STUDY OF THE GRINDABILITY OF POWDER METALLURGICALLY PRODUCED ALUMINUM METAL MATRIX COMPOSITE (Al - MMC)

Muhammad A. Shahzad and Jan C. Aurich

Institute for Manufacturing Technology and Production Systems
Department of Mechanical and Process Engineering
University of Kaiserslautern, Germany
shahzad@cck.uni-kl.de

ABSTRACT

Grinding of metal matrix composites is a challenging task on account of the hybrid nature of their constituents. In this study, the influence of grinding process and parameters on surface finish and surface integrity of MMC workpiece was investigated. A high performance resin bonded diamond grinding wheel was used owing to the abrasive nature of SiC reinforcements. As–ground workpiece was characterized by light microscopy, scanning electron microscopy, profilometry and by variations in near surface microhardness values. The emphasis has also been given to the influence of grinding parameters on surface residual stresses. A model of the reinforcement particles–grinding wheel interaction has been proposed. The experimental material was a powder metallurgically produced AA–2124 based metal matrix composite reinforced with 25 volume percent of fine (2-3 µm) SiC particles in T6 heattreatment condition.

1. INTRODUCTION

The present and future high-tech engineering applications require novel materials with unique combination of engineering properties for enhanced performance and optimized serviceability. To meet these milestones, in last two decades, metal matrix composites (MMCs) have emerged as an important class of engineering materials for the structural, wear, thermal, transportation and electrical applications. The combination of metallic matrix and reinforcement phase(s) exerts synergetic effects to produce a new kind of material with a set of physical and mechanical properties not found in the individual constituent materials [1-2]. The higher interest shown towards MMCs owes to their excellent engineering characteristics such as; exceptional stiffness to weight and strength to weight characteristics, higher fatigue strength, better wear and abrasion resistance, lower coefficient of thermal expansion and enhanced corrosion resistance.

The primarily problems in the wide spread industrial applicability of MMCs in high volume applications are higher raw material/processing costs and poor machinability. In order to minimize the costly machining steps and to increase the yield of material, the near step shape processing of MMC components could be a possible solution. Nevertheless, the final machining steps are still needed in order to meet the requirements of surface finish and dimensional accuracy. Among the conventional machining processes, there have been limited scientific efforts directed towards study of the grinding characteristics of MMCs [3-7].

Aim of this study is the analysis of the grindability of MMCs; secondary processing steps i.e. grinding are expected to exert a greater influence on surface finish/surface integrity profiles and ultimately on dynamic mechanical performance of MMC based components as compared to the monolithic metallic materials. The grindability criterion is based upon the data generated relating to surface roughness, surface/subsurface microstructure, residual stresses and variations in the near-surface microhardness. The results presented here may lead to a better understanding of the underlying grinding mechanism of metal matrix composites (MMCs).

2. EXPERIMENTAL PROCEDURE

The experimental material was an AA–2124 based aluminum metal matrix composite (AMC-225xe) reinforced with 25 volume percent of fine (2-3 µm) silicon carbide particles and produced by powder metallurgical processing route, followed by open die forging and T6 heattreatment. Fig. 1 depicts the uniformly distributed SiC particles in an aluminum alloy matrix while important mechanical properties are listed in Table 1.

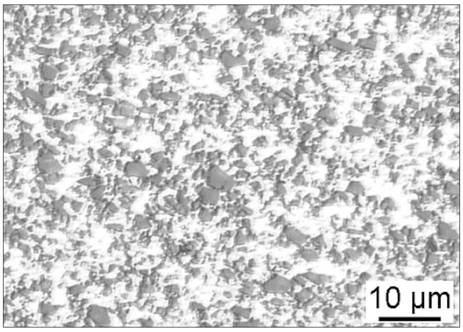

Fig. 1: Microstructure

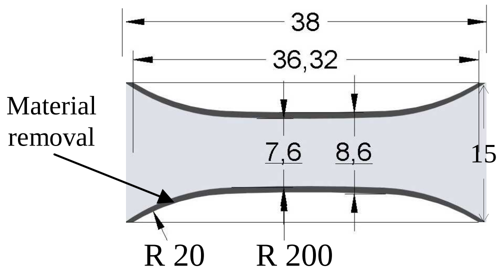

Fig. 2: Workpiece geometry (in mm)

