium Machining

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## Abstract

Titanium is a useful metal with various applications in the modern industry. Despite the increased usage and production of titanium, it is expensive when compared to many other metals because of the complexity of its extraction process as well as its machining process. Various lubricants and coolants have been introduced in the market for machining titanium but in this paper a new and unique ecofriendly approach has been discussed where recycled carbon dioxide will be used as the main driving component for cooling and lubricating the titanium. It has a significant impact on increasing the process speed and tool life without any negative impact on the environment.

## Introduction

Titanium is an extremely useful metal with a high strength-weight ratio. The titanium industry has experienced rapid growth in past few decades because of its unique characteristics like exceptional corrosion resistance and strength to weight ratio which is maintained at elevated temperatures. Titanium is a widely used element in aerospace, biomedical, chemical and petrochemical industry. The past century has witnessed significant advancements in cutting machines, cutting tools, machine controls, processing materials, and cooling-lubrication chemistries. However, surprisingly very little has changed with regards to the application of coolants and lubricants during machining – ***the machining atmosphere***. Many machining processes employ a low- or high-pressure flooding spray which is as old as metalworking itself. The flooding process serves several functions – cooling, lubrication, and cleaning (i.e., removing chips, particles, and carbonaceous residues) – and is easily adapted to through-system conduits, spindles, and cutting tools. Countless coolant and lubricant formulations are available for numerous machining applications. However, tradeoffs emerge between optimal lubricity and cooling power, and the need for dry processing. Although flood cooling-lubrication has been a benchmark, it may be good time to consider a change. In the past, flooding was necessary to compensate for excessive heat generated due to the inferior performance of cutting processes, cutting tools, machines, and cooling lubricant chemistries. Mounting evidence in the academic and industry literature indicates the many benefits of newer dry and near-dry cooling lubrication technology.

## Challenges

Titanium is widely used in aerospace, automotive and biomedical industry because of its high specific strength and exceptional corrosion resistance. However, the machinability of titanium alloys is difficult due to low thermal conductivity and elastic modulus, high hardness at elevated temperature, and high chemical reactivity (particularly at the cutting-edge during machining). Table 1 shows some comparative properties of Titanium and medium carbon steel for better understanding. As most titanium alloys are poor thermal conductors, machining heat generated during a cutting operation such as drilling doesn't dissipate quickly into part or tool but concentrates in the cutting zone. During machining, cutting edge temperatures can reach 1000°C, or higher. This leads to cutting edge chipping and deformation, and tool dulling. All of this generates more heat and leads to further reductions in tool life. Moreover, cutting temperatures can get so high that titanium chips can burst into flames. The high temperatures generated during the cutting process also causes a work hardening phenomenon that further impacts machinability and affects the surface integrity of titanium. If not properly controlled, excess machining heat can lead to geometric inaccuracies in the part and a severe reduction in its fatigue strength.

| Material | Tensile Strength MPa | Yield Strength MPa | Elongation % | Reduction in area % | Modulus of elasticity Tension GPa | Hardness Hv | Density g/cm$^3$ | Specific Heat at 20-100°C J/kg K | Thermal Conductivity W/m K |
|---|---|---|---|---|---|---|---|---|---|
| Ti-6A1-4V Annealed bar | 895 | 825 | 10 | 20 | 110 | 340 | 4.43 | 580 | 7.3 |
| Ti-6A1-4V Solution treated aged bar | 1035 | 965 | 8 | 20 | - | 360 | - | - | 7.5 |
| AISI-1045 Cold drawn | 625 | 530 | 12 | 35 | 207 | 179 | 7.84 | 486 | 50.7 |

Table 1 – Properties of Ti-6A1-4V compared to a medium carbon steel[1]

Many scientific researchers and experts claim[2] individually some of the following points as the reasons for the poor machinability of titanium:

1. The high strength is maintained to elevate temperatures that are generated in machining and this opposes the plastic deformation need to form a chip.
2. Titanium's chip is very thin with consequently an unusually small contact area with the tool is observed (one-third that of the contact area of a steel at the same federate and depth cut). This causes high stresses on top of the tool.
3. It has a high 'coefficient of friction' between the chip and the tool face.

4. There is strong chemical reactivity of titanium at the cutting temperature (>500 °C) with almost all tool materials available.
5. The adiabatic or catastrophic thermoplastic shear process by which titanium chips are formed. Titanium's low volumetric specific heat and relatively small contact area along with the presence of a very thin flow zone between the chip and the tool cause high tool-tip temperatures of up to about 1110 °C.
6. Low modulus of elasticity (Table 1) which can cause chatter, deflection and rubbing problems.
7. There is also a high rate of work hardening.

