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INFLUENCE OF THE PRECIPITATION TEMPERATURE ON THE THRUST FORCE AND TORQUE IN DRILLING AN Al 2219-SiC$_p$ COMPOSITE

VPLIV TEMPERATURE IZLOČEVALNEGA ŽARJENJA NA POTISNO SILO IN NAVOR PRI VRTANJU KOMPOZITA Al 2219-SiC

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This paper aims at understanding the influence of the precipitation temperature on the drilling performance of an Al 2219-SiC composite. This type of composite is currently in use in aerospace industries. Drilling is the most frequently employed secondary machining owing to the requirements of the fabrication. This composite was subjected to the precipitation heat treatment, hence calling for a study of the precipitation-temperature effect on the machining performance. The composite was fabricated through the powder-metallurgy route. The drilling trials were conducted with a PCD drill of a 5 mm diameter and 118° point angle. The experiments were conducted with different spindle speeds of (500, 1000 and 1500) r/min and feed rates of (10, 15 and 20) mm/min. The thrust force and torque were the performance indicators. The influences of the mass fraction of reinforcement, the precipitation temperature, the feed rate and the spindle speed on the thrust force and torque during drilling were analyzed. It was observed that the drilling performance was influenced significantly by the feed rate followed by the precipitation temperature, the mass fraction and the particle size of reinforcement. The spindle speed did not influence much the machining performance.

Keywords: powder metallurgy, polycrystalline diamond, precipitation temperature

Namen članka je ugotoviti vpliv temperature izločevalnega žarjenja na zmogljivost vrtanja kompozita Al 2219-SiC. Ta vrsta kompozita se uporablja v letalski industriji. Zaradi potreb pri izdelavi je vrtanje najbolj pogosto uporabljena sekundarna operacija obdelave. Ta kompozit je bil toplotno obdelan z izločevalnim žarjenjem, zato je potrebna študija vpliva temperature izločevalnega žarjenja na zmogljivosti pri obdelavi. Kompozit je bil izdelan po postopkih prašne metalurgije. Preizkusi vrtanja so bili izvršeni s PCD-svedrom premera 5 mm in s konico pod kotom 118°. Preizkusi so bili izvršeni pri različnih hitrostih vrtenja vretena (500, 1000 in 1500) r/min ter hitrostih podajanja (10, 15 in 20) mm/min. Pokazatelja zmogljivosti sta bila potisna sila in navor. Analiziran je bil vpliv masnega deleža delcev za utrjevanje, temperature izločevalnega žarjenja, hitrost podajanja, potisna sila in navor. Opaženo je, da na zmogljivost vrtanja najbolj vpliva hitrost podajanja, nato temperatura izločevalnega žarjenja, masni delež in velikost delcev SiC. Hitrost vrtenja vretena nima bistvenega vpliva na zmogljivost obdelave.

Ključne besede: prašna metalurgija, polikristalni diamant, temperatura izločevalnega žarjenja

