

Performance Evaluation of Custom Manufactured WC-12wt%Co Abrasive Grinding Wheel

A.A. Enever^{1,3}, G.A. Oosthuizen¹, N. Sacks^{2,3}

¹Department of Industrial Engineering, Stellenbosch University

²School of Chemical and Metallurgical Engineering, University of the Witwatersrand

³DST-NRF Centre of Excellence in Strong Materials, South Africa

Abstract

Grinding is a material removal process making use of geometrically nondefined tool edges, or abrasive particles, which is bonded together in the form of a grinding wheel to cut, or machine, a material into shape. The materials used as the abrasive is most commonly aluminium oxide or silicon carbide. These abrasives are normally bonded with a vitrified or resinoid bonding to form the grinding wheel. Grinding wheel applications typically range from wood and soft metal grinding to hard carbide steel and ceramic grinding. There is thus a gap in the variety of available grinding wheels for a multipurpose grinding wheel. This paper will explore the application of tungsten carbide (WC-12wt%Co) as an alternative abrasive material for a grinding wheel and will be bonded with inexpensive resin. Tungsten carbide falls in the cemented carbide family of hard materials, having a high hardness-to-toughness ratio. This is advantageous for the machining of titanium alloys and is the workpiece material. The paper will describe the process of custom manufacturing of the WC-12wt%Co grinding wheels for experimental purposes.

Keywords

Grinding, cemented carbide, titanium

1 INTRODUCTION

Grinding wheel usage date back many hundreds of years to when only simple hand-held tools were used due to the lack in machine tool technology. It's been utilised in manufacturing for more than 100 years. The 20th century saw the growing use of grinding wheels as a modern machining process, leading to scientific analysis and research of the grinding process [1].

The abrasives used in the production of grinding wheels have traditionally been the same for many years, mainly due to their successful performance characteristics and cost effectiveness. These abrasives are now being challenged by cemented tungsten carbide, which is harder and tougher than most traditional abrasives. WC-12wt%Co is used in this research work as abrasive medium in the production of mounted point grinding wheels. The performance characteristics of these custom manufactured mounted points are reported on, which is to some extent related to the effectiveness of their design and the manufacturing technique.

2 GRINDING

Grinding is the machining action of multiple abrasive grains on the face of a grinding wheel which resembles a complex cutting tool with cutting angles and voids for chip clearance. The abrasives are randomly shaped and arranged in the grinding wheel with the cutting edges undescribed with reference to a single particle, and thus nondefined.

The wheels rotate at high rotational velocities to remove material from softer workpiece materials in large volumes with coarse and uneven surface finishes or in small volumes with smooth and fine surface finishes [2].

A grinding wheel consists of three main components; the abrasive grains, binder and filler. The filler material is very soft and acts as space keeper to create voids, but is not found in all grinding wheels. The voids are necessary for chip clearance and cooling of the grinding wheel. There are six main classifications for grinding wheels which are related to the shape of the produced surface (face, peripheral, thread, gear, profile and form grinding) of which peripheral grinding is used in this study [2], [3].

The size of abrasive grains are made from material having a grain size numeral of 8 (coarse, $\pm 2.8\text{mm}$) up to 1200 (very fine, 0.003mm). The bonding medium produces extremely soft to extremely hard bonding strengths or grades. A resin bonding is used in this study, which is less sensitive to sudden temperature changes and shocks than vitrified bonded wheels [2].

Grinding wheel wear can take place in the abrasive grains or in the bonding material. The wear mechanisms are abrasive grain dulling or grain/bond breakage. When dulling occurs, flat wear areas are formed on the edges of the grinding surface, leading to increased grinding forces and elevated temperatures. This wear mechanism usually occurs when the wheel is submitted to gentle grinding

conditions. When the grinding loads are higher, the abrasive/bond breakage wear mechanism will lead to higher volumetric wear and cause constant grinding forces and temperatures [3].

There are three important cutting edge angles for chip formation, which are clearance angle (α), rake angle (γ) and wedge angle (β). These angles can only be indicated with statistical parameters such as mean values or distributions, since a multitude of cutting edges are present in different orientations on any given surface. These angles can be seen in Figure 1 [3].

