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ORIGINAL ARTICLE

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Use of wheel speed as a parameter to inhibit surface crack generation in the grinding of wear-resistant fillers

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Abstract At periodic intervals, aerospace engine parts undergo a refurbishment process to maintain stringent quality requirements. This process uses hard composite wear-resistant materials, which impose serious machining challenges particularly in overcoming surface damages. As a result, the process needs to be frequently interrupted for tool-sharpening and other preparation processes. This paper addresses one such issue for LPT vane blades and introduces high wheel speed as a parameter to overcome surface damage and to improve process efficiency.

Keywords High-speed grinding · Surface damage · Wear-resistant materials

1 Introduction

Refurbishment of aerospace parts such as vane blades, honeycomb seals and other engine parts are commonly practiced after every 2000 flight hours [1]. Unlike the original methods of manufacturing, this process adopts the blending of wear-resistant materials and the necessary machining to yield a final shape. The grinding of wear-resistant materials offers an immense challenge in two ways, as it results in poor grinding ratio as well as grinding induced surface cracks [2–5]. Wear-resistant fillers like Cm 64, Cm 32, and Triboloy 800 are often used in aerospace parts. When grinding an LPT vane blade (see Fig. 1) with alumina oxide wheels, the fine swarf often gums up the spaces between the grains. As a result, dressing is a required operation after every two to three components are ground. Furthermore, the wheel wear computed in terms of grinding ratio was found to be between 10 and 20, indicating a high wheel consumption [2]. This paper shares the result of using wheel speed as a parameter to overcome both the issues of surface cracks and poor wheel life.

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Fig. 1. LPT vane blade refurbished after treated with wear-resistant fillers such as L605, Cm 64, Cm 32, and profile grinding

2 Experimental details

Employed in the experiment was a high-speed surface grinder, which can reach up to 200 m/s in peripheral wheel speed while using a φ200 mm wheel. During the course of experiments, the wheel speed was varied from 33 to 125 m/s. An electroplated bond cubic boron nitride (CBN) wheel with a straight shape was used in the experiments. Table 1 gives the specifications of the grinding machine and wheel. Before the grinding tests, the wheels were dynamically balanced in the test-grinding conditions. The results obtained were theoretically analyzed and the feasibility of application of the high-speed grinding process on the shop floor was considered. For the measurement of wheel-wear, a half-portion of the straight-type wheel was used for grinding and the change in profile as different volumes of material was removed was observed to quantify the grinding ratio. The experimental conditions and wheel preparation conditions are given in Table 2. Weld coupons of size $60 \times 30 \times 4$ mm formed with an Inconel base and L605 wear-resistant fillers were used as the grinding workpieces.

Table 1. Specifications of the grinding machine and wheel

Detail	Specifications
Machine	High-speed grinder (OKAMOTO 63 DXNC)
Spindle speed (RPM)	1000 to 20 000
Capacity	650 × 350 mm
Movement	3-axis CNC controlled
Traverse feed (mm/min)	0 to 2000
Grinding wheel	CBN200N100EP CBN80N100EP CBN60N100EP

Table 2. Experimental conditions

Detail	Specifications
Wheel speed (m/s)	33 to 125
Table feed (mm/min)	200
Depth of cut (mm)	1.5
Truing and dressing	Cleaning with a coolant jet
Workpiece (welding coupon)	T 800,Cm 64, and Cm 32

3 Results

3.1 Grinding forces

Shown in Fig. 2 is the behavior of specific grinding force (f_n) versus wheel speed for grinding wear-resistant weldment (L605) with a CBN wheel (B200N100EP). The forces decrease in proportion to the wheel speed. The elevated wheel surface speed results in a decrease in chip thickness, and consequently, reduces the cutting force acting upon each cutting edge. A reduction in the chip thickness generates less ground surface stress, and the results are also shown in Fig. 2 [6]. The increase of wheel speed from 33 to 125 m/s reduces the normal grinding force from 15.5 to 6.6 N/mm and the ground surface stress from 4.6 to 3.4 GN/m^2. As a result, the surface cracks were significantly reduced while grinding was done at elevated wheel speed.