1 INTRODUCTION

The ongoing research on materials over the past decades has produced advanced materials with the properties superior to conventional materials such as metal-matrix composites (MMCs). Metal-matrix composites (MMCs) are one of the widely known composite groups due to their superior specific strength, stiffness, wear and corrosion resistances. Silicon-carbide-particulate (SiCp) reinforced aluminium-based MMCs are among the most common and commercially available MMCs due to their economical production.[1] These low-cost composites show their advantages in the applications requiring the ability to withstand a relatively high temperature besides high specific strength, stiffness and fatigue resistance, the typical features of the composite materials in the applications such as drive shafts, cylinder block liners, pistons and automotives.[2] However, because of the hard reinforcement particles in the matrix, MMCs cause very serious problems in machining.[3] For this reason efforts have been made to develop the near-net-shape manufacturing of these products. However, for joining and assembling, secondary machining processes such as drilling, milling, etc., are the prime requirements. Machining, especially drilling, of cast MMC parts is done using diamond-coated tools[4] causing a considerable increase in the tool life. The published literature on the machining of MMCs indicate that only polycrystalline-diamond (PCD) tools allow good tool life as PCD is harder than the reinforcement materials such as SiC or Al_2O_3 and it mostly does not chemically react with the workpiece material. Kilickap et al.[4] examined the tool wear and the machined-surface characteristics during machining SiC-reinforced aluminium-matrix composites with coated and uncoated tool materials for different feeds and speeds. They concluded that a higher cutting speed and a lower feed rate result in good surface quality. While a higher drilling speed reduces the mechanical, thermal shock affecting the machine, a low feed rate maintains an adequate flank clearance to avoid rubbing/sliding. Quan and Ye[5] investigated the hardness and residual stress of the SiC/Al composites in a surface layer affected by the machining and found that cutting at a larger removal rate increases the possibility for the tensile residual stress in the machined surface layers of the composites. A surface integrity study was done by Suresh Kumar Reddy et al.[6] during the end milling of Al/SiC composites. It was concluded from the study that the reinforcement in the composites enhances the machinability in terms of a lower tendency to clog the cutting tool than in the case of an unreinforced Al alloy. In addition, the tendency of the reinforcement to spall off can enhance the chip forcing tendency and the consequent machining. Ciftci et al.[7] proved that cBN is unsuitable for machining the MMCs containing the SiC particles of the average size of 110 µm as there was a heavy fracture of the cutting edge and nose. This could be due to the defects caused when the cBN was inserted onto the core substrate.[8] The tribological properties and mechanical properties of the Al_2O_3-SiC reinforced Al composites manufactured through the powder metallurgy route were investigated by Unlu,[9] Ramulu et al.[10] conducted a drilling of Al_2O_3–aluminium-based metal-matrix composites, using different drills and found that PCD drills outperformed all the other drills in terms of the drilled-hole quality and the drilling forces encountered. Basavarajappa et al.[11] studied the drilling of hybrid metal-matrix composites on the basis of Taguchi techniques and it was revealed that the dependent variables are more significantly influenced by the feed rate than by the speed. Brun and Lee[12] investigated the machinability of the volume fraction Al-40 % SiC composite and concluded that only polycrystalline diamond tools exhibit useful tool life. Quigley et al.[13] studied the factors affecting the machinability of the Al/SiC metal-matrix composite using different tool materials and found that the triple-coated carbide tool, having the top layer made of TiN performed the best in terms of the flank wear compared to the other materials. The literature is mostly concerned with the effect of the reinforcement on machinability; the machine-specific tool/drill/ performance is also reported. Only limited data on the significance of the precipitation temperature is available. The present experimental study aims at investigating the influence of the precipitation temperature, the mass fraction of reinforcement, the size of reinforcement and the machining parameters on the thrust force and torque when drilling the aluminium-matrix composites reinforced with SiC particles; the selected cutting tool for drilling was a fine-grained PCD drill.[14,15]

Table 1: Experimental detail
Tabela 1: Eksperimentalne podrobnosti

Workpiece	Al 2219-matrix composite reinforced with SiC-cold-compacted-reinforcement particle Size – 37 µm and 67 µm mass fraction – 10 %, 15 % and 20 %
Drilling machine	ARIX VMC 100 CNC drilling machine
Tool	PCD drill – twist drill of φ = 5 mm, 118° point angle
Drilling conditions	Speed – (500, 1000, 1500) r/min Feed rate – (10, 15, 20) mm/min Environment – Dry

2 EXPERIMENTATION

The details of the MMC used and the working conditions are listed in **Table 1**.

The matrix and reinforcement material are blended mechanically in a planetary ball mill in order to ensure a uniform distribution of the reinforcement for all the mass fractions and particle sizes. It is then cold compacted uniaxially to form cylindrical specimens with a diameter of 10 mm and length of 20 mm. The workpieces were precipitated in a muffle furnace at three different temperatures of 500 °C, 550 °C and 600 °C for 4 h, and then, each time, rapidly quenched in normal water and artificially aged for 10 h at 170 °C in the same furnace. This precipitation heat treatment was done to study the effect of the precipitation temperature on the machining performance of MMCs. The experimental set up is shown in **Figure 1**. The PCD drill used for the experiment is shown in **Figure 2**. The performance indicators such as the thrust force and torque were measured using a two-component piezoelectric dynamometer and the experiment was repeated three times for the same sample

Figure 1: Photograph of the experimental set up with the dynamometer attachment
Slika 1: Posnetek sestave za preizkuse z dodanim dinamometrom

Figure 2: Photograph of a 5-mm-diameter PCD drill used for the experimentation
Slika 2: Posnetek PCD-svedra s premerom 5 mm, uporabljenega pri preizkusih

and the average values of the output parameters were noted.

