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Abstract

Currently, the major challenges to researchers are enhancement of the machinability of difficult-to-machine (DTM) materials. The technology of cutting tool treatment is one of the approaches being implemented to overcome the challenges. Cryogenic and microwave treatments are two promising techniques to improve cutting tool properties in order to increase their effectiveness for enhancement of machinability. This paper presents the review of attempts made to enhance machinability of difficult-to-machine materials such as titanium alloys, nickel based alloys, ferrous alloys and composites materials using treated cutting tools. The objective of this work is to motivate the researchers and scholars to conduct further research, development, and innovations in this area.

Keywords
Machining, Cryogenic, Microwave, Tool wear, Machinability

1. Introduction

Higher grades of steels such as tool steels, stainless steels, and hardened steels etc.; other non-ferrous metals i.e. titanium, tungsten, and nickel based alloys etc.; and some composites are considered as difficult-to-machine (DTM) materials. These materials have wide range of applications in space, nuclear armaments, automobile, ship building, and power generation etc. (Kishawy et al. 2019). While cutting with conventional plane tool inserts, they possess poor machinability (Outeiro et al. 2008). High hardness, yield and tensile strength, and low thermal conductivity majorly cause frequent tool wear, high cutting force, and poor work surface quality (Karaguzel et al. 2015). Tool wear, cutting forces, surface roughness, material removal rate etc. are some of the major machinability indicators. Tool wear is the unavoidable phenomenon during machining, the cutting edge of the tool gradually wears out and at a certain stage it stops cutting. The main tool wear types are: flank wear, crater wear, nose wear, and auxiliary wear as shown in Figure 1.

![Figure 1. Different types to dominant tool wear types](image)

\[ V_B = \text{Average flank wear} \]
\[ V_N = \text{Notch wear} \]
\[ V_M = \text{Maximum flank wear} \]
\[ V_S = \text{Average auxiliary flank wear} \]
\[ V_{SM} = \text{Maximum auxiliary flank wear} \]
Flank wear occurs due to scoring action between tool and workpiece which generates high temperature at tool chip interface. Crater wear takes place at the top rake face of the cutting tool which affects the geometry of tool-chip interface (Senthil Kumar et al. 2006). In the beginning of the machining, the growth of rapid tool becomes high due to sharp cutting edge called break in wear. Fluctuations in cutting temperature, micro fracturing of cutting edge, thermo-mechanical shocks increase the break-in wear of cutting tool (Dhar et al. 2006). Many time cutting tool fails catastrophically due to plastic deformation, brittle fracturing, high abrasion etc. (Goindi and Sarkar 2017). The increase in tool wear results degradation in surface finish, increase in cutting force, high cutting fluid consumption and machining cost etc. (Prasanth et al., 2018). Researchers are busy investigating the ways to minimize tool wear. Tool material novelty, coatings, texturing and treatments etc. are some of the techniques being investigated. Tool treatment is mainly done by cryogenic and microwave environments. In this paper, a systematic review of previous work conducted on machinability enhancement of various DTM materials using treated cutting tool inserts is presented. It first introduces some DTM materials, that is followed by introduction to cryogenic and microwave tool treatment techniques and simultaneous discussion on the previous research where treated tools were used for machining of various DTM materials.

2. Difficult-to-Machine Materials

2.1 Titanium Alloys

Titanium is a wonder metal and available in abundance in the earth crust. High strength, corrosion resistance, and strength to weight ratio are some unique properties of Titanium. It is a low alloying element and it does not possess significant mechanical properties during its pure stage, it is generally soft. However, its mechanical properties can be improved by alloying, second phase hardening, and plastic deformation (Okafor 2020). Titanium alloys are widely used in engineering applications such as gas turbines, aerospace, and biomedical etc. Yield strength of Titanium varies as 410-1350 MPa, and due to its properties high speed machining is extremely difficult. Machinability of Titanium and its alloys is very poor due to properties mainly low thermal conductivity and high strain hardening. Therefore, their machining cost is high, and also environment unfriendly (Shokrani et al. 2012; Gupta and Laubscher 2017).