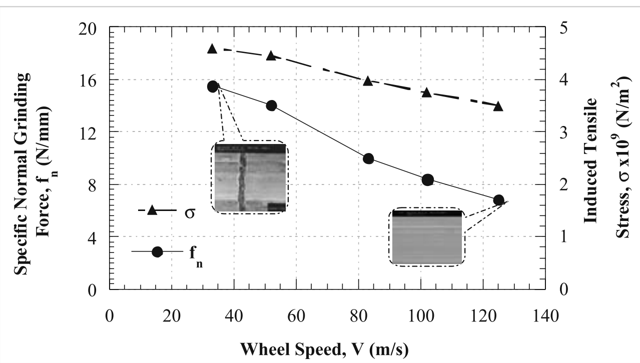


Fig. 2. Grinding force behavior versus wheel speed for L605 wear-resistant weldment material

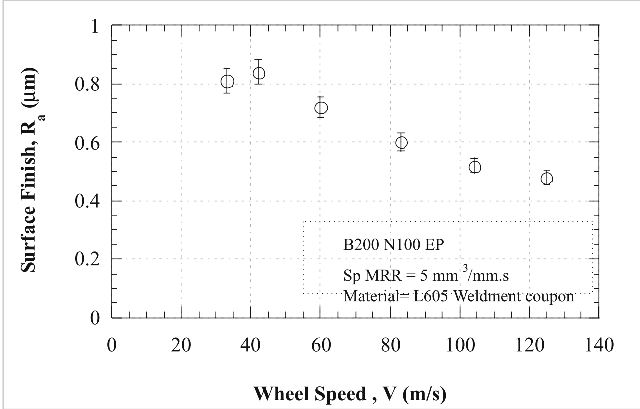


Fig. 3. Improvement in surface finish with an increase in wheel speed for a L605 weldment coupon when using a B200N100EP wheel

3.2 Surface finish

The surface roughness value for the L605 ground surface was reduced with an increase in wheel speed. Fragmentation of chips into small sizes and the filling of asperity with peaks resulted in an improvement to the surface finish. Figure 3 shows the result of the surface finish measured in terms of R_a values of the ground surface. When the wheel speed was increased from 33 to 125 m/s the surface finish (R_a) was reduced from a range of 0.78–0.82 μm to 0.46–0.52 μm.

3.3 Microstructure

Using a Cambridge stereoscan microscope, micrographs of the ground surfaces were taken to understand the grinding mechanism and to observe the surface texture at different wheel speeds. Figure 4 shows the microstructure of a L605 weldment coupon ground at different wheel speeds.

- At a wheel speed of 33 m/s and a specific material removal rate of 5 mm^3/mm · s, the ground surface produced has serious surface cracks. Also, clusters of cracks of length 0.1 to 2 mm are widely observed (see Fig. 4A-A).
- At a wheel speed of 104 m/s and a specific material rate of 5 mm^3/mm · s, the tendency of material pullout decreases and the grooves are filled with asperities to form a better surface. Also, at high wheel speed, shear fracture due to plastic deformation is widely observed.

Furthermore, the surface cracks induced are perpendicular to the grinding direction. Energy dispersive X-ray (EDX) analysis of the material at the zone of the surface crack found significant concentrations of hard elements like Si and poor a presence of bonding substances like Co as shown in Fig. 5. Therefore, further investigations in dispensing the L605 material to the worn vane blade are recommended.

3.4 Grinding ratio

The life of the grinding wheel is quantitatively expressed in terms of grinding ratio, which is a ratio of volume of mate-