3 RESULTS AND DISCUSSION

3.1 Density and porosity

From **Figure 3**, showing 37 μm SiC, it is clear that the structural density increases with the precipitation temperature and also with the mass fraction of reinforcement. A trend change can be seen around 550 °C. In the case of 67 μm SiC, a reduction in the density can mostly be seen above 550 °C. The SiC density increases up to 15 %, followed by a drop.

From **Figure 4**, showing 37 μm SiC, it is clear that the porosity reduces with the precipitation temperature; a visible reduction occurs above 550 °C. This complements the observation on density. In the case of 67 μm SiC, the porosity tends to drop up to 550 °C, followed by a rise (by 10–15 %). Above 550 °C it rises and falls by 20 %. This finding mostly complements the observation on density.

3.2 Hardness and compressive strength

The observed values of the hardness and compressive strength for different mass fractions and precipitation temperatures are illustrated in **Figures 5** and **6**. For 37 μm SiC, the hardness of the MMC tends to rise up to 550

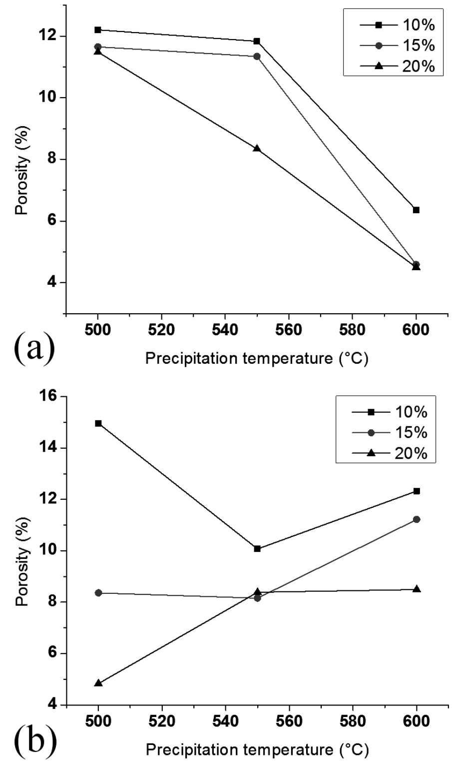

Figure 4: Observed porosity for different precipitation temperatures and mass fractions: a) 37 μm SiC, b) 67 μm SiC

Slika 4: Izmerjena poroznost pri različnih temperaturah izločevalnega žarjenja in masnih deležih: a) 37 μm SiC, b) 67 μm SiC

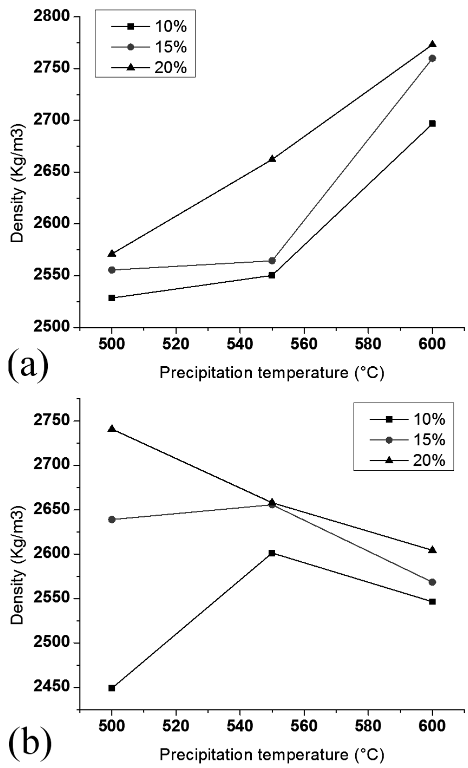

Figure 3: Observed density for different precipitation temperatures and mass fractions: a) 37 μm SiC, b) 67 μm SiC

Slika 3: Izmerjena gostota pri različnih temperaturah izločevalnega žarjenja in masnih deležih: a) 37 μm SiC, b) 67 μm SiC