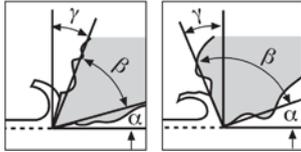


Figure 1 - Cutting edge angles important for chip formation [2].

A large amount of friction occurs between the grains and the workpiece during grinding. Almost all of the mechanical energy supplied for grinding is converted into heat due to the friction. Figure 2 shows the dissipation of mechanical input energy into various other output energies [3].

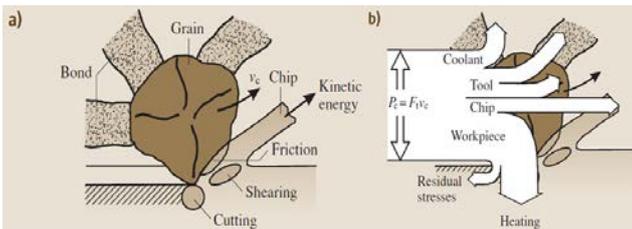


Figure 2 - Energy conversion; a) Effects of energy conversion, b) Energy flows [3].

Mechanical or thermal overstressing of the workpiece material may adversely affect its characteristics such as visible marks due to regenerative chatter, tensile residual stresses, surface hardening and even cracks [3].

3 WC-12WT%CO AS ABRASIVE MEDIUM

Tungsten carbide (WC) is a suitable material for wear and corrosion resistant applications due its high hardness and chemical stability. It has low toughness and is thus brittle. The toughness of WC is improved by adding a ductile metal, such as cobalt. The adding of cobalt shifts the category of WC-Co to that of a cemented carbide (or cermet), which has a good combination of hardness and toughness [4], [5].

Its application is extensive, ranging from cutting tools, rock-drilling bits, dies for powder metallurgy, wire drawing dies, and indenters for harness testers. WC-Co parts and components are commonly manufactured by compacting and sintering WC-Co powder into a desired geometry, or by thermally

spraying the powder onto the outside of an already manufactured geometrical part.

The mechanical, thermal and tribological characteristics of WC-Co are greatly dependent on the cobalt content and WC particle size. The grain size of WC is typically in the range of 0.1 μ m to 10 μ m and cobalt content of between 3 and 30 wt% is used. The decreasing of WC grain size increases the hardness of WC-Co and an increase of cobalt content increases ductility. Although a decrease in grain size increases hardness, coarser grains of hardness 1000 – 1600 HV has shown greater wear resistance than smaller grains. The smaller grains thus do not always produce better wear resistance [6].

The WC-Co used in this study has 12wt% cobalt content and was acquired from Global Tungsten & Powders in the USA as their SX408 powder type. The WC-12wt%Co was acquired in powder form with particle size ranging from 10 μ m to 44 μ m and having a spherically agglomerated geometrical structure.

4 GRINDING WHEEL BINDER

Resins are thermosetting composite plastics in a polymer matrix. They do not produce solid reaction products and thus have low cure shrinkage. Epoxy resins have good adhesion to other materials, environmental and chemical resistance and chemical and insulating properties [7].

The most commonly used resin in the production of resinoid bonded grinding wheels is phenolic resin. For this study however, an epoxy resin is used. The tensile and compressive strength mechanical property of both resins are similar, as well as their respective preparation methods.

The major advantage phenolic resin has over epoxy resin is its slightly higher thermal decomposing temperature limit. The phenolic resin can thus withstand slightly higher temperatures than the epoxy resin. This will however not affect the research study as the temperatures reached during grinding is well above that of either resin's decomposing temperature threshold [8].

Phenolic resins contain phenols which are toxic, leading to strict exposure limits. They are also more expensive than epoxy resins. From a safety and economic point of view it becomes clear that epoxy resins are preferred for the production of custom grinding wheels [8].

The epoxy resin used in this study is the AR 600 brand with AH 2336 hardener system from Aeronotec CC. It is a high performance epoxy resin with low viscosity, having a combination of good mechanical and thermal properties.

5 RESEARCH METHODOLOGY

5.1 Determination of resin content

The use of epoxy resin as binder in the manufacturing of mounted points poses the challenge of determining the optimal resin-to-binder ratio. It is suggested that the maximum resin content in a resin bonded grinding wheel should not exceed 30wt% if effective and functional grinding of the wheel is desired [9]. This amount of resin is based on the use of abrasive particles with a size range of 110 μm - 150 μm . Since the WC-12wt%Co powder used in this study is smaller ($\pm 46\mu\text{m}$), the amount of resin will be less than the suggested maximum of 30wt%.

