Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal 2024, 18(1), 76–88
https://doi.org/10.12913/22998624/175917
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Received: 2023.11.21
Accepted: 2023.12.27
Published: 2024.01.15

Influence of Aluminium Oxide Nanoparticles Mass Concentrations on the Tool Wear Values During Turning of Titanium Alloy under Minimum Quantity Lubrication Conditions

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ABSTRACT

Recently, environmental consciousness has led to the quest for ways to minimise negative elements in machining operations that threaten operator health and the environment. Titanium alloys are hard to cut, thus cooling the cutting zone is essential to reduce tool wear. Variations in Al_2O_3 nanoparticle concentrations supplied to the minimum quantity lubrication (MQL) cutting fluid affect cutting wedge wear during Ti6Al4V alloy turning. A diameter of 15 nm nanoparticles were utilised at 0.25, 0.5, 0.75, and 1 wt% mass concentrations. In the experiments, the flank face wear band width VB_B and crater width KB were measured. Comparisons were also made using dry-cutting tools and the MQL approach without nanoparticles. X-ray microanalysis was used to quantify and qualitatively assess the chemical composition of chosen rake surface micro-areas. Studies showed that Al_2O_3 nanoparticle mass concentration affects tool wear when turning a hard-to-cut alloy. 0.5 and 0.75 wt% mass concentrations had the lowest flank and rake wear of the four mass concentrations. The SEM examination showed that 0.5 wt% mass concentration decreased adhesive wear the most.

Keywords: Al_2O_3 nanoparticles, minimum quantity lubrication, nanofluids, tool wear, tribofilm.

INTRODUCTION

Reducing machining's and cooling's detrimental effects on the environment has been a hot topic of study in recent years. In addition, non-hazardous alternatives to traditional techniques of cooling the cutting zone are being investigated [1, 2]. Large amounts of heat are created during cutting, which can dramatically change machining conditions, making their use vital in many circumstances. Aside from lowering friction and clearing away heat from the cutting zone [3–5] cutting fluids also help form chips in a way that makes them more manageable to move out of the way of the action. Consequently, it causes shifts in the development of the technical surface layer [6], mostly by improving the quality of the machined surface [7, 8]. But dry machining causes tools to wear out more quickly, which lowers productivity [9]. The minimum quantity lubrication (MQL) method has been utilised to combine the benefits of employing cutting fluids with environmental preservation. To accomplish this, compressed air and very modest amounts of coolant (10-100 ml/h) must be supplied. Through the use of a nozzle, such an aerosol is delivered to the cutting region [10]. The MQL process saves as much as 20% of the total manufacturing cost due to its low cutting fluid consumption, which removes the issues connected with the disposal of large quantities of the fluid [11, 12]. Despite its many advantages, this cooling method may not provide sufficient temperature reduction during machining, especially when difficult-to-machine materials are being cut. These materials include titanium alloys, such as the Ti6Al4V alloy [13], which has a utilisation rate of up to 60% compared to other alloys of this metal [11] and is mainly used in the aerospace [14, 15], medical [16, 17] and marine [18, 19] industries. Titanium alloys are known for their high corrosion resistance [20] and low density [21], and also have low thermal conductivity and high strength at high temperatures [22], which increases the rate of tool wear during machining [23].

The potential use of nanoparticles to increase the thermal conductivity of the machining fluid and its tribological properties has been explored [24] in order to implement a minimum quantity lubrication approach while machining hard-to-cut alloys [25]. Lower friction and less tool wear are the results of their four modes of action in the cutting zone, which also include polishing and rolling as well as the mending effect and tribofilm generation [26, 27]. Cutting tool durability was improved by using nanofluids, as shown in a study by Yi et al. [28]. The researchers turned Ti6Al4V alloy with a cutting fluid based on mineral oil and vegetable oil, to which they added graphene oxide (GO) nanoparticles with a size of 50 nm and a concentration of between 0.1 wt% and 0.5 wt%. Results from an analysis of tool wear showed that using a nanofluid with a GO concentration of 0.3 wt% reduced build-up edge formation in comparison to using a conventional machining fluid, and also reduced wear on the flank and rake surfaces by 77.78% and 41.21%, respectively. The authors suggest that the increased thermal conductivity of the nanofluid may be responsible for such an outcome. Nanoparticles' better heat dissipation extended tool life, according to Anandan et al. [29]. They employed 1.5 g graphene nanoparticles in 250 ml ethylene glycol with sodium dodecyl benzene sulfonate surfactant this time. The MQL method utilised nanofluid to turn M42 alloy, compared to dry machining and minimum amount lubrication with a canola oil-based aerosol. Compared to alternative cooling methods, nanofluid reduced tool wear by 91% and 86%. Makhesana et al. [30] turned Inconel 690 alloy with 1-wt% MoS_2 nanoparticles in canola oil. Other methods included dry machining, wet machining with mineral oil-based cutting fluid, and MQL using canola oil without nanoparticles. MoS_2 and pure oil MQL reduced tool wear by 20–25% compared to dry machining, according to researchers. The increased penetration of oil droplets into the tool-chip and tool-workpiece material contact zone reduced friction and heat during cutting. Other cooling methods caused more tool wear than the aerosol with nanoparticles because the active medium cooled and lubricated. Due to pressurised air, nanoparticles, and oil droplets, the cutting zone temperature dropped, extending tool life. MQL cooling with MoS_2 dissipated heat best and helped remove chips from the contact surface, reducing friction and tool wear. Zhang et al. [31] turned 40Cr steel using the MQL process with varying SiC nanoparticle concentrations of 0.5, 1, 3, & 5 wt% and sizes of 40, 60, 80, and 500 nm. The MQL aerosol without nanoparticles was generated using rapeseed oil as the basis fluid in the nanofluids. Dry machining was used to compare turning. The nanofluid with 3 wt% SiC had the lowest *VB* index values for various nanoparticle concentrations during tool wear analysis. Tool wear at the flank surface was 10.6% and 55.1% lower with nanoparticles and dry machining than with MQL. The high pressure of the injected aerosol lowered the cutting zone temperature, according to the authors. The combination of nanoparticles and oil reduced friction, increased tribofilm load-bearing capacity, and improved tool wear resistance. The smallest nanoparticle size, 40 nm, reduced flank surface tool wear by 46.7% and 9.6% compared to dry machining and minimum quantity lubrication without SiC. SiC became less effective than rapeseed oil at diameters up to 500 nm, and its anti-wear impact decreased with nanoparticle size. Scientists say smaller nanoparticles reach the cutting zone more easily, minimising friction and wear. Additionally, Brownian motion controls the nanoparticles suspended in the oil, making such nanofluids more stable.