2.2 Nickel Alloys

Nickel based alloys are also known as one of the difficult to machine material due to high thermal fatigue resistivity, high hot hardness, low thermal conductivity, and high hardness. They retain at high temperatures due to excellent chemical and mechanical properties, and therefore find wide applications in aerospace, especially in high temperature conditions (Okafor 2020). During machining of nickel based alloys, it is evident that high levels of cutting forces are exerted by cutting tool on workpiece. This leads to an increase in tool wear and work surface deterioration due to high temperature machining (Qadri et al. 2019).

2.3 DTM Ferrous Alloys

Now a days, ferrous based alloys playing a vital role in modern industries. The limitless range of ferrous based alloys is available according to suitability and applicability. In ferrous based alloys, the principal element is iron (Fe) and remaining alloying elements such as carbon, phosphorus, silicon, manganese, nickel, vanadium, molybdenum, tungsten, and chromium etc are added to increases the mechanical and chemical properties (Goindi and Sarkar 2017; et al. 2019; Lawal et al. 2012). For Example, Mn, Cr, Mo, Ni, and Si are added to provide hardness at the higher temperature; Cr and Ni are added to improve the corrosion resistance property; Al and Ti are added to improve the machining properties. Steel is one of the most considerable ferrous based alloys used worldwide in all engineering applications (Trent and Wright 2000). The heat treatment process plays a vital role in changes the microstructure of steel which provides flexibility and develops a huge range of steel namely tool steels, carbon steels, alloy steels, stainless steels, cast iron, cast steel, and forging steel etc. (Lawal et al. 2013). But these materials are difficult-to-machine due to high work hardening, high strength, and low thermal conductivity (Lawal et al. 2013).
2.4 Composites

Fiber Reinforced Polymer (FRP) composites are modern materials address the need of various commercial and industrial requirements. The reinforcement phase made of fiber, platelets or aggregate form (Du et al. 2019). And the matrix phase that is made of a polymer protects the reinforced fiber from external damage and environmental conditions. Composite materials have excellent physical and chemical properties than homogenous materials that are anisotropic and inhomogeneous (Shokrani et al. 2012; Sozhamannan et al. 2018). The composite materials attribute high hardness, strong fracture toughness, specific strength that provides excellent performance in wear resistance, heat resistance during machining. Higher hardness, strong reinforcement fiber and usually brittle matrix make the machining of FRP composites difficult (Li et al. 2020; Shokrani et al. 2012; Shi and Wang 2020).

3. Tool Treatment

3.1 Cryogenic Treatment

Rapid growth of industrialization and developments in manufacturing require prominent solutions to the machining challenges for a sustainable and cost efficient product development. Cryogenic treatment of cutting tool materials is the prominent technique that refers to subject the materials in cryogenic temperature (-196 °C) far below than room temperature. A temperature between -80 °C and -196 °C is generally preferred for cryogenic treatment of different cutting tool materials and known as soaking temperature. Figure 2 presents the various temperature stages achieved during cryogenic treatment (Sharma et al. 2008; Khan and Maity 2017).

![Diagram of Cryogenic treatment and variation of temperature with respect to time](image)

**Figure 2.** Detail of Cryogenic treatment and variation of temperature with respect to time

Usually, liquid nitrogen is used in cryogenic treatment in which the tool inserts are kept for the different time period, known as soaking period. The range of soaking period for cryogenic treatment of tool materials lies between 1 and 40 hr. It is an essential parameter during which, internal structural conversion from austenite to martensite take place that results in improved material’s property such as wear resistance, toughness, and microhardness etc. The set-up for the cryogenic treatment of tool inserts is shown in Figure 3. As illustrated in Figure 3, liquid nitrogen stored in nitrogen tank flows through tight pipe line. The flow of liquid nitrogen and temperature of cooling chamber are monitored through control unit. The tool inserts are subjected to liquid nitrogen inside the cooling chamber for cryogenic treatment. The temperature starts decreasing from room temperature (25 °C) to optimal soaking temperature (between -80 and 196 °C) at a controlled rate of 1 °C/min. After this, the soaking temperature is maintained constant for 24 hrs. After 24 hrs, the soaking temperature increases up to room temperature gradually at controlled rate of 1 °C/min [20-24] and this is how cryogenic treatment of cutting tool inserts takes place.
This cryogenic treatment method brings morphological and microstructural changes in the cutting tool materials that are beneficial and effective to improve their performance in terms of reducing tool wear and increasing tool life while machining a wide range of DTM materials (Gill et al. 2011). Tungsten carbide (WC) tool inserts have been preferably used by the researchers to investigate the influence of cryogenic treatment, because WC responds appreciably well as compared to other tool materials. Researchers reported that cryogenic treatment enables complex phase transformation or harder phase in WC inserts which results in increase in hardness and wear resistance property.