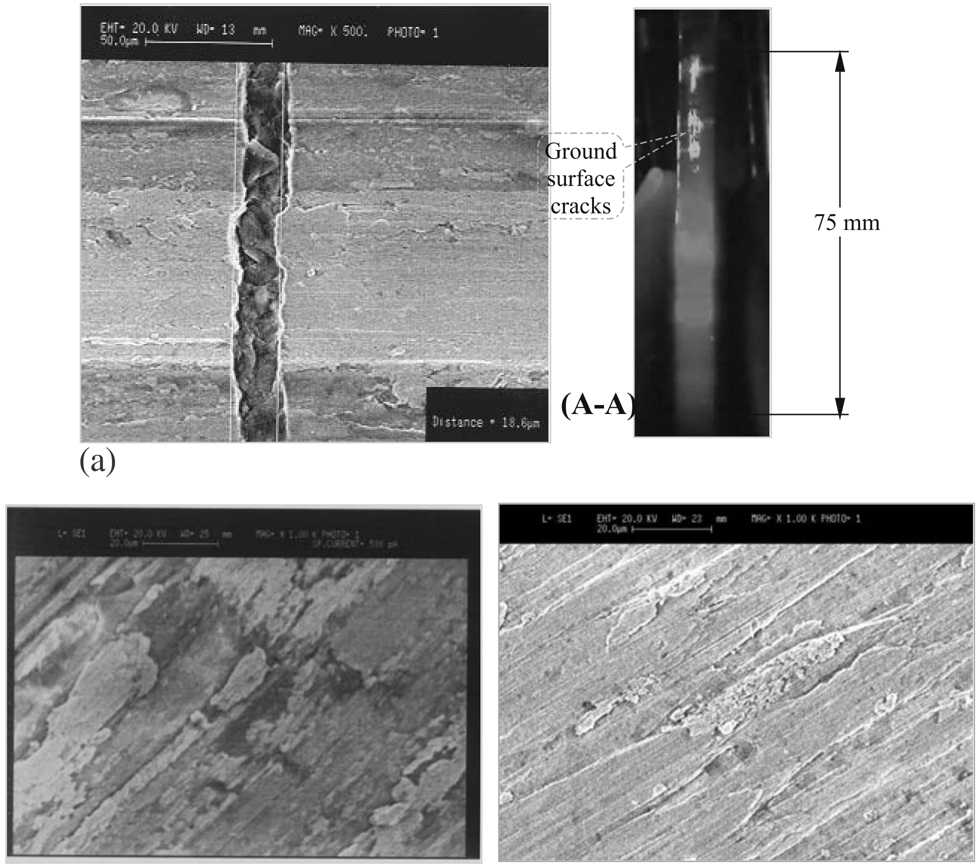


Fig. 4a–c. SEM images of an L605 weld coupon after grinding at $v = 200$ mm/ min and $\Delta = 1.5$ mm. **a** At a wheel speed of 33 m/s, we observe brittle fracture, surface cracks and shear with grooves. **A-A** At a wheel speed of 33 m/s, surface cracks are observable after using deep penetration tests. **b** At a wheel speed of 52 m/s, the ground surface shows effects of plowing and abrupt material pullout. **c** At a wheel speed of 104 m/s, a fine surface quality with extensive plowing and steak grooves is observed

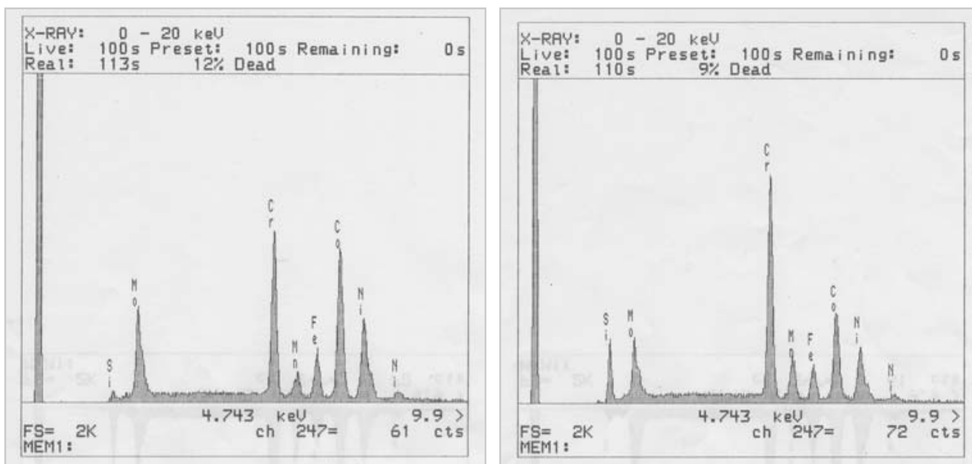


Fig. 5a,b. EDX analysis of the ground surface after treatment with L605 wear-resistant materials. **a** Zone that does not show any ground surface cracks. **b** Zone that exhibits significant surface cracks

rial removed from the workpiece to the volume of material removed from the wheel [7]. As the grinding wheel undergoes three different types of wear, viz, attrition wear, grain fracture, and bond fracture, the change in the physical dimensions of the wheel and surface topography were studied. The improvement in grinding ratio with use of a high wheel speed is shown in Fig. 6. The detailed calculations for the wheel-wear study and the related grinding ratio is given in the Appendix. To meet stringent industrial requirements, additional boundaries were included in the grinding ratio study and the wheel was considered to be unfit to use if one or all of the following conditions arose: the surface finish R_a exceeded 1.6 µm, there were cracks of length exceeding 125 µm, the process capability index, C_p, was less than 1.33, the profile deviation for the com-