Scientists also studied Al_2O_3 nanoparticles. The experiments carried out so far indicate that these nanoparticles are able to improve the heat dissipation capacity of the cutting fluid [32], but the degree of such effect depends on their concentration [33–35]. Pal et al. [36] drilled AISI 321 steel using dry, wet, MQL, and MQL with Al_2O_3 nanoparticles in sunflower oil at 0.5, 1, and 1.5 wt%. Nanofluids increased tool life when researchers examined the cooling methods' effects on tool wear. The MQL technique with Al_2O_3 minimised drill wear, with no micro-chipping or build-up edge at the highest concentrations of 0.5 and 1 wt%. Reduced tool wear was attributed to the nanofluid's increased cooling effect, the Al_2O_3 nanoparticles' lubricating film, and the 1.5 wt% concentration's effective separation of the contacting surfaces, which reduced adhesion compared to lower concentrations and other cooling methods. In contrast, Venkatesan et al. [37] examined how Al_2O_3 nanoparticles and their concentration affect tool wear during Incoloy 800H alloy turning under MQL cooling. The concentrations were 0.25, 0.5, and 1 wt%. It was found that the nanofluid at 0.25 wt% concentration enhances the thermal conductivity of coconut oil and reduces tool wear compared to other concentrations. The build-up edge was maximum at 0.5 wt% concentration, whereas increased flank wear was seen at 1 wt% due to lower cutting fluid lubrication and reduced temperature at the tool-workpiece interface.

Despite numerous experiments using nanoparticles in the MQL method during machining, there are few studies on the effect of Al_2O_3 nanoparticles with different mass concentrations on tool wear during the machining of the difficult-to-cut Ti6Al4V alloy, which would require a chemical analysis of the cutting wedge's rake surface. Thus, this paper compares dry machining and aerosol without nanoparticles to a polyol ester-based nanofluid with an Al_2O_3 concentration of 0.25-1 wt% on VB_B and *KB* indicators and wear mechanisms.

MATERIALS AND METHODS

Nanofluid preparation

Polyol ester was used as the starting material to create the nanofluid. In order to achieve mass concentrations of 0.25 wt%, 0.5 wt%, 0.75 wt%, and 1 wt%, 15 nm Al_2O_3 nanoparticles were added. After 60 minutes of ultrasonic homogenization with a Hielscher UP200St (Fig. 1a), the nanoparticles were evenly distributed. The nanofluid was stored in a Lubrimat L60, which then sprayed it through two nozzles directly onto the cutting area. The air flow rate was 40 l/min, and the machining fluid flow rate was 58 ml/h.

Workpiece material and tool wear measurement details

The mostly used titanium alloy i.e., Ti-6Al-4V has been used to perform the turning tests in the current work. The chemical composition of workpiece is depicted in Table 1 and for machining of subjected material, CNC CKE6136i lathe has been used. The physical vapour deposition (PVD) coated 3 mm thick AlTiN layers on carbide inserts were used to perform the machining experiments. The tool geometry used is: major cutting edge angle κ_r = 95°, minor cutting edge angle κ_r' = 50°, rake angle γ = 0°, clearance angle of the main cutting edge α = 0°, major cutting edge inclination angle λ_s = 5°, corner angle ε = 35°, corner radius r_ε = 0.4 mm; SVLBR2020K16 toolholder; VBMT160404-F1 insert, respectively. During machining, the cutting parameters v_c = 70 m/min, f = 0.065 mm/rev, and a_p = 0.6 mm were kept fixed.

Tools were was measured by following the ISO 3685:1993. Using a Dino Lite AM7013MZT universal microscope, the width of a wear band on the flank face (VB_B) and the width of a crater on the rake face (KB) was measured. In the first round of experiments, the cooling method was varied and the tool was used for 30 minutes while readings were obtained every 6 minutes. For each type of cooling, three repetitions of tool wear tests were made. In order to determine the level and nature of wear on the cutting wedge, a JEOL JSM-5600LV scanning microscope was used (Fig. 1c). In the end, the EDS mapping was performed to analyse the specific composition with the help of X ray micro-analyser.