All the above factors operating separately or in combination cause rapid wear, chipping or even catastrophic failure of the tools.[2]

Most complexities and challenges during machining of Titanium arise because of the high temperature. Konig[3] has studied the heat generation in machining Ti-6A1-4V with various tool materials and has produced a curve of the heat distribution (Fig. 1). Data for steel have also been included as a basis of comparison. When machining Titanium 80% of the heat generated can be absorbed by the tool as compared to 50% in machining steel.[2] The temperature gradients are usually much steeper and the heat-affected zone smaller and much closer to the cutting edge when machining titanium as compared to steel.

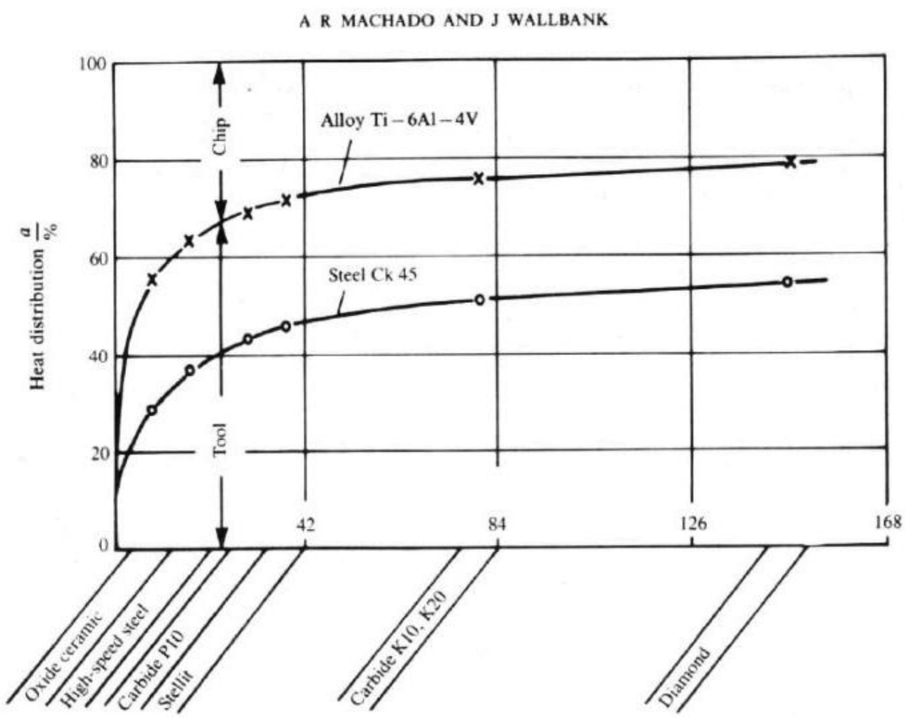
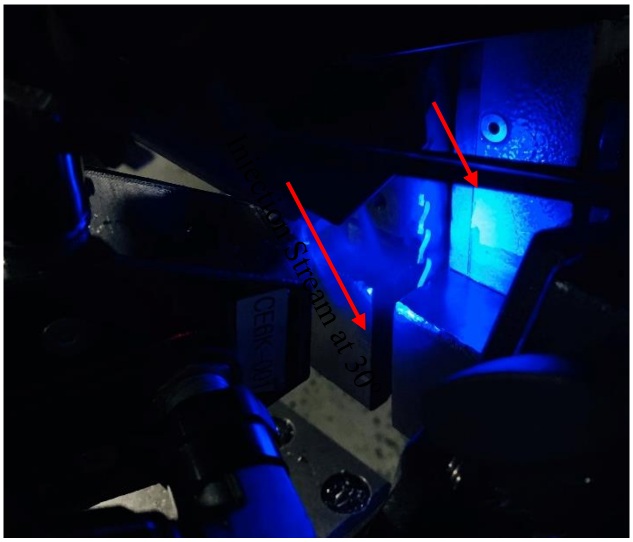
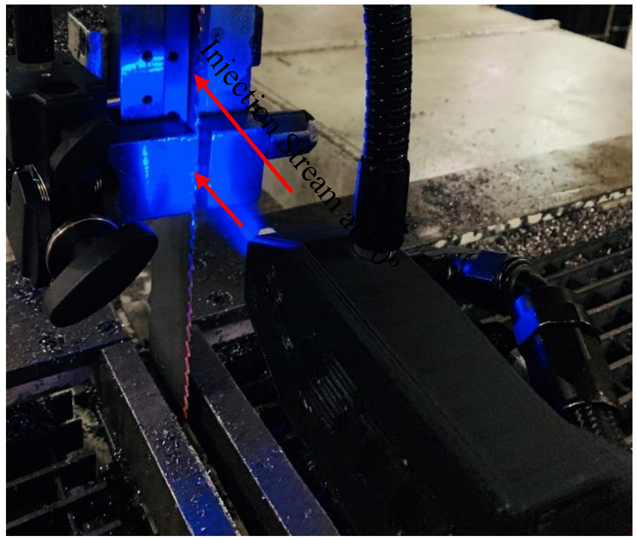