External cylindrical plunge grinding was carried out on a Studer S20 conventional grinding machine using a profiled resin bonded polycrystalline diamond (PCD) grinding wheel. The initial diameter of workpiece was 8.6 mm and was ground until diameter of 7.6 mm; workpiece geometry is illustrated in Fig. 2. Grinding parameters and properties of the grinding wheel are summarized in Table 2. Surface roughness was measured by a stylus profilometer and an average of three measurements was recorded. Light and scanning electron microscopic studies were carried out for the characterization of surface integrity. In order to investigate material adhesion and entrapment, the grinding wheel surface was analyzed by a stereoscope. Based on the microscopic observations, a micromechanical model of the reinforcement particles–grinding wheel interaction has been proposed.

Grinding induced surface residual stresses in axial direction in the matrix alloy were measured by x-ray diffraction using uniaxial sine square ($\sin^2\psi$) method. The residual stresses were measured at four different points separated at a distance of 90° along the circumference of workpiece. Vickers microhardness variation beneath the machined surface was characterized by an indentation of a diamond pyramid using a load of 50 grams for 45 seconds. Grinding chips were collected with the help of a filter cloth at the exit of coolant pipe, mounted in cold curing epoxy resin and was microscopically studied. The grinding experiments were performed using a water based coolant (Petrofer –Emulcut 500, 5% volume) having a flow rate of approximately 5 liter per minute per 1 mm width of the grinding wheel.

MMC Material	E- Modulus	U. T. S.	0.2% Yield Strength	Strain to Fail	Hardness	Density
AA 2124 + 25 % SiCp	115 GPa	650 MPa	480 MPa	5 %	2.158 GPa (HV 220)	2.88 g / cm^3

Table 1: Properties of the experimental material [8]

Grinding wheel		Grinding Parameters	
Grain	Polycrystalline diamond (PCD)	Grinding wheel peripheral speed (m/min)	1870, 2310
Bond	Resin-bonded (KU 144)		
Grit size	D 54	Workpiece speed (m/min)	2.0, 4.5, 10.0, 21.0
Diameter	350 mm		
Width	38 mm	Radial infeed rate (µm/sec)	2, 10
Profile	R 20/R 200		
Concentration	C 125 (31.25 % Volume)	Grinding mode	Up and down
Lining thickness	8 mm		

Table 2: Grinding wheel properties and grinding parameters

3. RESULTS AND DISCUSSION

3.1 Surface roughness

Three surface roughness parameters i.e. average roughness (Ra), ten-point roughness (Rz) and maximum roughness depth (Rmax) were tabulated in order to assess the surface finish of ground MMC workpiece. Fig. 3 shows the effects of grinding mode i.e. down grinding and up grinding. In down grinding, the workpiece rotated along the direction of the rotation of the grinding wheel while in up grinding the workpiece rotation was counter to the direction of rotation of grinding wheel. Down grinding produced a marginally better surface profiles as compared to up grinding, furthermore, the higher peripheral speed of grinding wheel resulted in improved surface roughness. Fig. 4 shows the effects of workpiece speed and grinding wheel peripheral speed on surface finish. Increasing the workpiece speed did not have a positive impact on surface roughness profiles instead it slightly deteriorated Rz and Rmax values.