Table 1. Ti6Al4V chemical composition

Chemical composition, %							
Fe_{max}	O_{max}	Al	H_{max}	C_{max}	N_{max}	Ti	V
0.16	0.160	6.05	<0.0006	0.012	0.010	≈89.36	4.16

RESULTS AND DISCUSSION

To evaluate the impact of Al_2O_3 nanoparticle concentration on tool life, the VB_B and *KB* wear indicators were measured on the inserts following the Ti6Al4V turning process. Figures 2 and 3 display the results obtained.

Analysis of the flank wear band width (Fig. 2) showed that the smallest VB_B values were obtained using Al_2O_3 nanoparticles at a concentration of 0.5 wt% in the cutting fluid, with a significant difference compared to the other concentration values used after 12 minutes of operation. After 12 minutes of operation, the discrepancies in the VB_B values achieved by applying 0.25 wt%, 0.75 wt%, and 1 wt% Al_2O_3 concentrations in the

Figure 1. Apparatus used for the research: (a) Hielscher UP200St ultrasonic homogenizer, (b) Dino Lite AM7013MZT digital microscope, (c) JEOL JSM-5600LV SEM microscope

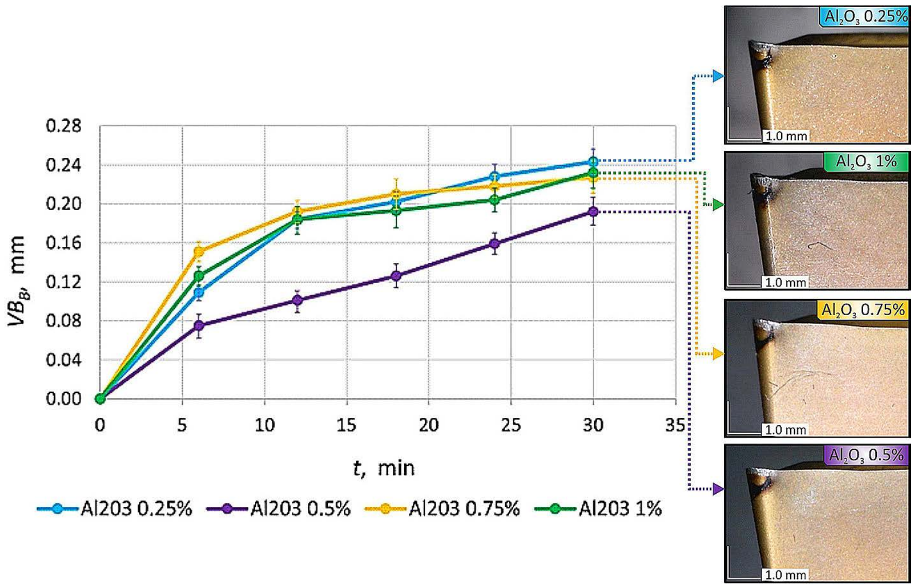

Figure 2. Flank wear results with respect to the different ratio of Al_2O_3 nanoparticles

MQL method rarely exceeded 10.5%. However, after only 6 minutes of blade operation, the introduction of 0.5 wt% Al_2O_3 nanoparticles reduced the width of the wear band on the flank surface by 14.5% to 50%. After 30 minutes of turning Ti6Al4V with nanofluid cooling at an Al_2O_3 concentration of 0.75 wt%, the insert showed the smallest values of crater width on the rake surface (Fig. 3). The greatest *KB* value was seen for the whole insert monitoring period when cooling using the MQL method with nanoparticles at concentrations of 0.25 wt% and 1 wt%, respectively. When using the MQL technique, the wear on the rake's surface (measured with the *KB* indicator) was consistent throughout all except the smallest of mass concentrations of Al_2O_3 nanoparticles. Increases in concentration, up to 0.75 wt%, reduce *KB* values because of enhanced thermal

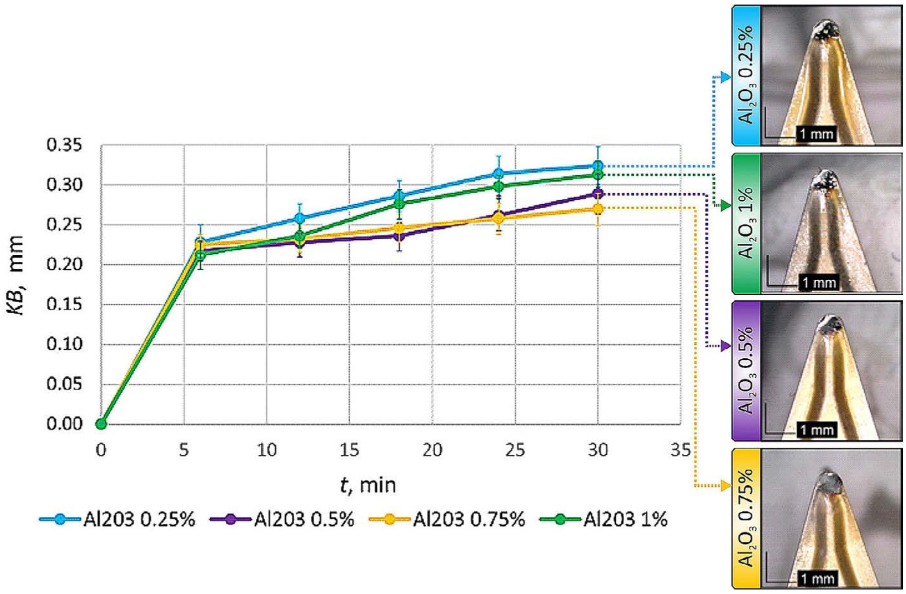

Figure 3. Crater wear results with respect to the different ratio of Al_2O_3 nanoparticles

conductivity and wetting ability of the active medium. When the concentration was raised by 1 wt%, however, a little widening of the craters was seen. Reduced nanofluid aerosol penetration into the cutting zone has been linked to precipitation and excessive viscosity caused by an increase in the mass concentration of Al_2O_3 nanoparticles [38]. SEM observations of cutting wedges in MQL + Al_2O_3 settings (Figures 4-7) reveal that adhesion phenomena is the primary wear process on the rake surface.