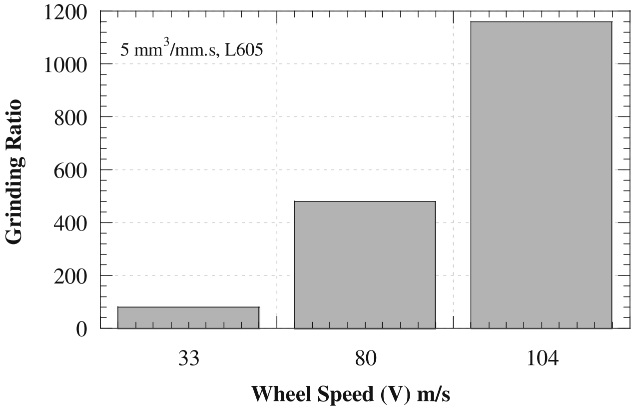


Fig. 6. Grinding ratio behavior with the use of wheel speed as parameter for L605 wear-resistant fillers

plete grinding width (75 mm) was not more than $8 \sim 15\,\mu m$ and free from any visible burns [8]. Shown in Fig. 7 is the change of wheel profile measured at different intervals. As a result of wheel speed administration, the grinding wheel life was increased from the 3–4 weld coupons to 250 weld coupons, resulting in significant savings in grinding wheel cost and wheel preparation time.

Using an optical microscope, the wheel surfaces before and after extensive grinding of the L605 weldment coupon was studied and the results are shown in Fig. 8. It was observed that neither visible (40×) grain flattening nor fracturing had taken place even after grinding 35 pieces of weld coupon when employing (i) a B200 electroplated CBN wheel, (ii) a specific material removal of $5\,mm^3/mm \cdot s$, (iii) a wheel speed of 104 m/s, and (iv) a water-based coolant.

Fig. 7a–c. Wheel profile behavior for high-speed grinding of L605 wear-resistant filler. **a** Before grinding **b** & **c** Wheel profile measured on the graphite replica **b** after 35 weld coupons **c** after 70 weld coupons

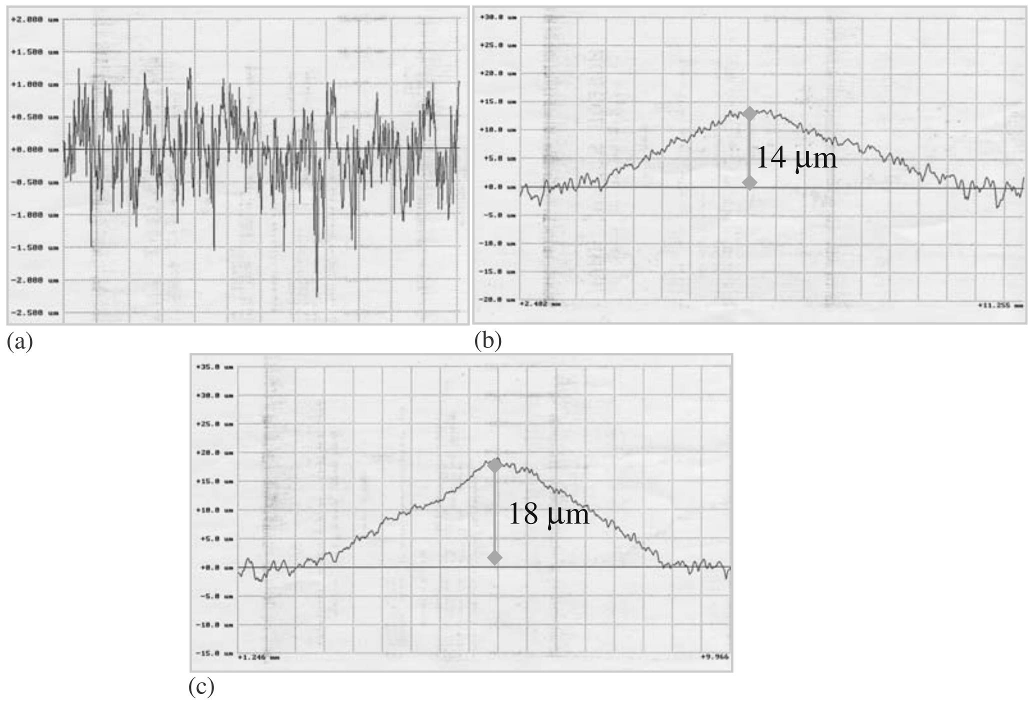
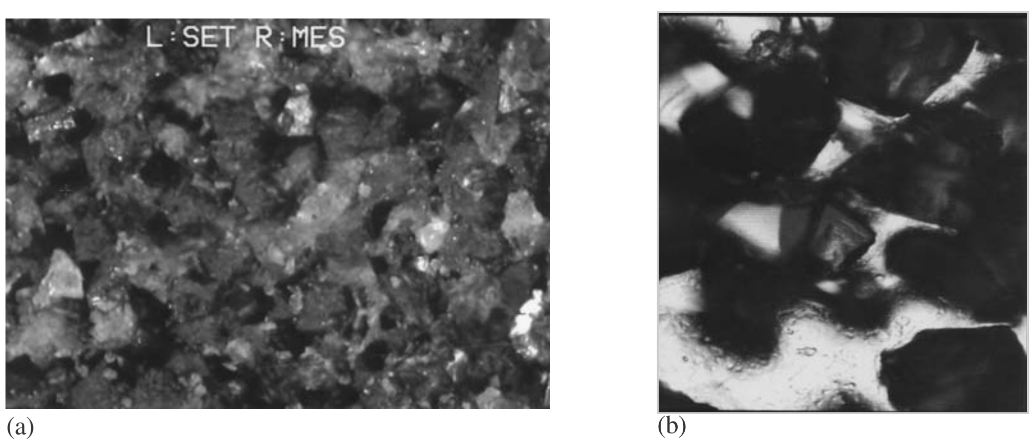