The presented data depicted that there were no pronounced influences of different grinding parameters on surface finish of the ground metal matrix surface. This illustrates that the surface finish might be a function of the inherent properties of the grinding wheel and, to a larger extent, was independent of different grinding parameters. Results presented in [7] have also shown that the grinding parameters exert a limited influence on measured roughness of alumina short fiber reinforced Al-MMC. Following equation shows the theoretical correlation of grinding parameters and surface roughness and explains limited influence of grinding parameters on surface roughness;

$$Ra \infty V_w^{0.22} a^{0.27} \quad [9]$$

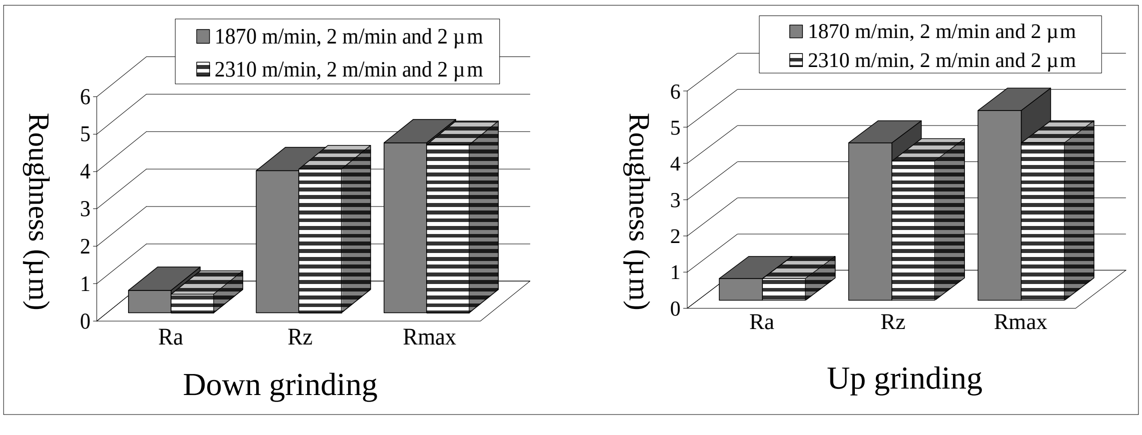

Fig. 3: Effects of down grinding and up grinding on surface roughness profiles

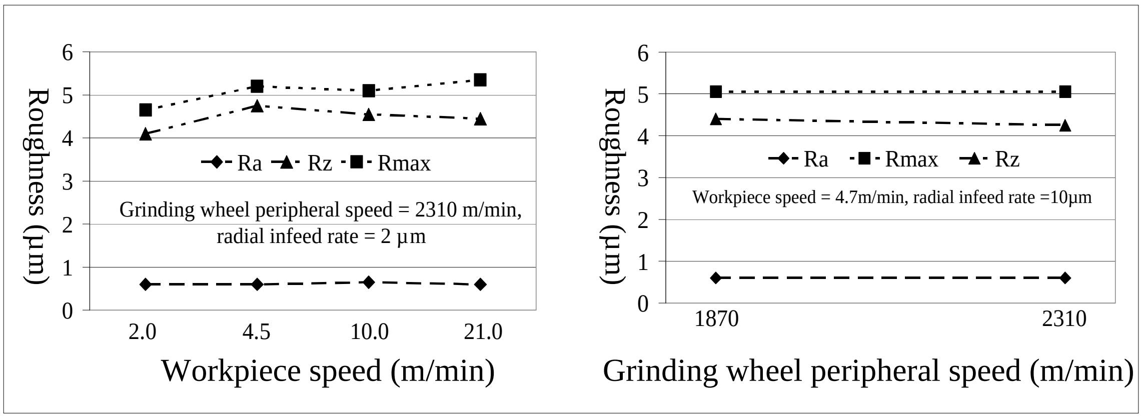

Fig. 4: Effects of work piece speed and grinding wheel peripheral speed on surface roughness profiles

3.2 Microstructure

Study of the surface and sub-surface microstructure revealed that the damage was confined to 0-10 µm top-layer in terms of surface cracks (Fig. 6. C), loose particles (Fig. 6. B) and surface pits/holes (Fig. 6. A). Silicon carbide and aluminum have different grinding characteristics due to their inherent brittleness and ductility respectively. The phenomenon of grinding induced ductile streaks and material spreading was observed in the aluminum matrix alloy while the SiC particles were not cleanly cut due to there higher hardness and fine sizes, instead, they were pulled away from the surface creating deep holes/scratches or pushed in resulting in loosely bonded particles at the surface and/or cracks at the interface between reinforcement particles and matrix alloy. These microstructural irregularities could be potential crack initiation locations during static and especially dynamic mechanical loading. A generalized model of reinforcement particles and grinding wheel interaction, based on microscopic observations, has been discussed in section 3.7. No phenomenon like white layer, common in grinding of steels, was observed in this study.