SEM observations of the cutting edge after turning of the Ti6Al4V titanium alloy with 0.25 wt% Al_2O_3 nanofluid cooling (Fig. 4b) showed that the predominant type of wear is adhesive wear on the rake surface and abrasive wear on the main flank surface, where characteristic grooves were also observed. Chipping was noted on the rake surface, which is the cause of more rapid wear of the main cutting edge. Higher intensity of the tungsten occurrence (Fig. 4c) is an indication of increased wear of the AlTiN coating of the cutting edge. A higher content of vanadium (approximately 2.5%), an element present in the workpiece material, was observed in micro-area 3 (Fig. 4a). The lowest mass concentration of nanoparticles used in the active medium under minimum quantity lubrication conditions may indicate less tribofilm formation in the cutting edge-workpiece material contact zone. However, due to the AlTiN coating on the cutting insert and the presence of aluminium in the workpiece material, Ti6Al4V titanium alloy, it was challenging to subject the conditions of tribofilm formation on the cutting wedge surfaces to accurate scanning analysis when using Al_2O_3 nanoparticles. Similarly, oxygen was ruled out because it was already present in the base fluid into which the nanoparticles were injected as a byproduct of chemical reactions in the cutting zone.

Adhesive wear on the contact surface was diminished when the mass concentration was increased to 0.5 wt% (Fig. 5). The vanadium concentration in micro-areas 2, 3, and 4 (Fig. 5a) does not go above 1.5%, confirming this. A small build-up edge was observed in the groove formation zone, which can protect the cutting edge from wear under suitable cutting conditions [39]. The use of a 0.5 wt% nanoparticle concentration also resulted in a lower tungsten occurrence intensity (Fig. 5c), but with a greater length along the main cutting edge. The smallest amounts of oxygen and carbon were found under these cooling conditions, which may indicate good penetration of the smaller nanofluid droplets with the considered mass concentration of Al_2O_3. Cutting edge wear can be reduced by increasing the mass concentration of the nanoparticles put into the cutting fluid, which reduces friction in the cutting zone and increases the wettability of the nanofluid [40]. More vanadium (2.10 percentage points) was found in micro-area 2 when using a 0.75 wt% Al_2O_3 concentration in the MQL method, indicating more intense adhesive wear on the tool compared to the cutting tool operating with MQL + Al_2O_3 0.5 wt% (Fig. 6a). Tungsten distribution analysis (Fig.