The reason for this lower resin content is due to the wetting effect the resin has on the abrasive particles. In the case of a large particle, more liquid resin is required to cover the entire particle's surface due to its relatively large surface area. When the smaller particles are used, less liquid resin is required to cover and wet the particle's relatively small surface area. The complete covering/wetting of a particle's surface area with resin is necessary to ensure the bonding of the particles to one another and to form a grinding wheel, or in this study, a mounted point.

The amount of resin in a grinding wheel can also affect its strength and grinding efficiency. Excessive resin with relatively small abrasive particles produces a strong grinding wheel, but the resin will prohibit the effectiveness of grinding. Conversely, if too little resin is added, the abrasive particles will be able to do the machining work effectively, but the wheel will not be strong enough to withstand the grinding forces. The strength and work effectiveness of the grinding wheel is thus dependent on the wheel's resin content.

The lowest resin content producing the strongest mounted points should thus be determined. The main stress during operation should first be determined and since the mounted points are spinning at high rotational velocities, the main stresses imparted on the mounted point will be due to centrifugal forces from spinning. By using rotating disc theory, the main stress during rotation can be determined. Figure 3 below indicates the mechanics during centrifugal loading.

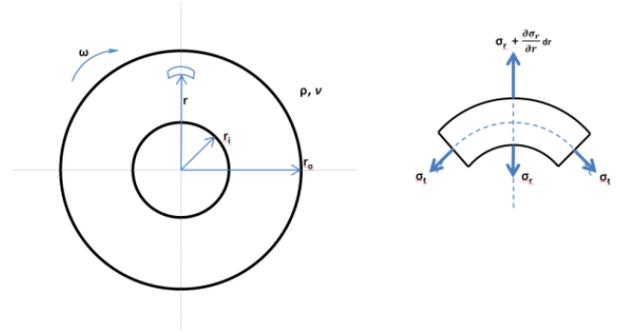


Figure 3 - Induced stresses during centrifugal loading of a rotating disc [8].

The disc has rotational angular velocity ω (rad/s), relative composite density ρ (g/cm^3), Poisson's ratio ν (dimensionless), inner radius r_i (m) and outer radius r_o (m). A section can be taken at any radial distance r from r_i to r_o where the stress equilibrium indicates the internal stresses. Stress in the radial direction is radial stress, σ_r , while stresses along a circular path are tangential stress, σ_t [8].

For the given section, the tangential stress is equal in opposite directions, while the radial stress increases from the inner to outer radii of the section. These stresses can be calculated for a given radial distance between r_i and r_o with the following equations [10]–[12].

$$\sigma_r = \frac{3+\nu}{8} \rho \omega^2 \left(r_i^2 + r_o^2 - \frac{r_i^2 r_o^2}{r^2} - r^2 \right) \quad (1)$$

$$\sigma_t = \frac{3+\nu}{8} \rho \omega^2 \left(r_i^2 + r_o^2 + \frac{r_i^2 r_o^2}{r^2} - \frac{1+3\nu}{3+\nu} r^2 \right) \quad (2)$$

The composite density and Poisson's ratio is required, which can be calculated with Equation (3) and (4) with the variables as seen in Table 1 below.

	Density (g/cm^3)	Poisson's ratio	wt%	vol%
WC-12wt%Co	3.4	0.23	90	74
Resin	1.1	0.31	10	26

Table 1 - WC-12wt%Co and epoxy resin material characteristics [8].

$$\rho_{\text{composite}} = \text{wt}\%_{\text{WC-12Co}} \cdot \rho_{\text{WC-12Co}} + \text{wt}\%_{\text{resin}} \cdot \rho_{\text{resin}} \quad (3)$$

$$\nu_{\text{composite}} = \text{vol}\%_{\text{WC-12Co}} \cdot \nu_{\text{WC-12Co}} + \text{vol}\%_{\text{resin}} \cdot \nu_{\text{resin}} \quad (4)$$

The density of cemented tungsten carbide in Table 2 is that of its apparent powder density. The fully dense true density of WC-12wt%Co is 14.88 g/cm^3 . By implementing Equation (1)-(4) with the variable values in Table 2, the resulting stress distribution of Figure 4 can be generated along the radius of the mounted point for a sample containing 10wt% of resin.