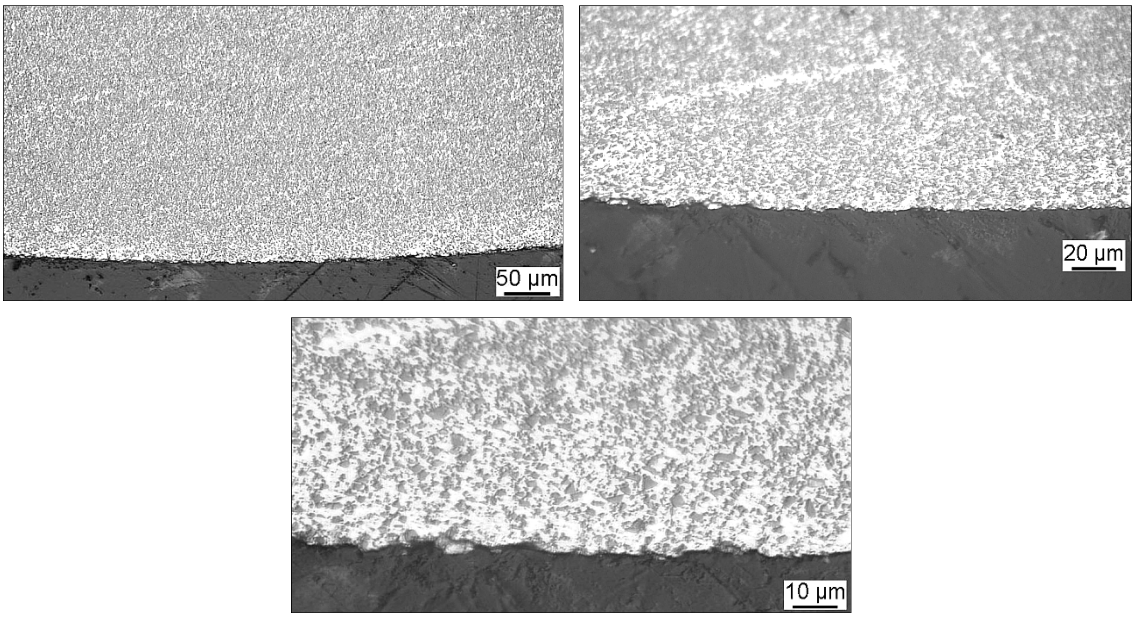

Fig. 5: LM observation of sub-surface microstructure (up grinding, grinding wheel peripheral speed = 1870 m/min, workpiece speed = 2 m/min, radial infeed rate = 2 µm)

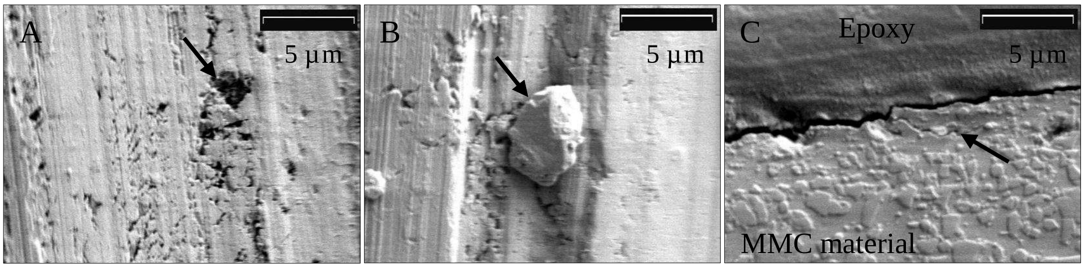

Fig. 6: SEM observation of surface and sub-surface microstructure (A and C; up-grinding, grinding wheel peripheral speed = 1870 m/min, workpiece speed = 2 m/min, radial infeed rate = 2 µm/sec: B; down grinding, grinding wheel peripheral speed = 2310 m/min, workpiece speed = 2 m/min, radial infeed rate = 2 µm/sec)