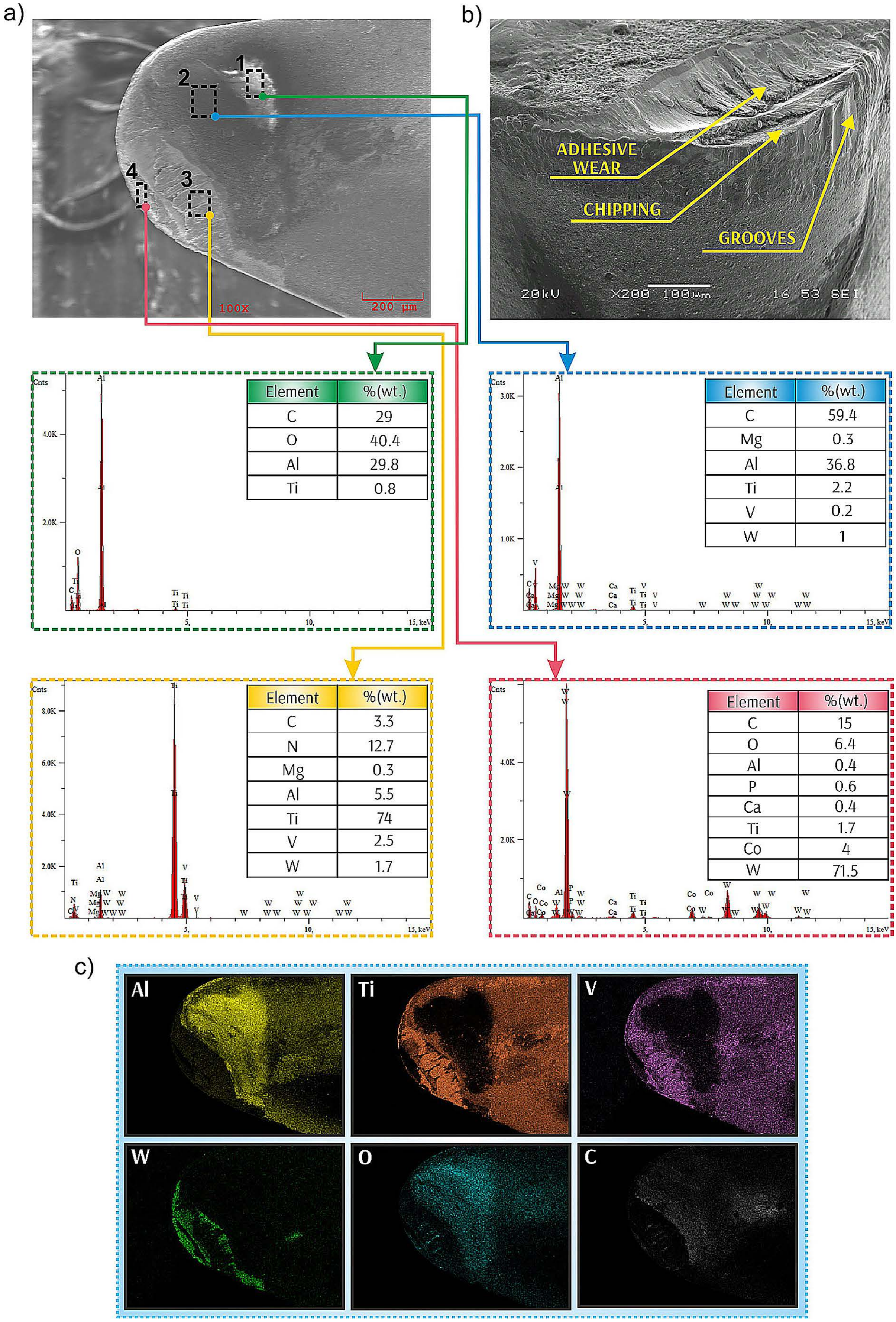

Figure 4. SEM of cutting tool with 0.25 wt% Al_2O_3 nanoparticles at (a) Rake face (b) Flank face and (c) EDS mapping of cutting tool

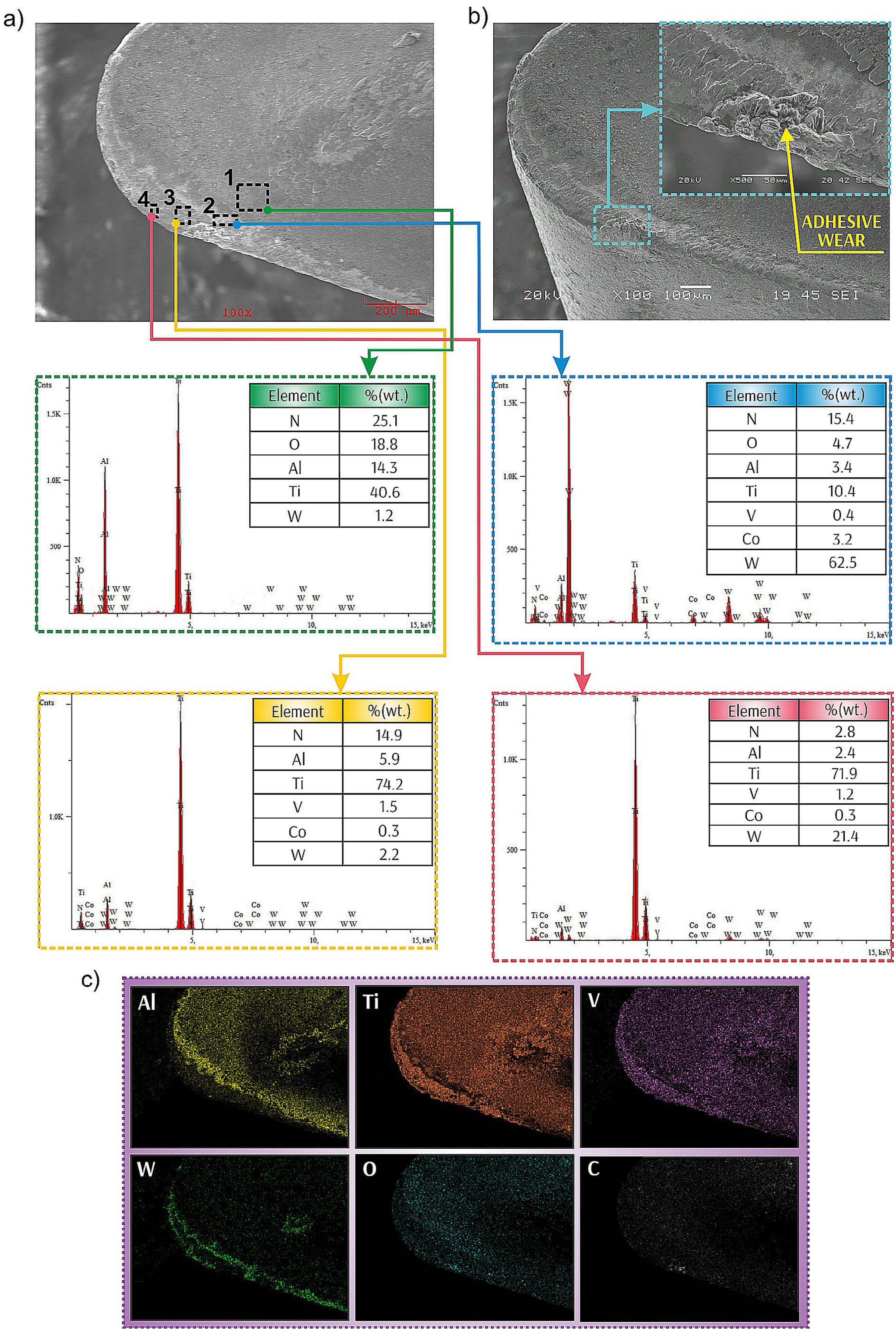

Figure 5. SEM of cutting tool with 0.5 wt% Al_2O_3 nanoparticles at (a) Rake face (b) Flank face and (c) EDS mapping of cutting tool

