The Mechanics of the Grinding Process

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ABSTRACT

Grinding is the fundamental method in making the tools that make other tools, such as endmills and drills. It is also a process that is used in finishing and sharpening other tools such as screwdrivers, diagonal cutters, and knives. Understanding the complex and random nature of the grinding process is essential to understanding the effect that it has on producing individual characteristics. The variables which cause the individuality of a ground surface is discussed.

Introduction

Grinding is a complex abrasive method of material removal. Historically, grinding has been employed during prehistoric times to sharpen axes as early as 5300 BC [1]. The modern grinder for tools and cutters was invented in 1783, by Samuel Rehe in France [2]. Currently grinding is used to sharpen machining tools and finish the surfaces of tools such as screw drivers, prybars, chisels, knives, etc. [2, 3, 4].

Grinding Process

The grinding process uses abrasive particles, typically aluminum oxide or silicone carbide [5], to remove metal. The grinding wheel can be considered a multiple edge cutting tool since more than one grain is contacting the workpiece surface at any one time. Grinding removes metal by chip formation similar to other machining methods such as milling or turning, but on a much smaller scale. When a cutting tool (abrasive grain) interacts with a surface, it does so with either a positive or negative rake angle. If the leading edge of the tool is behind the perpendicular, the angle is by definition, positive (Figure 1). If the leading edge of the tool is ahead of the perpendicular, it is a negative rake angle (Figure 2).

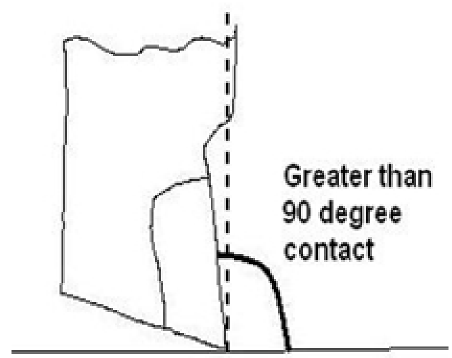

Figure 1: Positive Rake Angle of a tool contacting a workpiece

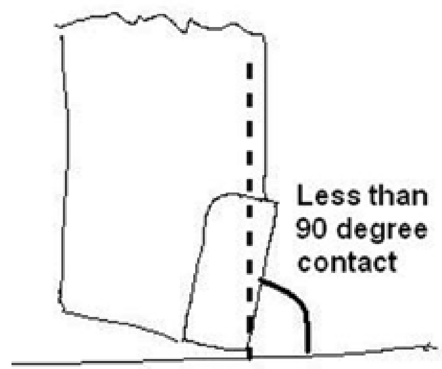

Figure 2: Negative Rake Angle of a tool contacting a workpiece

The force of the grain coming in contact with the workpiece changes based on the amount of contact, angle of contact, and friction. That force causes the grain to microfracture, macrofracture, or tear entirely from the grinding wheel (Figure 3). The macrofracture and bond fracturing of grains gives the grinding wheel its gross characteristics. The microfractures are a result of the fracture of a grain at the immediate contact area of the workpiece. The bond is formulated not only to hold the particles together for safety when turning at a high rate of speed, but also determines the holding strength to fit the application [6]. For example, if the bonds were too strong, the grains would not break loose allowing the wheel to self-sharpen. Additionally, if the bonds were too weak, the wheel would erode prematurely. Therefore, the grinding wheel is considered a self sharpening-tool [7].

Grinding wheels and abrasive belts are partially defined by their grain size. To understand the physical size of grain size, one must understand how the size is determined. The number of openings per inch in a sieve will determine the grit designation. For example, a sieve with 46 openings per inch

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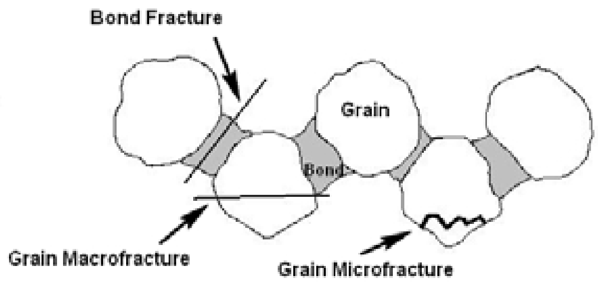