3.3 Surface residual stresses

Extensive plastic deformation during grinding process changes the surface texture and induces surface residual stresses in the matrix alloy and SiC particles. It is conceivable that both matrix alloy and SiC particles depict different residual stress states. In this study, however, grinding induced surface axial residual stresses in matrix alloy were measured by X-ray diffraction at four different points along the circumference of the specimen, the results are shown in figure 7. The measurements were performed for representative test coupons prepared in up and down grinding mode. The average compressive axial residual stresses for up grinding and down grinding were 134.2 MPa and 137.7 MPa respectively. The idea behind residual stress measurements along circumference of the specimen was to guage the homogeneious distribution of residual stresses. It could be concluded that the measurements were in close tolerance and almost uniformly distributed along the cicumference of the workpiece.

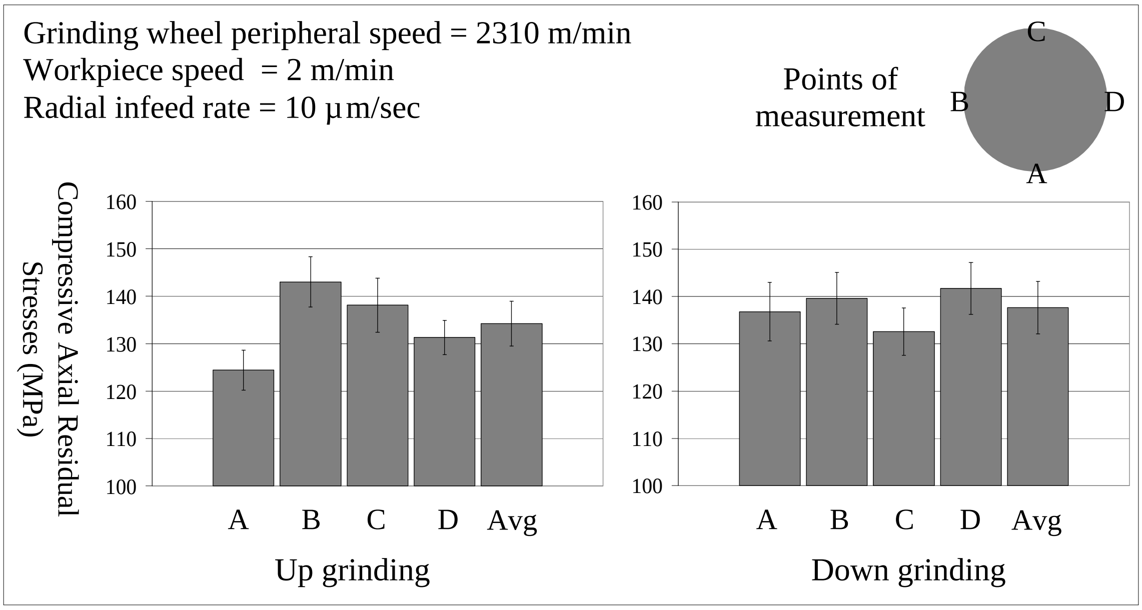

Fig. 7: Surface residual stresses in the matrix alloy AA – 2124

3.4 Microhardness

Tests were conducted in order to assess the sub-surface changes in the microhardness. Measurements were repeated three times at a specified depth of indentation from the ground surface, the results are summarized in Fig. 8. It was found that there was no formation of sub-surface soft heat affected zone and that the microhardness values were scattered and a maximum of HV 274 was observed at a distance of 90 µm from the top surface, the core hardness of the experimental material was HV 220. The higher thermal conductivity of the matrix alloy might have played a dominant role in dissipating the heat from grinding zone and minimizing the sub-surface heat affected zone. Increase in dislocations density and residual stresses owing to severe plastic deformation might have contributed towards an increase in sub-surface microhardness until a depth of 120 µm from the machined surface.