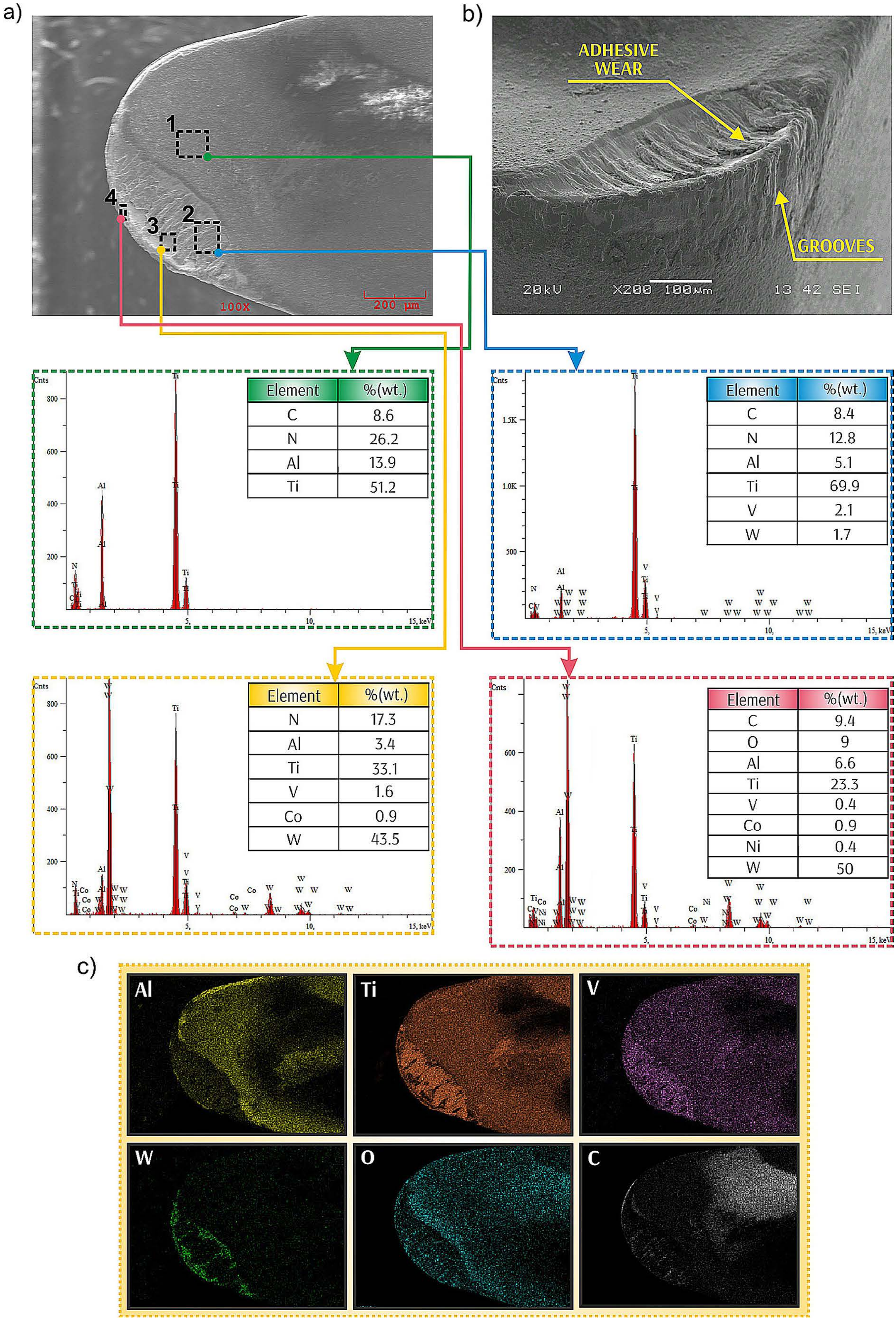

Figure 6. SEM of cutting tool with 0.75 wt% Al_2O_3 nanoparticles at a) Rake face (b) Flank face and (c) EDS mapping of cutting tool