Fig. 8a,b. Topographical change of the CBN wheel after grinding L605 weld coupons with (i) a B200N100EP wheel, (ii) a wheel speed of 104 m/s, (iii) a specific material removal rate of 5 mm3/mm · s, and (iv) a water-based coolant (4 bar, 20 lpm). **a** Before grinding. **b** After grinding 35 pcs of weld coupons



4 Discussion

When an abrasive grain interacts with the workpiece, indentations are produced, yielding one or a combination of the features shown in Fig. 9 depending upon the load and material properties [9].

The micro-cracking of the weld coupon (L605) during grinding associated with plowing, as well as the indentation of harder abrasives, could be attributed to possible cohesion failure. The fragmentation of the chips and grinding with a critical chip thickness can change the grinding mechanism of hard and brittle materials [10]. Under highly loaded conditions and with the use of a small indenter radius, plastic deformation would be promoted in the brittle material subjected to the indentation force; this behavior was exploited in the high-speed grinding process. With the use of a large indenter radius, a cone crack is normally initiated for brittle materials. Thus, it is possible to obtain plastically deformed surfaces without the initiation of surface cracks in high-density, high-strength brittle materials if a small indenter radius and small force/grit conditions are applied during grinding [11]. In the grinding experiments, when the wheel speed was increased by 4 times the force/grit was reduced by nearly 2.3 times, and thus, the formation of surface cracks was averted. The nature and extent of plastic deformation depend on several grinding process variables and a systematic understanding of this interaction is necessary to quantify the wheel-work relations.

A quantitative analysis is made using Hertz's elastic contact theory to ascertain the influence of high wheel speed through an evaluation of the reduction in normal forces. The grinding wheel-work interaction is assumed to exhibit convex-flat surface behavior, and in such conditions, the point of maximum tensile stress is susceptible to ring fractures at conditions exceeding the theoretical tensile strength. The maximum tensile stress ($\sigma_{\max}$) at the periphery of the contact circle is given as [12]

$$\sigma_{\max} = 0.0516 \left(\frac{PE^2}{R^2} \right)^{\frac{1}{3}} \tag{1}$$

where P is the indenting load (N), R is the radius of the grit (m), and E is the longitudinal elastic modulus (N/m^2). The indenting load (P) is proportional to the grinding force divided by the contact area and is further computed as follows;

$$P = Cp \frac{\pi \cdot v \cdot \Delta \cdot b}{2 \cdot V} \tan\alpha \tag{2}$$

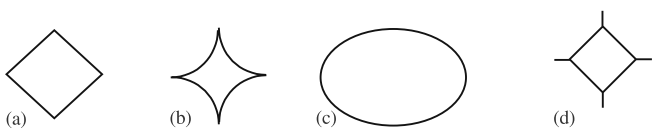


Fig. 9a–d. Indentation associated with different grinding conditions. **a** Ideal shape. **b** Low load (re-bouncing). **c** Too soft a material and no cracking. **d** Excessive load and cracking