Özbek et al. (2016) reported an increase in \( \eta \)-carbides (Co\(_6\)W\(_6\)C) in cryogenic-treated inserts. The fine \( \eta \)-carbides improved the machinability of carbide tool inserts during turning of AISI 316 austenitic stainless steel. The authors concluded that an increase in grain size increases the thermal conductivity of treated inserts that results from reduction in tool wear by 53%. Gill et al. (2011) investigated the performance of shallow (-110°C) and deep cryogenic treated (-196°C) TiAlN coated square-shaped tungsten carbide (P25) inserts. The difficult to machine material, hot rolled annealed steel (C-65) was selected for turning operations. Results reveal that microstructural alteration of \( \eta \)-carbides improved the tool wear resistance and machinability. 

Titanium and its alloys can also be easily machined by cryogenically treated inserts. Sivalingam et al. (2018) reported that during milling of titanium-based alloys (Ti-6Al-4V alloy), cryogenic treated inserts resulted in reduction in tool wear, surface roughness, cutting force, vibration acceleration signals as compared to untreated inserts. Yong et al. (2007) analyzed the tool wear of cryogenic treated insert during milling of medium carbon steel in dry and wet cutting environment. Results reveal that tool life has increased by 28.9-38.6% after cryogenic treatment with less chipping. In an interesting study, chip phenomenon, tool wear, friction coefficient, and microstructure for untreated and cryogenic treated inserts. It was observed that surface hardness has increased due to an increase in cobalt (Co) content and the formation of hard eta (\( \eta \)) phase. Microhardness recorded 9% higher in cryogenic treated insert as compared to untreated inserts Yong et al. (2006). The machining performance of uncoated inserts has been improved by cryogenic treatment subjecting them for different periods.

Seah et al. (2003) explored the other combination of cryogenic treated inserts with tempering and cold treatment. The authors reveal that there is no significant difference in hardness obtained in the aforementioned treatment methods. However, cryogenically treated and cold treated tool inserts performed better in higher cutting speeds during machining of ASSAB 760 carbon steel. Kumar and Senthil (2019) observed cutting force, surface roughness at the different levels of treatment of WC insert viz. 12hr, 24 hr, 36 hr, and 48 hr. Results report that more than 36 hours of cryogenic treatment, the WC inserts start decaying chemically. This chemical degradation reduces the hardness and wears resistance of the treated inserts. Other than ferrous based and titanium based workpiece materials, nickel based alloys and composite materials have also been machined using cryogenic treated inserts. (Thamizhmanii et al. 2011) conducted machining of Inconel 718 (nickel based alloys) using deep cryogenically treated milling inserts. The machining performance has been evaluated using tool wear (flank wear, crater wear) and surface roughness. Results reveal that as compared to untreated insert, cryogenic treated inserts performed significant better at high cutting speed and produced low surface roughness.
3.2 Microwave Treatment

Microwave treatment of cutting tool material (WC) refers to the treatment at high temperature generated by microwave energy. Microwave heating is also known as the volumetric heating process in which the substrate exposed under electromagnetic radiation volumetrically at the frequency range of 0.915 and 2.45 GHz (El Khaled et al. 2018; Rajkumar and Aravindan 2010; Mondal et al. 2010). The volumetric heating process is completely different from conventional heating because in the volumetric heating process the electromagnetic energy is converted into thermal energy. The heat generated inside the substrate through intermolecular interaction with microwave which moves towards the surface. Whereas in conventional heating process, heat transfer via conduction process through energy source. In conventional heating, the heat first generates on the surface of material and moves towards the core or inside (Agrawal 2006). Jhodkar et al. 2018 reported that microwave post treatment enhances the machining ability of tool material through metallurgical and microstructural change. They concluded that wear resistance, fracture toughness, and microhardness of treated WC insert have improved significantly. Microwave heating is also known as dielectric heating in which only those materials can be kept into microwave irradiation which have dielectric properties or which can absorb microwaves (Thakur et al. 2014). Materials are divided into three categories (a) reflector (b) transparent (c) absorber, as illustrated in Fig. 4. Reflector material does not allow to pass microwave. In transparent materials, microwaves pass through material without any losses, such as oxides material. Whereas, absorbent materials, absorb the microwaves depending upon dielectric loss factor value. Carbide is having high dielectric value therefore it is a well-known microwave absorber material.