Composite density (ρ_c)	3.17 g/cm ³	
Composite Poisson's ratio (ν_c)	0.25	
Rotational speed (ω)	20 000 rpm	2094.39 rad/s
Inner radius (r_i)	0m	
Outer radius (r_o)	0.02m	

Table 2 - Tangential and radial stress calculation variables.

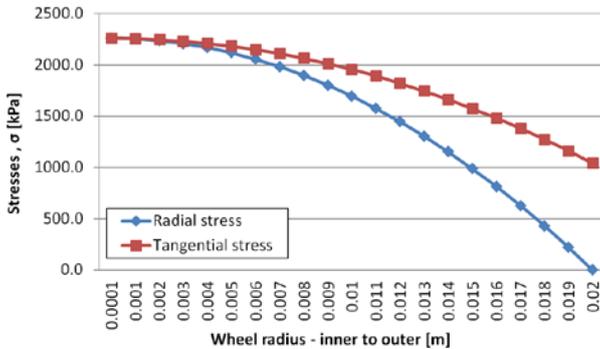


Figure 4 - Tangential and radial stress distribution along the radius of a mounted point [9].

The resulting stress distribution in Figure 4 indicates the major stress in a rotating mounted point is a tangential (tensile) stress. Thus the tensile strength of samples with various resin-to-abrasive ratios has to be tested. The structure of the resin-abrasive composite mixture resembles that of concrete or stone and thus the Brazilian Disk test can be used to determine its tensile strength.

The Brazilian Disk test is an indirect tensile strength test in which a disk-shaped sample is diametrically compressed to failure. This testing method assumes that failure of the disk samples will occur within the material at the point of maximum tensile stress. The failure point occurs at the centre of the disk where the tensile stress is greatest. As the disk is compressed from the top and bottom, a tensile force is applied to the central line trying to pull the sides away from each other. The testing orientation, loading direction and failure mode during the Brazilian Disk test can be seen in Figure 5 [13], [14].

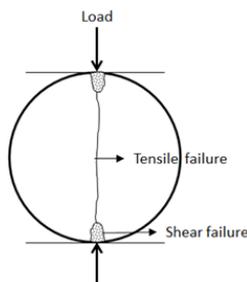


Figure 5 - Test sample orientation, loading direction and failure mode during the Brazilian Disk test [13].

Samples in the form of a 30mm diameter disk were made containing 10wt%, 12wt%, 14wt% and 16wt% resin. They were compressed unto failure and the failure pressure recorded. Figure 6 shows the four disks after failure. Note the upper and lower loading points (flattened area on outside periphery of disks),

shear failure area (triangular failure section adjacent to loading points) and central crack.

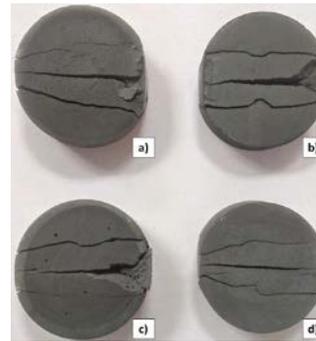


Figure 6 - Brazilian Disks test specimens after failure: a) 10wt%; b) 12wt%; c) 14wt%; d) 16wt%.

The tensile strength of the samples is calculated with Equation (5) below.

$$\sigma_t = 0.636 \frac{P}{Dt} \quad (5)$$

In Equation (5) P represents the applied load at failure (N), D the diameter of the disk (m) and t the thickness of the disk (m). The variables for each tested sample and its respective tensile strength can be seen in Table 3. Figure 7 depicts the tensile strength of the samples graphically.

	10wt%	12wt%	14wt%	16wt%
Disc thickness (mm)	8.94	9.5	9.9	11.6
Load at Failure (N)	188	214	321	374.5
Tensile strength (kPa)	445.86	477.75	687.74	684.55

Table 3 - Brazilian Disk test samples thickness, load at failure and tensile strength.