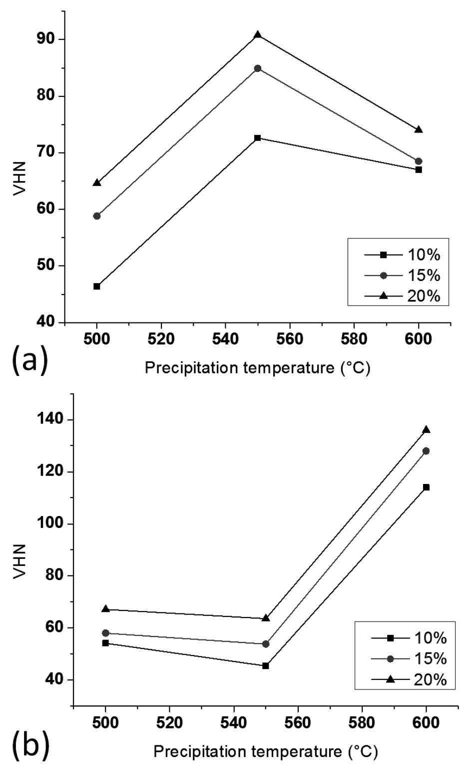

Figure 5: Observed VHN for different precipitation temperatures and mass fractions: a) 37 μm SiC, b) 67 μm SiC

Slika 5: Izmerjena VHN pri različnih temperaturah izločevalnega žarjenja in masnih deležih: a) 37 μm SiC, b) 67 μm SiC

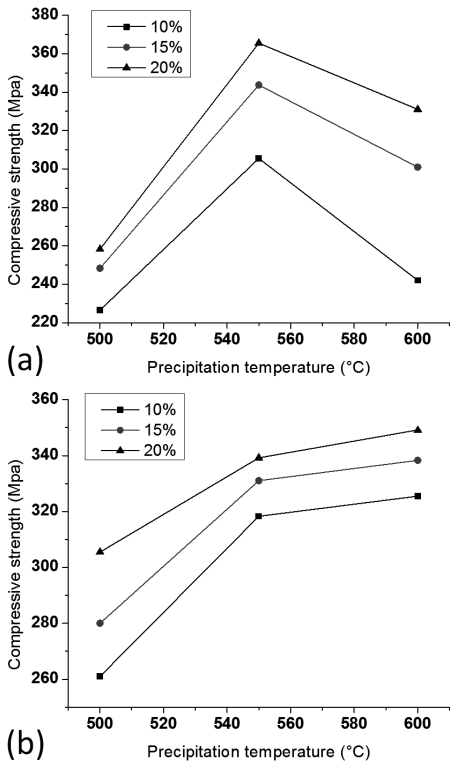

Figure 6: Observed compressive strength for different precipitation temperatures and mass fractions: a) 37 µm SiC, b) 67 µm SiC

Slika 6: Izmerjena tlačna trdnost pri različnih temperaturah izločevalnega žarjenja in masnih deležih: a) 37 µm SiC, b) 67 µm SiC

°C, followed by a reduction. With the increasing mass fraction of reinforcement, the hardness increases. The compressive strength increases up to 550 °C, followed by a drop. It also increases with the massfraction of reinforcement. Considering the finer-sized SiC-particulate reinforcement and precipitation temperature, the density increases with the reduction in the porosity. With a high temperature (above 550 °C) the rise in the density is associated with the hardness or compressive strength. With the rise in the temperature, the matrix densifies heavily. This is associated with a reduction in the flow strength and the consequent densification but also a reduction in the hardness.

The tendency to agglomerate is also lower. With 37 µm SiC, unlike in the case of 67 µm SiC, the MMC exhibits a reduction in the density, especially at the temperature above 550 °C. A high mass-fraction (15 % and 20 %) reinforcement also exhibits only a marginal difference. The porosity of the MMC tends to drop and rise beyond 550 °C. With the increasing reinforcement percentage, a mixed influence on the porosity (especially with the 15 % and 20 % reinforcements) is seen. With the coarser particulates and the increasing precipitation temperature, a great portion of the heat flux could have been absorbed by SiC resulting in a lower matrix flow and the consequent increase in the porosity. However, the MMC exhibits a rise in the hardness beyond 550 °C due to the agglomeration or pooling of reinforcement, the lower matrix flow and increased hardness, also reflected in the increased compressive strength.