Fig. 4 Microwave property (a) Reflect (b) Transparent (c) Absorber

Tungsten carbide(WC) is one of the extensively recommended cutting tool materials which is a good microwave absorber (Fang et al. 2014). The setup for microwave treatment of WC insert is shown in Fig.5 in which WC tool insert is subjected under microwave irradiation at the frequency range of 2.45 GHz. Tungsten carbide is widely used for machining of difficult to machine materials (Sharma et al. 2008). Many researchers used tungsten carbide for the machining of ferrous, titanium, and nickel alloys as well as for composites. In many articles, researchers attempted to improve the machining performance of tungsten carbide via microwave post treatment techniques. During microwave post treatment, microwaves penetrate tungsten carbide and effectively couples with carbide grains due to which translational and rotational motion of ions and dipoles initiates internal heating. This internal heating liquefies the binder metal cobalt (Co) of tungsten carbide inserts and liquefied cobalt starts depleting on the surface and creates WC skeleton matrix (Jhodkar et al. 2018). Varadarajan et al. (2006) reported an increase in microhardness and complex carbide formation during the treatment of K20 carbide tool inserts. The turning of Al/Sic metal matrix composite was done using microwave treated and untreated inserts. Results reveal that tool wear, cutting force, and surface roughness reduced significantly by using treated inserts. From the series of experiments performed, it was confirmed that WC is a suitable material for the microwave post heat treatment. In an interesting study, Jhodkar et al. (2018) investigated the effect of microwave treatment on tungsten carbide insert by varying treatment time viz.
10, 20, 30, and 40 mins. Maximum microhardness obtained in 30 min treated inserts. XRD analysis confirmed complex carbide formation due to cobalt depletion on the surface of the WC insert. Perumalla et al (2020) attempted to enhance the surface hardness of bronze and ferrous alloy material using microwave post-heat treatment method. Ramkumar et al. (2005) performed drilling operation on GFRP composite material using microwave treated and untreated inserts. It was concluded that complex carbide formation indicates less material distress and low or der surface roughness values.

![Experimental setup for the microwave post treatment of WC tool inserts](image)

The microwave tool treatment also prompts towards sustainability, as it minimizes the lubrication or cutting fluid requirements during machining. Jhodkar et al. (2018) explored that microwave treated inserts performed better in dry machining conditions than wet and MQL cutting environments. Turning operations performed on AISI 1040 steel using WC treated and untreated inserts. It is observed that microwave treatment improves the cutting edge stability with the reduction in abrasion. Apart from ferrous based alloys, nickel-based alloy Inconel 718 efficiently machined by microwave treated inserts. In which reduction in abrasion and plastic deformation tool wear mechanism on tool nose area have obtained in treated tool insert (Jadam et al. 2020).

### 4. Summary

Cryogenic and microwave treatment techniques and their effectiveness have been discussed in this paper. Based on the review of previous work where post treatment techniques have been used for machinability enhancement of a wide range of materials, the following conclusions can be drawn:

- Cryogenic and microwave treatment techniques are very effective for the enhancement of mechanical properties such as wear resistance, fracture toughness, and cutting edge stability etc. of cutting tool inserts.
- Cryogenic treatment technique has been found effective for a wide range of cutting tool materials such as high carbon steel, cemented carbide, tungsten carbide, ceramics, and cubic boron nitride. Whereas, microwave treatment is found effective especially in case of tungsten carbide.
- It is obvious to achieve better machinability indicators i.e. improved surface quality, lower tool wear and longer tool life, higher material removal rate, lower cutting forces and temperature etc. after machining various materials using treated cutting tool inserts.
- Investigating the combined effect of cryogenic and microwave treatments, combination of tool coating and treatment, and usage of treated tools in different machining environments etc. can be explored as future research avenues.

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Biographies

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