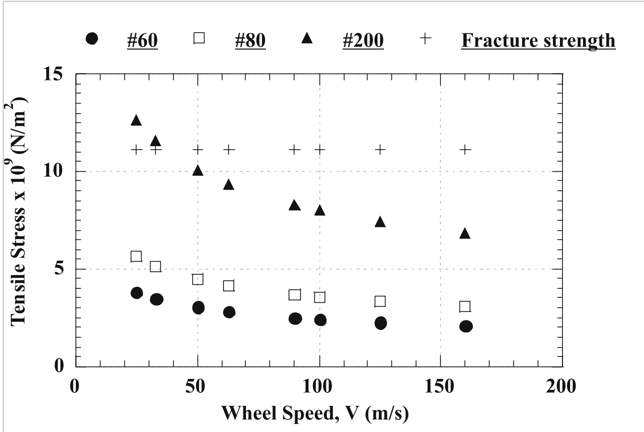


Fig. 10. Behavior of induced tensile stress with wheel speed as a parameter to facilitate crack-free grinding

where, $C_p = 4.9 \times 10^9$ N/m^2; $\tan\alpha = 5.8$; wheel speed $V = 33$ to 160 m/s; table feed rate (v) = 200 mm/min; wheel width b and depth of cut (Δ) = 1.5 mm.

Using Eqs. 1 and 2, the behavioral relationship between the induced stress and the wheel speed was established and is given in Fig. 10. The computation results suggest that for a #200 wheel at a wheel speed lower than 33 m/s, the induced stress exceeds the fracture strength and hence the occurrence of surface cracks is common. When the wheel speed is increased from 33 to 160 m/s, the tensile stress decreases from 13 to 7 GN/m^2 as a result of reduced normal forces. As a result, the wheel speed inhibits the growth of ground-surface cracks. Furthermore, the grinding wheel life is increased from the current 2–3 weld coupons to 250 weld coupons. The fragmentation of long chips into smaller sizes reduces wheel-gumming, and hence, the higher grinding ratio of 920 to 1390 was achievable.

5 Conclusion

The grinding of L605 wear-resistant fillers with use of wheel speed as a parameter has produced damage-free ground surfaces. An increase of the speed from 33 to 125 m/s has reduced the grinding forces from 15.5 to 6.6 N/mm and also improved the surface finish from 0.78–0.82 to 0.46–0.52 µm. At a specific material removal rate of 5 mm^3/mm·s and a low wheel speed (33 m/s), a frequent occurrence of surface cracks of 0.1 to 2 mm with extensive micro-fractures were observed. At higher wheel speed, grit cut load was significantly reduced, and the surface stress was thus reduced from 13 to 7 GN/m^2, leading to a ground surface free from cracks and other surface damage. Furthermore, use of wheel speed as a parameter has increased the grinding productivity from 3–4 weld coupons to nearly 250, and the grinding ratio was computed to be between 920 and 1390. On the whole, this method is of significance in producing high-quality ground surface features with increased productivity.

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Appendix (Grinding ratio calculations)

Grinding ratio was computed based on the volume of abrasives lost using the measured values of wheel wear shown in Fig. 7a–c and the volume of material ground. Both wheel-wear data and the grinding geometry of traverse plunge grinding are used to assess the exact volume of lost abrasives as given below

Grinding contact area	90.7 mm^2
Volume of each grit for B200	0.000697 mm^3
Grit weight (CBN density: 3.48 gm/cm^3)	0.000002425 gm
Number of grits/mm of wheel width for B200N100EP	51 900
Wheel surface area ($\varphi 200 \times 10$)	6280 mm^2
Volume of rim eroded for 35 nos of weld coupons	27.475 mm^3
Volume of rim eroded for 70 nos of weld coupons	35.325 mm^3
Volume of rim eroded for 250 pcs of weld coupons	117 mm^3
Number of grits lost during grinding 35 welding coupons	39 420 (0.0956 gm)
Number of grits lost for 70 welding coupons	50 680 (0.122 gm)
Total number of grits lost for 250 welding coupons	168 160 (0.407 gm)
Weight of L605 material ground for 35 pcs	88 gm
Weight of L605 material ground for 70 pcs	142 gm
Weight of L605 material ground for 250 pcs	566 gm
Weight of L605 weldment ground / grit for 35 pcs	0.00223
Weight of L605 weldment ground / grit for 70 pcs	0.0028
Grit-protrusion length for the B 200 N 100 EP wheel	31.5 to 49.5 µm
Weight of metal grind / grit	0.002515 gm/grit
Grinding ratio computed for 35, 70, and 250 welding coupons	920, 1163, 1390

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