3.3 Thrust force and torque

The drilling performance was evaluated in terms of two indicators: the thrust force and torque. The drill thrust force and torque were monitored for all the trials. The effects of the drilling conditions, the precipitation temperature and reinforcement percentage, on the drilling indicators are illustrated in **Figures 7** to **10**. It is

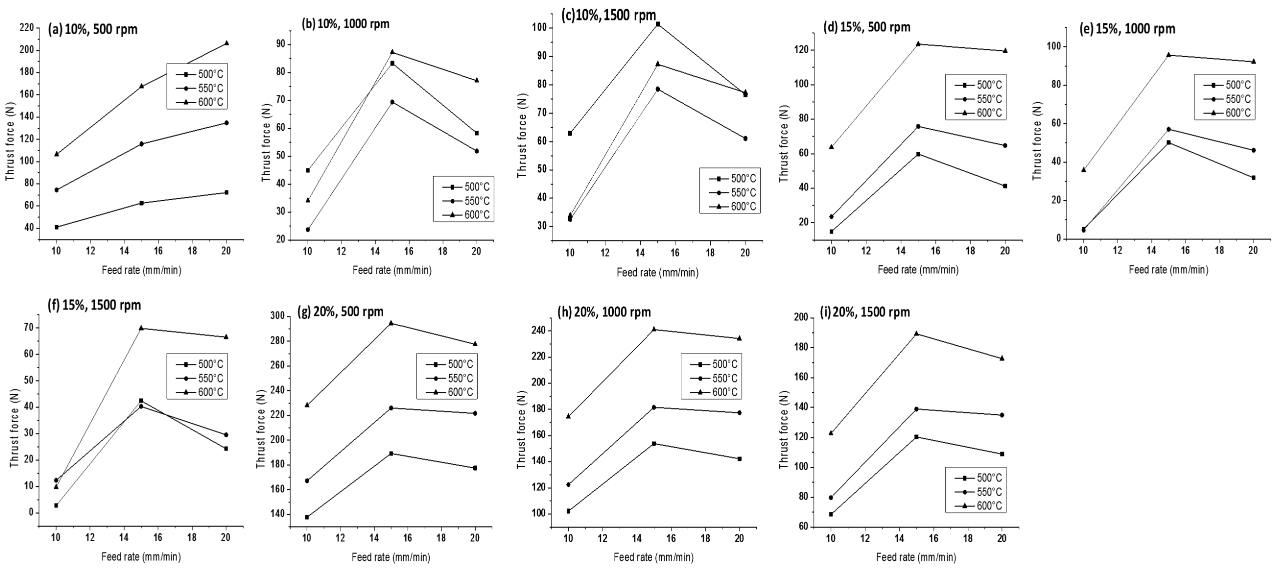

Figure 7: Observed thrust force during the drilling of 37 µm SiC reinforced composites for different mass fractions of reinforcement, precipitation temperatures, cutting speeds and feeds

Slika 7: Izmerjena potisna sila pri vrtanju kompozita, utrjenega s 37 µm SiC, pri različnih masnih deležih, temperaturah izločevalnega žarjenja, hitrostih rezanja in podajanja