Figure 3: Grain and bond fracture of a grinding wheel

that would allow most of the grit to remain on the sieve would be 46 size grit. The range of grits that would be classified as 46 size grit is based on using the 46 sized sieve for the maximum diameter particles and the next sized sieve up, 54 for the minimum particles. So the range of grit particles ranges from 0.354 mm (46 grit size sieve opening) to 0.291 mm (54 grit size sieve opening), with an average size of 0.323 mm. [8]

When grinding wheels are manufactured, the grit size is a collection of the nominal distribution of particles. There are some fine and smaller grains deliberately added to the nominal grit ensuring consolidation and sintering of the grinding wheel. The most frequently encountered grain on the wheel will be the mean size. The orientation and distribution of the grains in the wheel is entirely random which makes the grinding process stochastic in nature [9,10]

There are two categories of the grinding process, form and finish grinding (FFG) and stock removal grinding (SRG). Form finish grinding produces a desired form, finish and accuracy to the final product. Grain sizes for FFG is generally over 100 to achieve an acceptable finish state. Stock removal grinding (SRG) is used to remove a large amount of material such as removing sections of metal. SRG utilizes course grains of 24-46 in a resin bonded grinding wheel and is mounted in an angle grinder or abrasive cut-off saw for use [11].

Contact in the Grinding Process

A grinding wheel is different than most cutting tools in that there are multiple points of contact between the wheel and the workpiece. Additionally, the amount of surface area of the cutting tool (grain) varies throughout the contact process. However, studies have demonstrated that most of the grains do not participate in the cutting process. Many grains which are not protruding far enough from the wheel are rubbing and/or plowing. A small percentage (approximately 5-10%) of grains is actively involved in the cutting process (Figure 4) [12].

The actual number of grains which come in contact with a workpiece can be calculated based on the characteristics of the grinding wheel and the specifications of the process. This calculation can be applied to the actual production of screwdrivers during the finishing process to demonstrate the number of grains effecting the surface finish and individuality of screwdrivers.

In November of 2009, a tour of a major screwdriver manufacturer was attended as part of training to gain a firm understanding of the machining process involved in the manufacture of their product. During the tour, it was observed that the screwdrivers had the tip finish ground by a robotic machine. Each screwdriver was subjected to the exact same parameters designated by manufacturer to achieve the desired finish. Based on the parameters that the screwdrivers were subjected to, the actual contacting grains can be calculated.

Grinding Wheel: 120 grit, resin bond structure 6 - volumetric fraction 52% (Appendix A)
Wheel Speed, v_{wheel} : 35 m/s (6889 fpm)
Down feed: 60 ipm
Width of screwdriver tip, *b*: 4.7625 mm (3/16 in.)
Contact Time, *t*: 3 seconds per edge
The nominal grain of the wheel is 120. Based on that information, the mean grain abrasive sive can be calculated.

$d_{mean} = (d_{max} + d_{min})/2$
$d_{mean} = (0.165 + 0.051)/2$
$d_{mean} = 0.108$ mm

First, the number of grains per unit of length must be calculated and converted to cm:

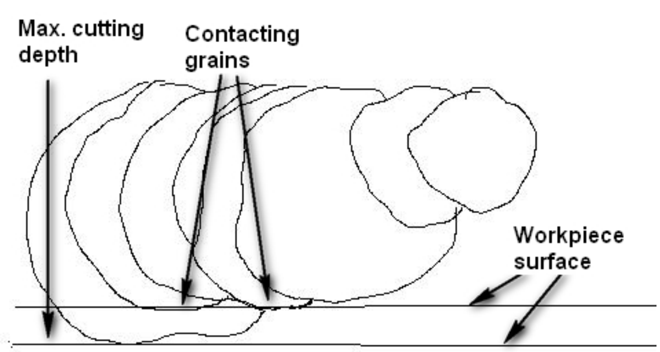

Figure 4: Abrasive grains cutting and contacting the workpiece

$N_l = 10/d_{mean} \times (\text{volumetric fraction of abrasives in wheel})^{1/3}$
$N_l = 10/0.108 \times (0.52)^{1/3}$
$N_l = 74.5$ grains/cm