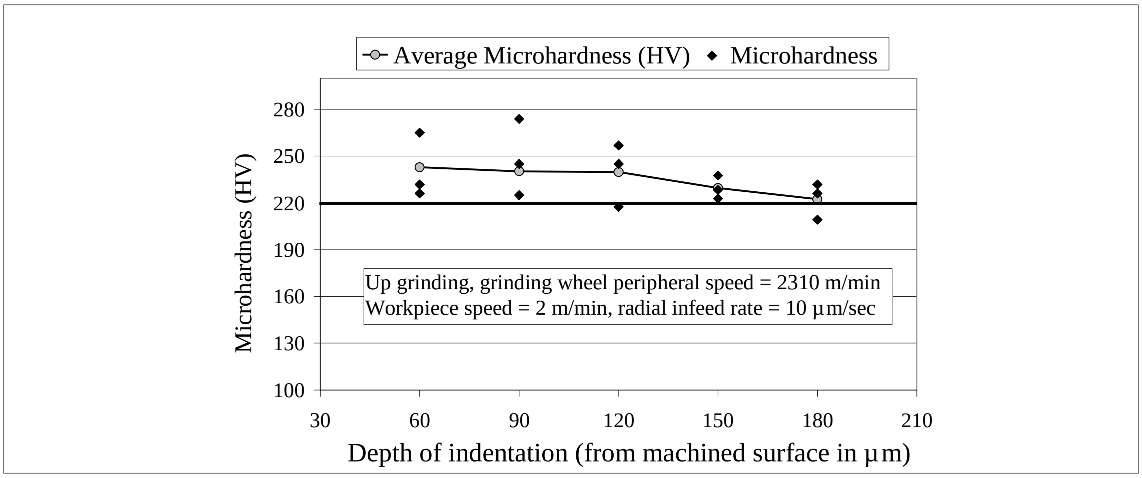

Fig. 8: Microhardness variations beneath the machined surface

3.5 Grinding chips

Grinding chips were collected using a filter cloth at the exit point of coolant pipe, dried, mounted in cold curing epoxy and were microscopically studied. Fig. 9a shows the typical form and shape of chips obtained in this study. It was observed that chips were present in the form of a cluster of slightly elongated shape and were not melted. Chips microstructure is also indirect assessment of interface strength between reinforcement particles and matrix. In some instances, silicon carbide particles embedded in aluminum were observed exhibiting good interface bond strength. Material adhesion in the form grinding chips was also noticed during the microscopic observation (Fig. 9b) of grinding wheel; the PCD grains are also clearly visible. The soft aluminum matrix alloy might result in wheel clogging because of inherent lack of response of soft alloys towards grinding.