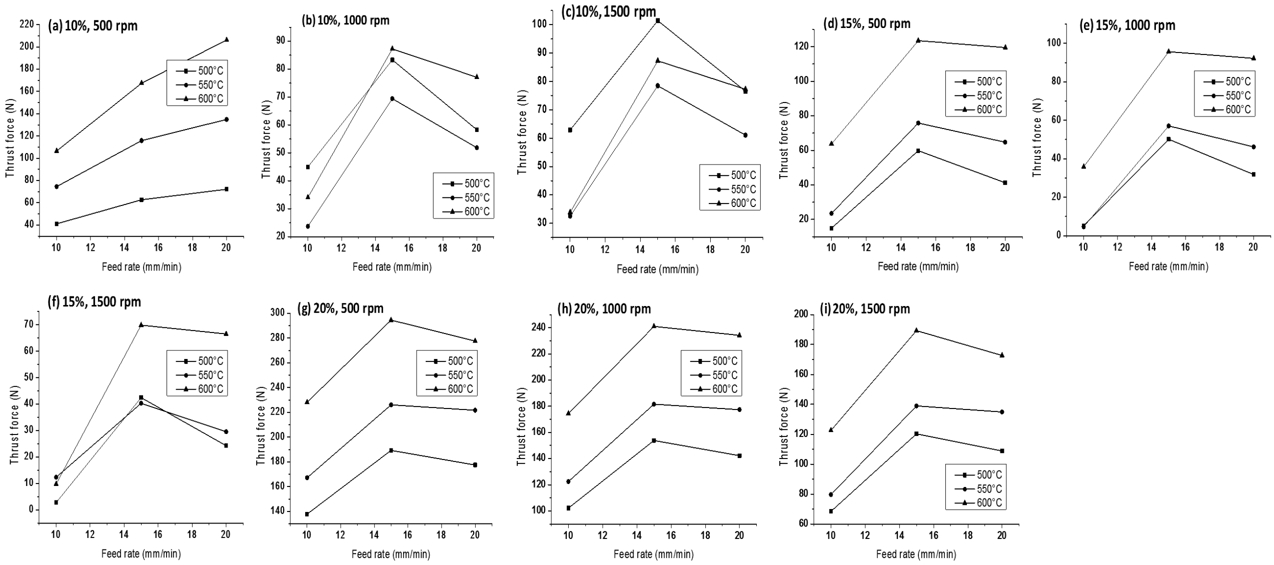

Figure 8: Observed thrust force during the drilling of 67 µm SiC reinforced composites for different mass fractions of reinforcement, precipitation temperatures, cutting speeds and feeds

Slika 8: Izmerjena potisna sila pri vrtanju kompozita, utrjenega s 67 µm SiC, pri različnih masnih deležih, temperaturah izločevalnega žarjenja, hitrostih rezanja in podajanja

seen that the thrust force increases with the feed rate and speed for all the composites. An increase in the feed rate results in a reduction in the effective clearance on the flank surface (the point region) and the consequent rise in the sliding and thrust force. The observed rise in the thrust force with the increasing drill speed could be attributed to a possible thermal softening of the matrix aluminium with the increasing temperature and the consequent clogging of the drill. With regard to the precipitation temperature, it is seen that with the increasing precipitation temperature, the MMC encounters a higher-order thrust force. It is also clear that with a small percentage of reinforcement a distinct influence of a higher precipitation temperature (600 °C) on the thrust force can be observed. With the increasing percentage of reinforcement, the influence of the precipitation temperature is more or less evenly spread. With the increasing precipitation temperature, the microstructure becomes more densified, resulting in the observed rise in the thrust force.

Unlike in the case of the MMC with the small-sized SiC particle (37 µm), the MMC reinforced with the

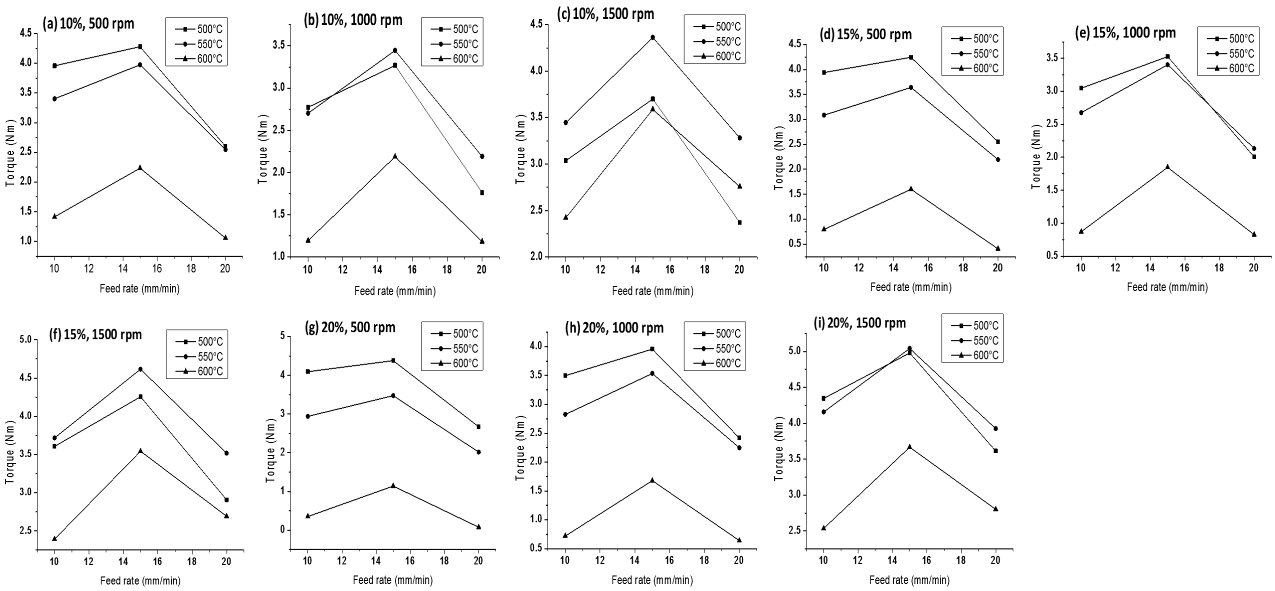

Figure 9: Observed torque during the drilling of 37 µm SiC reinforced composites for different mass fractions of reinforcement, precipitation temperatures, cutting speeds and feeds