Then the number of grains per unit area can be calculated:
$N_a = N_l^2$
$N_a = 74.5^2$
$N_a = 5550$ grains/cm^2

The total number of grains passing through the grinding area per second is then calculated:
$N_{Total} = v_{wheel} \times b \times N_a$
$N_{Total} = 3500 \times 0.47625 \times 5550$
$N_{Total} = 9.2 \times 10^6$ grains/second

The total number of grains in contact with each side and the tip of the screwdriver can be calculated:

$N_{contact} = N_{Total} \times t$
$N_{contact} = 9.2 \times 10^6$ grains/second x 3 seconds
$N_{contact} = 2.7\ 10^7$ grains
Therefore, 27,000,000 abrasive grains interact with each surface of the screwdriver tip during its finishing process.

Additional Sources of Random Marks

In addition to the removal of metal in the grinding process, the grinding wheel effects the work piece in other ways. The metal of the workpiece can be displaced by plowing, side flow, and vibration. The grains of the grinding wheel are randomly arranged in their orientation and that is the main cause of these random marks.

Plowing is a result of plastic deformation of material passing under the cutting edge without removal [13]. When the cutting edge passes through the grinding zone, it initially makes elastic contact which is followed by plastic deformation (Figure 5) [14]. A contributing factor to causing plowing is a negative rake angle of the cutting tool. Due to the random orientation of the grains of the grinding wheel, there is a very good likelihood of a negative rake angle engaging the workpiece.

Side flow is a form of plowing that is defined as displacement of workpiece material in a direction opposite to the feed direction, such that burrs form on the feed mark ridges. Side flow is attributed to the squeezing of workpiece material between the tool and the machined surface. Tool sharpness and the characteristics of metal contribute to the likelihood of sideflow occurring [15]. For example, metals such as titanium, nickle-based alloys, and austenitic stainless steels which are more adhesive are more likely to product side flow. Grinding wheel vibrations come from two sources: forced vibrations and self-excited vibrations. Forced vibrations are produced by external factors of the grinding process such as an out of balance wheel, electric motor, bearings, or arbor. The chatter that results from the vibration source will exhibit corresponding harmonic frequency. Additionally, the strength of the vibration will effect the amplitude (size). The second source of vibration is self-excited vibrations. Self-excited vibrations are attributed to regenerative feedback effects on the workpiece and the wheel. The irregularities in the cutting surface of the grinding wheel topography cause variations of cutting force which excite the machine tool. The flexible contact between the wheel and workpiece raises the chatter frequencies above the resonant frequency. The release of that energy results in vibration between the wheel and workpiece [14].

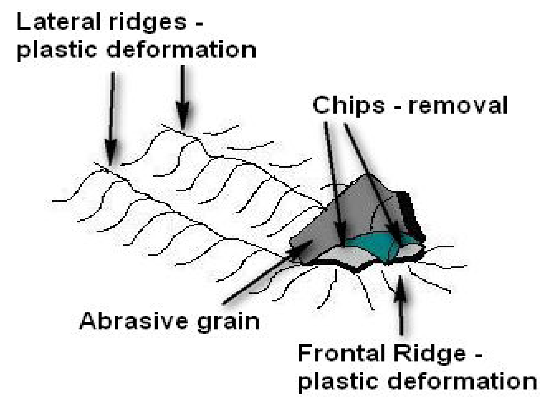

Fig. 5. Abrasive grain cutting and plowing the work-piece material

Summary

Grinding is a vital process in the manufacture of tooling and finishing of metal products. The grinding process is a material removal process which yields marks resulting from the contact of the wheel and the workpiece surface. The grinding wheel is a self-sharpening tool with essentially an infinite combination of topography. In addition to the marks made from cutting material, there are marks caused by plowing, side flow, and vibrations. These attribute to the random nature of the surface topography of machined items.

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Structure Number	Grain (vol. %)
3	58
4	56
5	54
6	52
7	50
8	48

Appendix A
Structure chart for resinoid bonded grinding wheels [16]