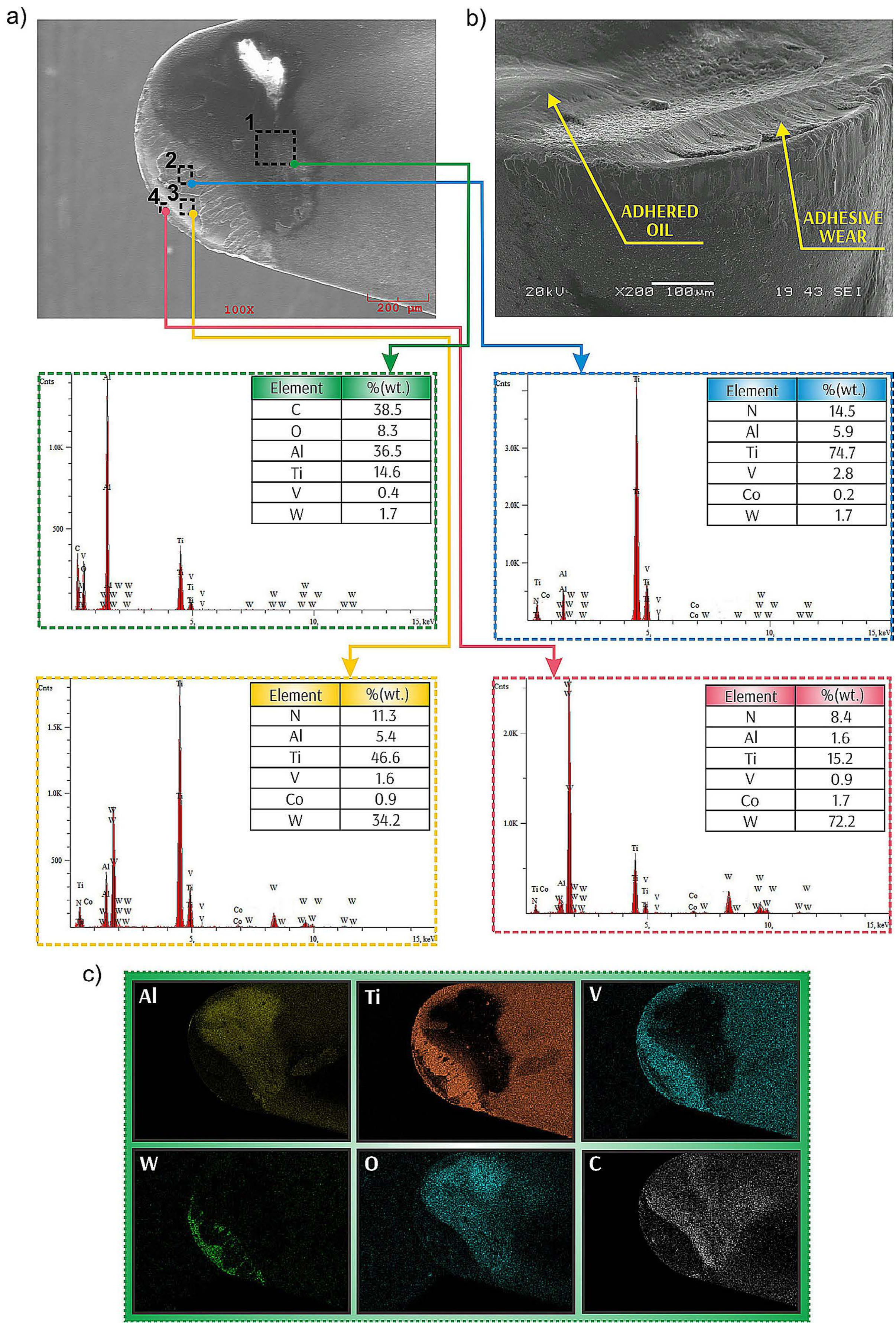

Figure 7. SEM of cutting tool with 1 wt% Al_2O_3 nanoparticles at (a) Rake face (b) Flank face and (c) EDS mapping of cutting tool

6c) reveals a decrease in tungsten content when compared to the tool running under MQL + Al_2O_3 0.25% cooling and an increase when compared to MQL + Al_2O_3 0.5% cooling. The primary flank surface showed signs of wear and tear in the form of distinctive grooves. Precipitation of the Al_2O_3 nanoparticles after a certain time period prevents the aerosol from reaching the cutting zone due to a significant increase in viscosity, leading to an insufficient cooling and lubricating function of the nanofluid and an increase in wear [41]. SEM analysis of the cutting wedge's rake surface while running on MQL with 1 wt% Al_2O_3 nanoparticles confirms this mechanism. According to the carbon occurrence intensity (Fig. 7c), oil adhesion was shown to be enhanced under these cooling circumstances. Micro-area 2 also showed an increased vanadium content (up to 2.8 wt%), indicating increased adhesive wear. This could be attributed to inadequate lubrication of the nanofluid due to subpar conditions for the formation of thin tribofilm layers in the cutting edge–workpiece material contact zone [42]. At a concentration of 0.5 wt%, a distinct distribution of oxygen and aluminium was discovered on the rake surface (Fig. 5c), which may lead to a decrease in the selected wear indicator values due to the creation of a thin tribofilm layer. There was a comparison made between using nanoparticles in the cutting fluid, dry machining, and the MQL technique. Al_2O_3 nanoparticles at a concentration of 0.5 wt% were used in the comparison because they produced the lowest VB_B values. Figures 8 and 9 demonstrate how the cooling procedure affects the size of the wear band on the flank face and the crater on the rake face.

Wear band width values on the flank surface were reduced by 45.5% (Fig. 8) and crater width values were reduced by 22.7% (Fig. 9) when Al_2O_3 nanoparticles were used in the MQL process instead of dry machining. These variations stood at 26.1% and 8.3% from the MQL technique devoid of nanoparticles, respectively. Reductions in temperature in the cutting zone and consequently lower friction lead to decreased wear of the cutting wedge when using the MQL method without nanoparticles compared to dry machining [43]. The cutting fluid in the aerosol has excellent lubricating properties, and this is why the MQL method reduces tool wear; in the case of the MQL process with nanoparticles, this is due to the formation of an additional tribofilm on the flank surface, which in turn reduces friction in the chip–tool contact zone.

CONCLUSIONS

Cutting tool wear during turning of Ti6Al4V titanium alloy was investigated in order to ascertain the effect of Al_2O_3 nanoparticles and their concentration in the MQL method. The values of cutting edge wear indicators were also compared between the results obtained and those of dry machining and the MQL method without nanoparticles. The following findings emerged from the analyses performed.