Slika 9: Izmerjen navor pri vrtanju kompozita, utrjenega s 37 µm SiC, pri različnih masnih deležih, temperaturah izločevalnega žarjenja, hitrostih rezanja in podajanja

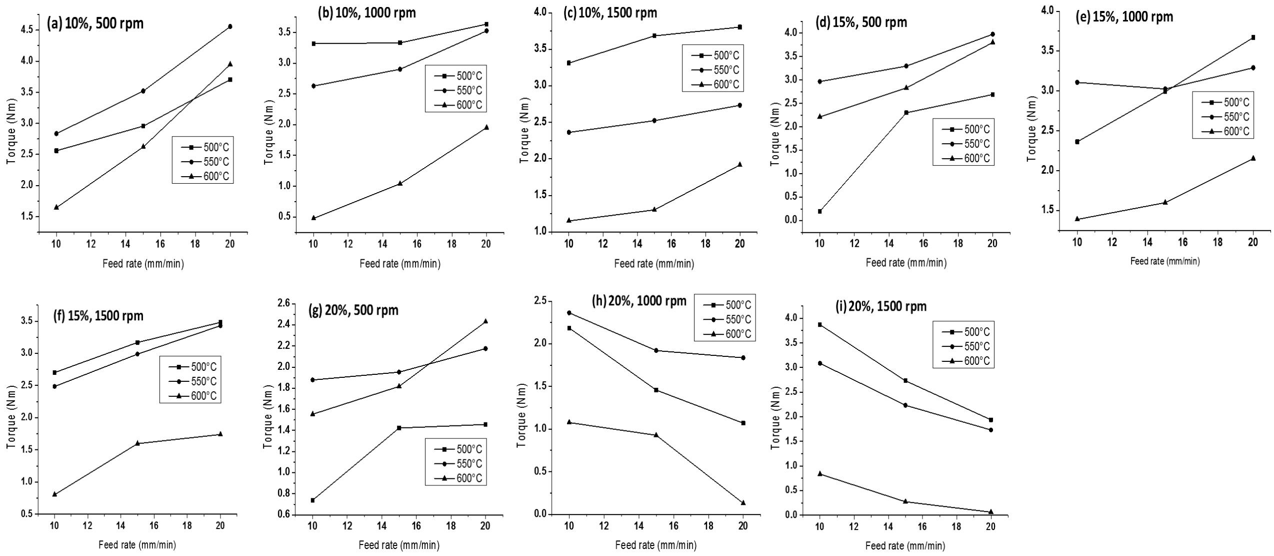

Figure 10: Observed torque during the drilling of 67 μm SiC reinforced composites for different mass fractions of reinforcement, precipitation temperatures, cutting speeds and feeds
Slika 10: Izmerjen navor pri vrtanju kompozita, utrjenega s 67 μm SiC, pri različnih masnih deležih, temperaturah izločevalnega žarjenja, hitrostih rezanja in podajanja

coarse SiC particle (67 μm) exhibits a distinctly different trend. The MMC with 67 μm SiC mostly encounters a smaller-order thrust force, barring a higher mass fraction. Unlike in the case of the 37 μm SiC reinforcement, the MMC reinforced with the coarser particle, encounters a visible reduction in the thrust force with a high feed rate. Also, with the precipitation temperature, a relatively higher-order thrust force is encountered. Unlike in the case of the 37 μm SiC reinforcement, the MMC with the coarser particulate reinforcement encounters a reduction in the thrust force with the increasing drilling speed. With the coarser reinforcement, the MMC experiences a pooling of reinforcement, resulting in a higher heterogeneity of the structure. With the coarser particulate, the heat partition induces a great heat absorption by the SiC reinforcement, resulting in a more porous and less densified structure. The observed rise in the thrust force for the 20 % reinforcement is attributed to the pooling of reinforcement/higher-order heterogeneity, causing an excessive wear of the drill and the consequent rise in the thrust force.