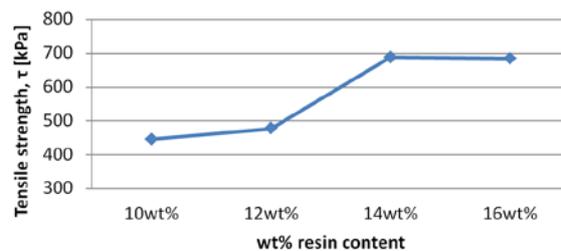


Figure 7 - Resulting tensile strength of resin-abrasive composite material [8].

From these results, the 12wt% and 16wt% resin contents were chosen for mounted point production. The 12wt% resin content is chosen for its slight strength advantage over that of the 10wt% resin content, as well as its lower resin content compared to the 14wt% and 16wt% resin content samples. The 16wt% resin content is chosen for its high strength, as well as its internal structure. The internal structure of this sample contains many air pockets, which is beneficial to the grinding process in that it helps to remove heat and grinding swarf from the area being grinded.

The comparison of the internal structures of the 12wt% and 16wt% resin content samples can be seen in Figure 8.

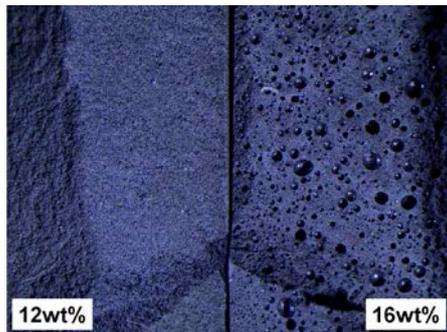


Figure 8 - Internal structure of the 12wt% and 16wt% resin content samples.

5.2 Mould design and mounted point production

The mounted points are produced in a mould with specific geometrical dimensions. These dimensions are important to ensure consistency of produced mounted points and accuracy of grinding. The design of the mounted points is a combination of W185 and W202 mounted points from the ISO 603-17 standards document.

The mounted points have a central stainless steel spindle onto which the resin-abrasive composite is bonded. The mould for producing the mounted points consists of a base plate onto which the main mould body is bolted and an end cap to stabilize the top part of the spindle while the resin is curing. The mould will produce a mounted point with diameter 20mm, height of 13mm and a spindle diameter of 3mm. The assembly of the mould can be seen in Figure 9.

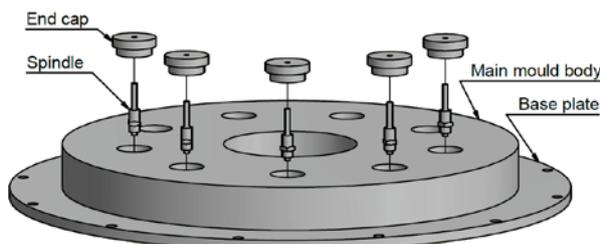


Figure 9 - Mould assembly for the manufacturing of custom mounted point grinding wheels.

The resin and abrasive powder is mixed prior to moulding in specific quantities to produce a 12wt% or 16wt% resin content. This mixture is placed in the mould and left to pre-cure at ambient room temperature for a minimum of 12 hours. After this pre-curing stage, the entire mould is placed in a hot box thermal resin curing oven to thermally cure the resin-abrasive composite to maximum strength. The process takes place at 80°C for 2 hours, followed by 150°C for 3 hours and finally at 180°C for 4 hours.

The hot box oven is switched off after the 9 hours and the mould left inside to slowly cool to ambient room temperatures. At this stage the resin is fully

cured and the mounted point(s) can be removed from the mould. Figure 10 shows a cross section of the setup of the mould with cured resin-abrasive composite.

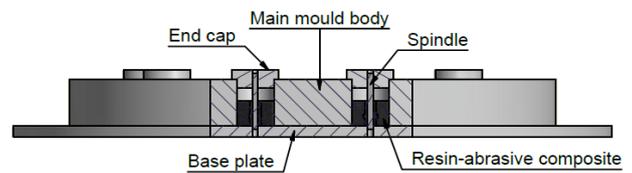


Figure 10 - Cross section of mould setup before mounted point removal.