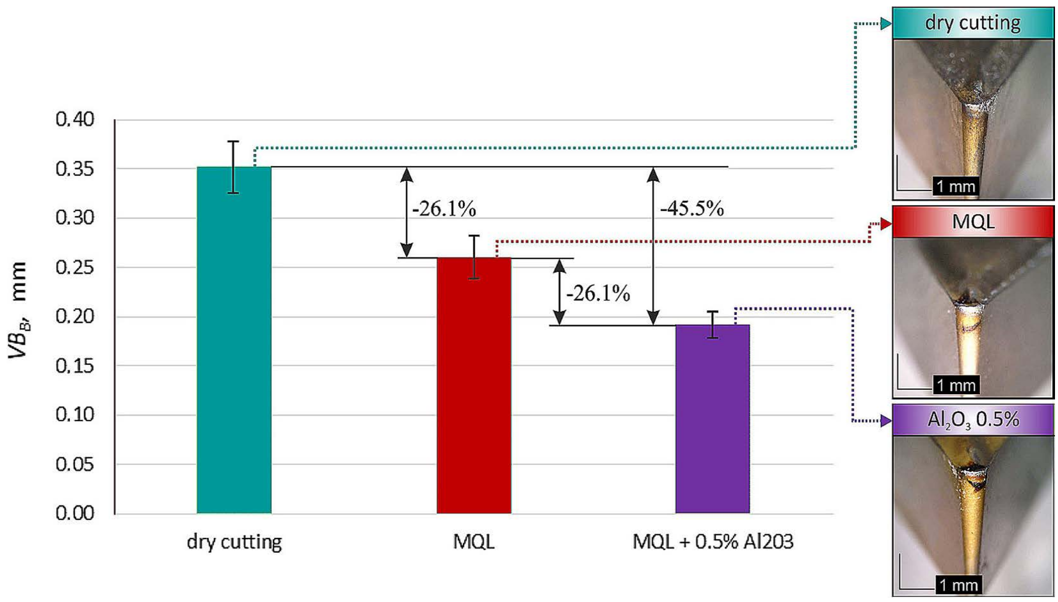

Figure 8. Flank wear results under different cooling conditions

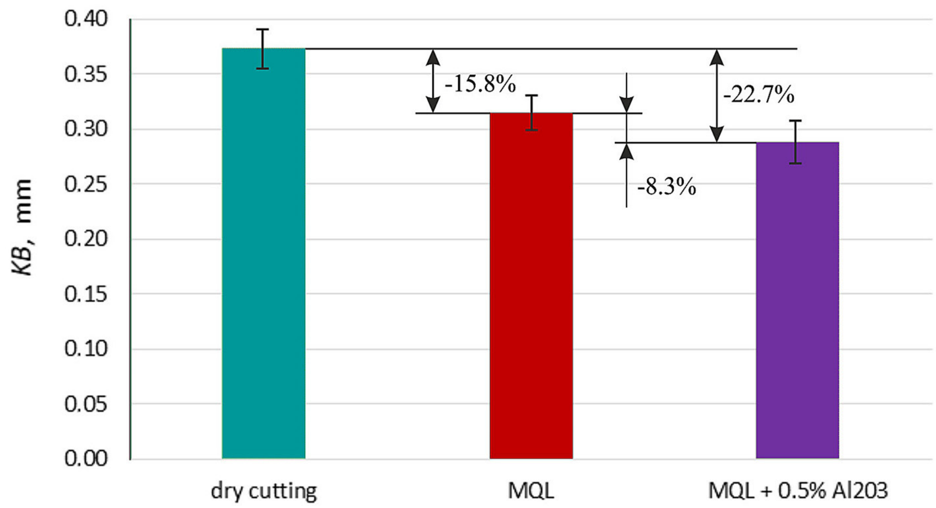

Figure 9. Crater wear results under different cooling conditions

The width of the crater on the rake surface and the thickness of the wear band on the flank surface are both significantly affected by the mass concentration of Al_2O_3 nanoparticles in the nanofluid. Because of an improvement in wettability and thermal conductivity, the active medium's VB_B value was found to be lowest at a concentration of 0.5 wt%, while the *KB* value was found to be lowest at a concentration of 0.75 wt%. However, the nanofluid's viscosity increases and its ability to penetrate the cutting zone decreases as its mass concentration increases more.

According to SEM and EDS, adhesive wear was predominant on the rake surface after turning under MQL + Al_2O_3 0.25 wt% conditions, while abrasive wear was concentrated on the flank surface. The lowest nanoparticle content of the nanofluid may have made tribofilm formation harder. However, increasing the concentration to 0.5 wt% reduced adhesive wear on the rake surface and reduced carbon and oxygen levels, showing nanofluid-based aerosol droplets penetrated the cutting zone. The 0.5 wt% Al_2O_3 nanoparticle composition reduces cutting zone friction and improves nanofluid wetting. Due to increased nanofluid viscosity and decreased cooling and lubricating capabilities, adhesive wear increased at 0.75 wt%. Abrasion was also found on the flank. Increased concentration to 1 wt% increased adhesive wear due to nanofluid reduced cutting zone lubrication and hampered thin tribofilm layer development. A nanofluid with 0.5 wt% Al_2O_3 nanoparticles reduces wear band width on flank surfaces, compared to dry cutting and MQL without nanoparticles. The minimum quantity lubrication with nanofluids creates a flank tribofilm compared to MQL without them. MQL with nanoparticles produces the smallest rake surface crater widths.

Acknowledgements

This work was supported by the National Science Centre (Decision No. 2019/35/B/ST8/00552) "Modeling of problems related to hydrodynamics of nanoparticles-filled active medium formation during machining in minimum quantity cooling and lubricating conditions".

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