With regard to the torque, for 37 μm SiC composites, it increases with the feed rate from 10 mm/min to 15 mm/min and decreases by 20 mm/min for all the mass fractions of reinforcement and precipitation temperatures. On the other hand, for 67 μm SiC composites, it shows an increasing trend for the 10 % and 15 % mass fractions at all the cutting speeds and precipitation temperatures, but also a decreasing trend for the higher mass fraction of 20 %. The torque was also observed to have an increasing trend with the feed rate for all the mass fractions and precipitation temperatures when the spindle speed was increased from 500 r/min to 1000 r/min; however, it dropped after 1000 r/min. The feed rate is associated with the chip thickness. A high feed rate results in a larger cross-sectional area of the undeformed chip, therefore, increasing the value of the thrust force and torque. It was also observed that the thrust force was high for the composites precipitated at 600 °C and low for the ones precipitated at 500 °C. This may be attributed to the fact that at the higher precipitation temperature, the matrix material becomes soft and increases the area of contact between the tool and the workpiece. At the higher spindle speeds, there was a slight drop in the torque because of a decrease in the contact area between the tool and the workpiece. With

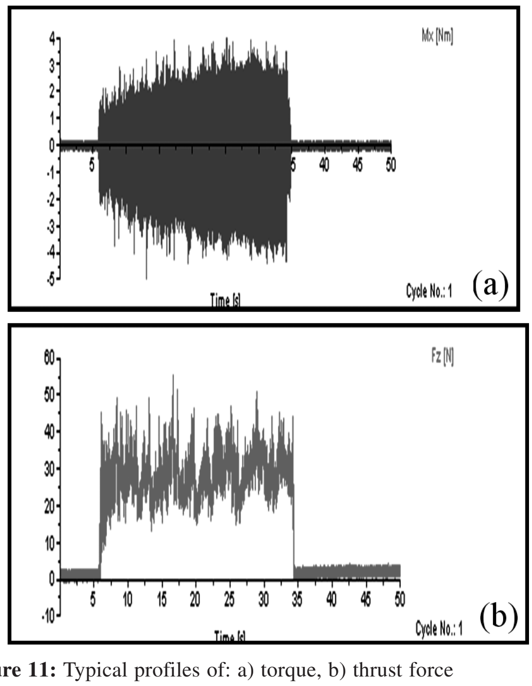

Figure 11: Typical profiles of: a) torque, b) thrust force
Slika 11: Značilen profil: a) navora, b) potisne sile

67 μm SiC composites, the trend for the thrust force and torque was similar to that of 37 μm SiC composites, but the thrust force drops at the higher feed rate of 20 mm/min for all the spindle speeds. This may be due to the larger particle size of reinforcement. The larger particle size results in a poor bonding between the matrix and the reinforcement. At the higher mass fraction and higher spindle speeds, the torque decreases with an increase in the feed rate due to an insufficient bonding between the matrix and reinforcement. In general, for both 37 and 67 SiC reinforced composites, with an increase in the spindle speed, the thrust force and the torque, there is a fall-and-rise trend. This may be initially due to the reduction in the material hardness with the significant increase in the temperature, whereas later the softening of the matrix increases the contact area of the matrix/reinforcement interface, thereby increasing the thrust force and torque. The typical profiles of the thrust force and torque obtained with the data-acquisition system connected to the dynamometer is illustrated in **Figure 11**.

4 CONCLUSION

The thrust force and torque results of the experimental study of the influence of the precipitation temperature during the drilling of the Al 2219-SiC_p composite material using a PCD drill indicated the following conclusions:

The thrust force increases with the feed rate at all the cutting speeds, mass fractions of reinforcement and precipitation temperatures for 37 μm SiC composites, but it shows an increasing and decreasing trend for 67 μm SiC composites. As the mass fraction of reinforcement increased, the thrust force also increased significantly. The thrust force was highly dependent on both the spindle speed and the feed rate, showing an increasing trend in the same way, regardless of the mass fractions of reinforcement and precipitation temperature. The size of the reinforcement particle has an appreciable influence on the thrust force under different experimental conditions. The precipitation temperature also has a significant influence as the lowest thrust force was observed at the higher precipitation temperature of the specimens.

The torque follows the rise-and-fall trend of the feed rate for 37 μm SiC composites, whereas the increasing trend is observed for 67 μm SiC composites. The torque was observed to be the lowest at the lower feed rate and for the higher mass fraction regardless of the sizes of reinforcement. The trend of the torque remains the same for all the precipitation temperatures. The size of the reinforcement particle has an appreciable influence on the torque under different experimental conditions, whereas the precipitation temperature does not have a significant influence on the torque.

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