5.3 Experimental design and setup

To determine the performance of the resin-abrasive ratios and the manufacturing process to produce the mounted points, the manufactured points is to grind a workpiece material and characteristics measured. The performance of the mounted points is characterized by the wear rate of the point, the workpiece material surface integrity and surface finish. The chosen workpiece material for experimental testing of the mounted points is Ti6Al4V. This titanium alloy is both hard and tough and has a unique strength-to-weight ratio [15].

For the experimental tests, only two variables are changed; spindle rotational speed and traversing feedrate of the mounted points. All mounted points for experimentation are manufactured with the same size abrasive particles. During grinding, the depth of cut for each grinding pass will stay constant and thus the perpendicularly applied grinding force as well. The transverse grinding force will change due to the different combinations of spindle speed, feedrate and resin content.

Each variable is changed between three values. For each combination of spindle speed and feedrate, only one mounted point will be used to ensure consistency and that each data set starts with the same initial diameter and with the same surface finish and texture. Also, at each variable combination, each mounted point will be tested three times to ensure statistical consistency of data. Each variable is independent of one other and has three values which are tested.

The amount of experimental grinding passes adds up to 54; 2 different resin contents, 9 variable combinations and 3 runs per mounted point. The value range of spindle speed and feedrate can be seen in Table 4.

Spindle speed, v	[RPM]	15 000 – 20 000
Feedrate, f	[mm/min]	30 - 90
WC-12wt%Co content	wt%	12, 16

Table 4 - Randomized execution order for mounted point experiments.

Grinding is done on a 3-axis CNC micro machining machine that is computer controllable. A Dremel 4000 multi-tool with variable speed control is used to

drive the mounted points. The titanium alloy workpiece is placed in the machine, levelled and clamped in place. The machine controller software is calibrated and the zero-point indicated for positional referencing of the system. The g-code for controlling the movement path of the machine is imported into the software. The zero-point of the system and the implemented g-code can be seen in Figure 11 and Figure 12.

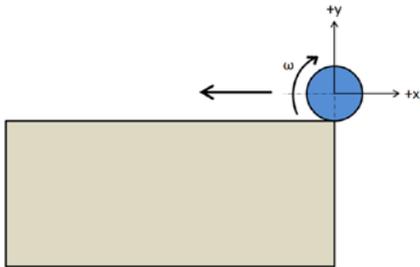


Figure 11 - Zero-point positional indication (viewing direction from above) [8].

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G90
G01 X0 Y0 Z0 F1100
G01 X0 Y30 Z0 F1100
G01 X0 Y30 Z-5 F1100
G01 X0 Y1 Z-5 F600
G01 X0 Y-0.1 Z-5 F80
G01 X-102 Y0.4 Z-5 F60
G01 X-102 Y30 Z-5 F1100
G00 Z40

M30
%
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Figure 12 - G-code implemented in computer software to control mounted point movement [8].

The depth of cut is 100 μm. This value is adjusted with 100μm for each grinding pass of the same mounted point to ensure the depth of cut stays constant at each pass. This means that for the second machining pass, the depth of cut will be 200μm from the zero reference point to produce a 100μm cut over the already 100μm deep first cut. Similarly, the third grinding pass depth of cut is adjusted in the same way.

The experiments were conducted without lubricating and cooling fluids. These fluids are known to affect the grinding performance of grinding wheels in both positive and negative ways. It was decided to not make use of these fluids for the main purpose of determining the effect of the mounted points under dry conditions. It is however wise to use cooling fluids during machining of titanium alloys because of the reactivity of titanium at elevated temperatures. It is thus suggested to use these fluids in future work.

The mounted points are securely fixed to the Dremel. A vacuum is used to suck up the grinding dust (extractor close to the mounted point). The experimental setup can be seen in Figure 13 and Figure 14.

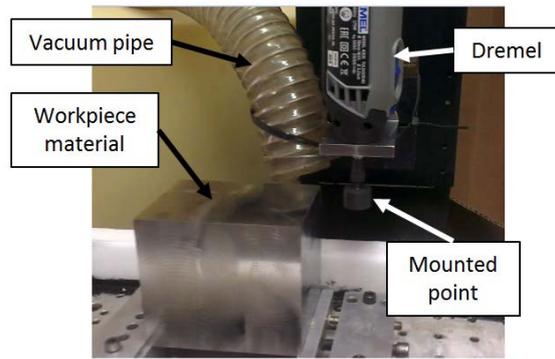


Figure 13 - Titanium alloy workpiece material clamped in position with mounted point securely fixed in the Dremel.