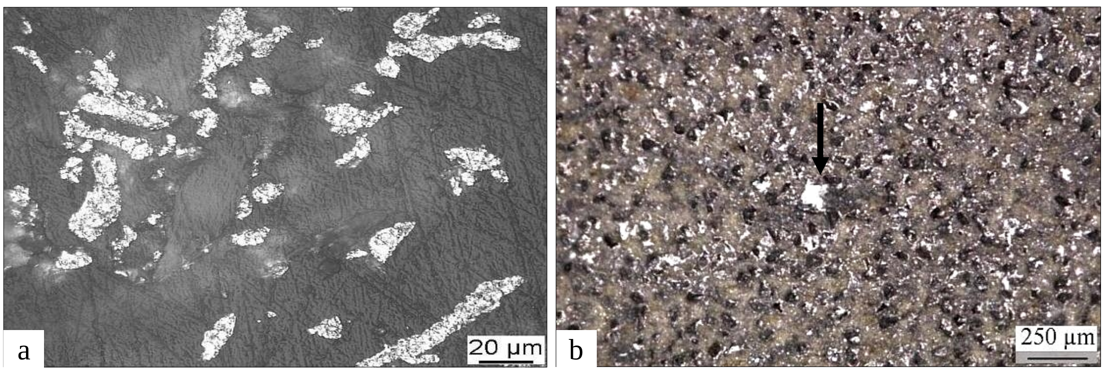

Fig. 9(a): Grinding chips produced during grinding

(b): Material adhesion at the grinding wheel surface (25 minutes of grinding work

3.7 Micromechanical model of reinforcement particles – grinding wheel interaction

SiC particles due to their higher hardness and fine size were not completely cut; instead, they were pulled away from the surface creating deep holes/scratches or pushed in resulting in loosely bonded particles at the surface and/or cracks at the interface between reinforcement particles and matrix alloy. Based on microscopic observations, a theoretical model of the reinforcement particles and grinding wheel interaction is illustrated in Fig. 10. This model shows the inherent characteristics of the grinding process of MMCs. First sketch in Fig. 10 shows the imaginary line of grinding pass and the orientation of reinforcement particles falling in the path of grinding wheel, surface formation as a result of single grinding pass is shown in second sketch. It is thought that the orientation and centroid of reinforcement particles with respect to the cutting path of grinding wheel plays important role in removing the particle from matrix and in the formation of interface crack or loosely adhered surface particles.

If the centroid of reinforcement particle is above the cutting axis of the grinding wheel, it will be most probably plucked away from the matrix leading to the formation of surface hole/pit (particle 1). For particle 2, the centroid is falling well below the cutting axis of the grinding wheel. This particle is not removed from the surface; however, the impact of grinding wheel might result in the formation of the crack at particle – matrix interface. At the point of impact, the grinding wheel is also slightly deflected creating a bumpy surface profile. The center of particle 3 falls just below the imaginary cutting axis of the grinding wheel. Depending upon the grinding parameters and grinding forces at the point of impact, the particle will be probably removed in case of rough grinding and higher grinding forces. Fine grinding parameters and lesser grinding forces might result in loosely adhered particle at the surface. However, the higher hardness of PCD grit may result in micro-machining of the SiC particle.