Figure 2 - Distribution of heat generated when machining titanium and steel (after Konig[3])

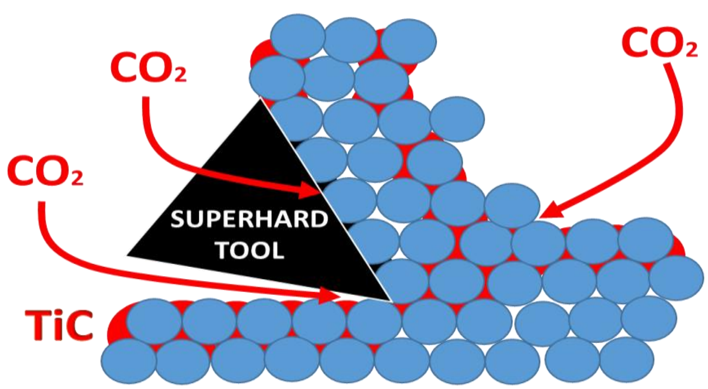
## Optimization

A new high-performance machining fluid called carbon dioxide ($CO_2$) minimum quantity cooling-lubrication (**$CO_2$ MQCL**) has been developed for optimizing the cutting atmospheres for difficult-to-machine materials such as Titanium. $CO_2$ MQCL employs fully adjustable compositions of oil droplets, compressed air, and carbon dioxide ($CO_2$) aerosol as a coolant-lubricant spray. The benefits of employing $CO_2$ MQCL include better machining economics in terms of faster machining and lower labor inputs, water and energy savings, and less waste by-products. Below are the pictures of $CO_2$ MQCL injection on the cutting tool at various angles.





In one example, $CO_2$ MQCL enables portable drilling speeds exceeding 1200 rpm on 6Al-4V-Ti, providing exceptional through-tool cooling-lubrication performance without the need for additional lubricant chemistry. During titanium drilling, the chips produced typically remain room temperature, which is very uncharacteristic of titanium drilling operations, and particularly at higher drilling speeds. Besides $CO_2$ sublimation cooling effects, it is speculated by the present author that the injection of $CO_2$ into the Titanium cutting zone produces endothermic cooling through thermal-catalytic dissociation of $CO_2$ on heated and highly reactive titanium surfaces to form carbon and oxygen, which is followed by reaction of the carbon with juvenile titanium metal ($Ti_j$) surfaces to form titanium carbide (TiC).




$$CO_2 + heat \rightarrow C + O_2 : +394 \text{ kJ/mole (absorbs heat from system, Endothermic)}$$
$$Ti_J + C \rightarrow TiC + heat : -184 \text{ kJ/mole (releases heat to system, Exothermic)}$$
$$CO_2 + Ti_J + heat \rightarrow TiC + O_2 : +209 \text{ kJ/mole}$$

## Conclusion

$CO_2$ MQCL is a process-adaptable machining atmosphere providing optimal chemistry, pressure, and temperature for a titanium cutting system – workpiece, tool, and machining process. It is readily adaptable to titanium machining platforms and processes such as sawing, turning, portable drilling, and precision abrasive grinding. There are multiple benefits afforded by $CO_2$ MQCL technology. Cutting tools last longer, machining centers produce parts faster, less coolant and lubricant is needed, and coolant management systems are needed less. $CO_2$ MQCL embodies the "less is more" principle, with fully adjustable compositions ranging from completely dry to near-dry, and without sacrificing lubricity and cooling power. $CO_2$ MQCL is an opportunity to provide better performance using substantially less resources.

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