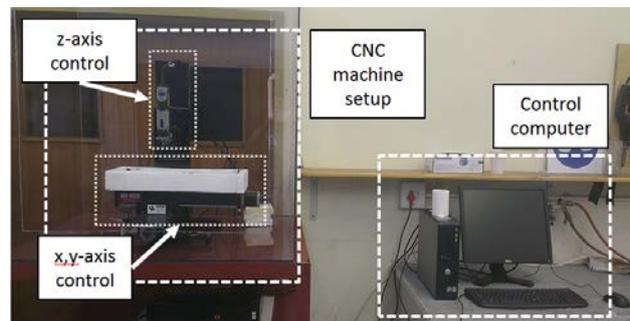


Figure 14 - CNC micro machining setup (left) with control computer (right).

5.4 Data acquisition

Machining data is recorded and measured to determine effectiveness of grinding. The rate of wear of the mounted points is determined as a change in volume. The change in volume is calculated by measuring the change in diameter of the mounted point after each grinding pass. This is done with the use of a coordinate measuring machine (CMM).

The CMM's software is programmed to automatically measure multiple circles on the periphery of the mounted point from top to bottom. This set of measurements is used to incrementally calculate the volume of the mounted point. This measuring process is conducted after every grinding pass and thus for 54 total sets of diametral data collected.

The integrity of the workpiece material's surface refers to the effect grinding forces and thermal exposure has on the surface of the material. It is determined by the measurement of the micro hardness of the surface of the workpiece material. A change in hardness indicates a structural change and possible integrity compromise. The rise in hardness could also lead to micro cracks and/or crack initiation areas. The micro hardness of the workpiece material is measured on multiple points along the grinding path after grinding.

The surface finish of the workpiece material indicates the efficiency of the abrasive particles to remove material. The grinding process used for

testing the mounted points is a micro grinding process, and thus the surface finish should be smooth after material removal. The method for testing the surface finish is by measuring the surface roughness of the workpiece material with a surface roughness tester at the end of grinding.

The measured data is processed, compiled and is discussed in the following section.

6 EXPERIMENTAL RESULTS & DISCUSSION

During the execution of the experiments, three mounted points failed and was completely destroyed. These three mounted points all contain 12wt% resin and was manufactured with/during the same process. Mounted point #4 and #7 had the same spindle speed, but different feed rates, while #7 and #8 had the same feed rates, but different spindle speed. Mounted point #4 and #8 has no parameters in common, except resin content and depth of cut. The reason for failure can thus not be attributed to the set of parameters.

The wear of all mounted points are shown in Figure 15 as the cumulative amount of volume lost. The data for the three failed mounted points are not included as it is considered as outlier data point. The wear is determined by calculating the amount of volume of grinding composite material worn after a grinding pass with the change in diameter measurements. Figure 15 shows all mounted point wear data of less than 300 cm³, with the 12wt% as solid lines and the 16wt% as dashed lines. From the graph it can be seen that the amount of resin does not have a definite influence on the wear of mounted points. The rate of wear is thus more dependent on the spindle speed or feedrate.

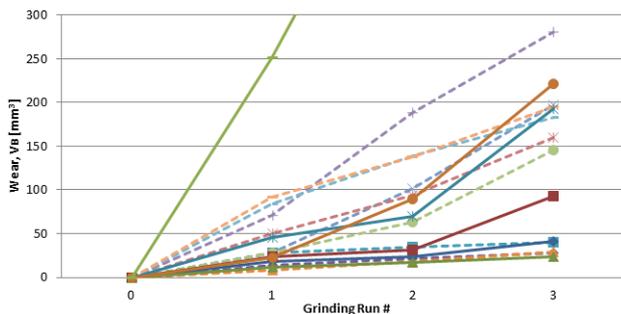


Figure 15 - Measured wear of mounted points after three grinding passes.