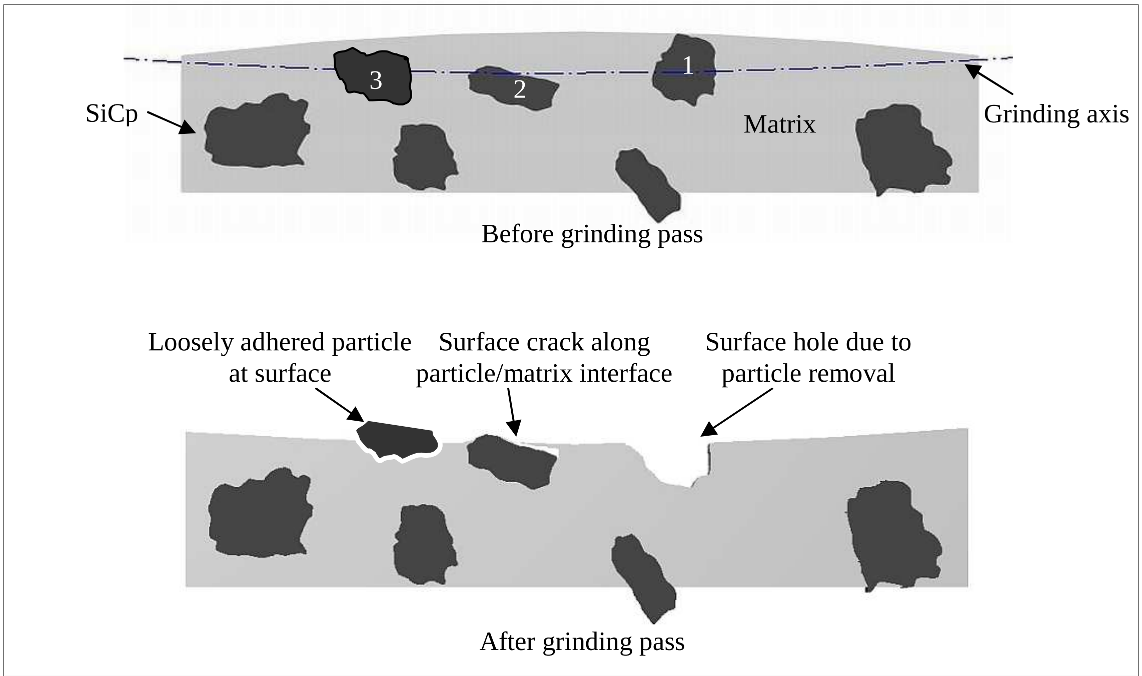

Fig. 10: Micromechanical model of the interaction of reinforcement particles and grinding wheel

4. CONCLUSIONS

Aluminum metal matrix composite (Al-MMC), 25 volume percent of fine (2-3 µm) embedded in an AA–2124 matrix alloy, was ground using a high performance polycrystalline diamond based grinding wheel. Analysis of the surface finish profiles (Ra, Rz and Rmax) illustrated that the surface finish of the ground Al-MMC is mainly a function of the inherent characteristics of the grinding wheel. Study of surface and sub-surface microstructure revealed that the damage was confined to 0-10 µm top-layer in terms of surface cracks, loosely adhered particles and surface pits/holes. Micromechanical model depicted possible scenarios during interaction of reinforcement particles with grinding wheel. X-ray diffraction analysis showed the presence of compressive axial residual stresses in the matrix alloy. Microhardness measurements showed that there was no formation of grinding induced soft sub-surface heat affected zone, possibly due to the higher thermal conductivity of matrix alloy. Grinding chips were present in the form of a cluster of slightly elongated shape and were not melted, chips adhesion on the surface of grinding wheel was also observed.

Further studies involving varied size and volume percentage of reinforcement particles are recommended in order to arrive upon an enhanced understanding of grinding behavior of metal matrix composites.

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REFERENCES

1. Clyne T. W., Withers P. J., *“An introduction to Metal Matrix Composites”* Cambridge University Press, U. K.1993.
2. Aurich Jan C., Shahzad Muhammad A., “Performance oriented machining of metal matrix composites”. *Composite Materials; Development-Applications-Recycling*, 1/2008:24-25.
3. Zhong Z. W., “Grinding of aluminum -based metal matrix composites reinforced with Al_2O_3 or SiC particles”, *Int. J. Adv. Manuf. Technology,* 2003; 21: 79-83.
4. Sun F. H., Li X. K., Wang Y., Chen M., “Studies on the grinding characteristics of SiC particle reinforced aluminum-based MMCs”. *Key Engineering Materials*, 2006; Vols. 304 – 305: 261-265.
5. Antoniomaria D. Ilio, Alfonso Paoletti, “A comparison between conventional abrasives and superabrasives in grinding of SiC-aluminum composites”. *International Journal of Machine Tools & Manufacture*, 2000; 40: 173-184.
6. Zhong Z., Hung N.P., “Diamond turning and grinding of aluminum–based metal matrix composites”. *Materials and Manufacturing Processes*, 2000; 15/6: 853-865.
7. Chandrasekaran H., Johansson J. O., “The role of material and grinding parameters in grinding of alumina fiber reinforced aluminum alloys” *Machining of Advanced Materials,* Proceedings of the International Conference, Gaithersburg, USA, July 20-22, 1993: 55-70.
8. Product Datasheet, Aerospace Metal Composites Limited, England
9. A. D. Ilio, A. Paoletti, V. Tagliaferri, F. Veniali, “An experimental study on grinding silicon carbide reinforced aluminum alloys” *International Journal of Machine Tools & Manufacture*, 1996; 36-6: 673-685.