The surface roughness (R_a) of the workpiece material is expected to be of higher quality after grinding. The surface roughness was measured on multiple points before grinding took place, as well as on areas where grinding would not take place, and the average R_a value calculated. After all grinding passes were completed, the surface roughness was measured of every area where grinding took place and again an average R_a value calculated from multiple measurements. The average R_a measurements of the pre- and post-grinded

surfaces can be seen in Figure 16. The measured data shows that about 66% of the mounted points produced a higher quality surface roughness by having a R_a value less than the non-grinded surface, which is an improvement.

The micro hardness measurements were done similarly to the surface roughness. Multiple measurements were taken on the pre- and post-grinded surfaces. This data is shown in Figure 17. Except for three mounted points, all grinding produced a harder surface than the non-grinded material surface. This is expected as grinding induces stresses on the material being grinded due to frictional heat, changing the micro structure of the surface of the grinded material.

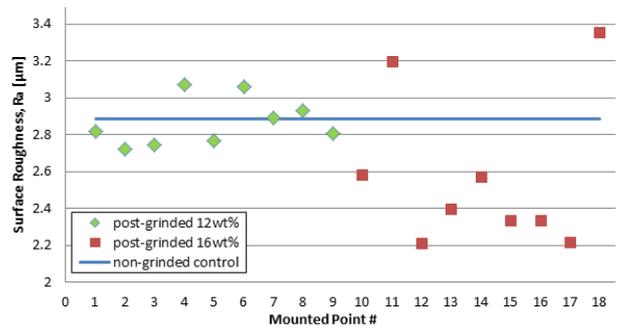


Figure 16 - Average surface roughness prior to and after grinding.

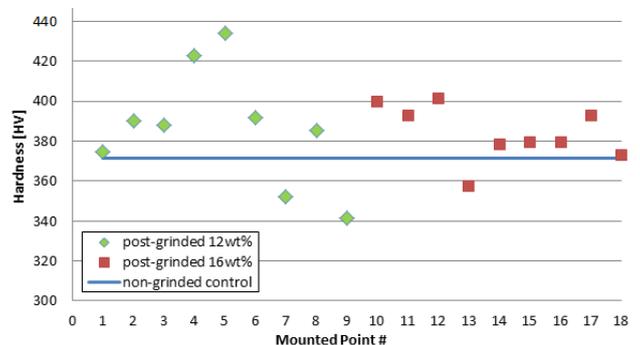


Figure 17 - Surface micro hardness prior to and after grinding.

For both Figure 16 and Figure 17 the average pre-grinding data is shown as the solid blue line. The average measured post-grinding data is shown as dots, green diamonds representing the 12wt% samples while the red squares represents the 16wt% samples.

7 CONCLUSION

The custom manufactured mounted point grinding wheels performed similar to conventional grinding wheels. It also removed material during the micro grinding process, produced on average higher quality surface finishes and caused work hardening of the workpiece material surface. The design and manufacturing process was thus successful and can be applied for future production of mounted points, but improvements can always be implemented.

It is recommended that the manufacturing process be revised and improved for automation purposes. Instead of using epoxy resin, a phenolic resin can be used to examine its influence on the performance of the mounted points.

Larger abrasive particles can also be used to determine the effect grain size has on the production process and on grinding performance of mounted points.

8 ACKNOWLEDGEMENTS

The authors would like to thank the Department of Science and Technology and the Centre of Excellence in Strong Materials for the provided funding and the Department of Industrial Engineering at Stellenbosch University for their technical support in the execution of the experiments.

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10 BIOGRAPHY



Alex Enever obtained his BEng Mechanical degree from the Department of Mechanical and Mechatronic Engineering, University of Stellenbosch. He is currently a Masters student at the Department of Industrial Engineering, University of Stellenbosch.



Gert Adriaan Oosthuizen obtained his PhD degree from Stellenbosch University. In 2011 he became a CIRP research affiliate and senior lecturer. In 2014 he became head of the Rapid Product Development Laboratory at Stellenbosch University.



Natasha Sacks is an Associate Professor in Metallurgical and Materials Engineering at the University of the Witwatersrand in Johannesburg, South Africa, and a Member of the South African Institute of Mining and Metallurgy. She is the research leader of the Carbides and Cermets group within the DST-NRF Centre of Excellence in Strong Materials, and is on the editorial board of the *International Journal of Refractory Metals and Hard Materials*.