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Effect of Manual Grinding Operations on Surface Integrity

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Abstract

Manual grinding operations are influenced by a number of variants such as a worker's posture and motion, in addition to the general parameters affecting automated grinding processes, for example, tool speed and feed rate. Moreover, dry cutting conditions and poor control of the machining process can negatively influence chip formation and part quality in terms of roughness, microhardness, microstructure, etc. The goal of this work is to analyze the processing energy, resulting surface integrity, and prospective part performance, considering the above-mentioned variants, with the aim to give a detailed insight into manual grinding processes and fill the existing knowledge gaps. For this paper, we have limited our subject to one and thus have not studied the effect of worker's skills involved in manual grinding.

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Keywords*: Manual Grinding; Surface Integrity; Dry Cutting*

1. Introduction

Manual abrasive finishing operations (e.g. manual grinding or polishing) are prominently used in repair, construction, burr removing, foundry and in welding industry. Compared to automated grinding operations, grinding with power tools is critically dependent on worker's knowledge, skills, posture, gripping forces and personal strength. Moreover, accidents with manual power tools account for 2/3 of accidents with grinding machines and cause severe health issues with irreversible medical effects [1]. In addition, poor control of the machining process may influence the geometrical and physical properties of the machined surfaces. The abrasive tool's geometry plays a major role in generating surface texture/roughness and altering part functionality, especially under dry sliding condition.

Conventionally, average surface roughness (Ra) or mean roughness depth (Rz) is the most commonly used term to characterize the surface topography. However, there are various roughness parameters other than Ra or Rz, which have close relationships to the mechanical and metallurgical properties of the surfaces, for example, depth of the roughness core profile (Rk) or skewness of the profile height distribution (Rsk) and so on. Different roughness parameters are important for different surface functionalities. For example, Ra gives an idea about the arithmetic average of the surface profile but insensitive to peak to valley variations, Rk provides information about different portions of the surface profile and Rsk is significant for tribological application, such as wear control or bearing surface functionality.

Although, manual abrasive finishing processes have a growing market (e.g., construction market, foundry, repair, or welding industries) but these sectors are under-researched. Limited research has been done in the literature about manual process parameters and their effect on surface integrity. The aim of this paper is to show how the manual grinding processes, under dry cutting conditions, affect the surface properties (i.e. hardness, force ratio, microstructure, etc.) of stainless steel surfaces. Process optimization requires minimizing the energy consumption and increasing the process efficiency. In this paper, a Dremel 4000 hand held power tool has been used for finishing operations.

Nomenclature

μ	Force Ratio
e_c	Specific energy
F_t	Tangential force
Q_w	Material Removal Rate
Ra	Average surface roughness
Rk	Depth of core profile

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Rsk	Skewness of the profile height distribution
Rz	Mean roughness depth
SI	Surface integrity
v_c	Cutting speed

2. Characterization of Surface Integrity (SI)

Grinding is a complex material removal process, where the abrasive tools consist of geometrically undefined cutting edges and engage with the workpiece to form chips. The chip formation process in grinding involves elastic-plastic deformation, cutting, rubbing, and plowing in ductile material [2]. In brittle material, crack formation and propagation lead to material removal as particles. The geometry of the abrasive tool and penetration depth of grits are responsible for rubbing and plowing conditions and affect the surface quality [2, 3]. In the automated grinding processes, the abrasive cutting wheels are running under a constant rotational speed, which apply a precise pressure on the workpiece. Whereas in manual grinding processes, the manual feed rate causes three dimensional force (tangential, normal, and axial) variations on the workpiece, which have a direct impact on friction, chip thickness, and specific energy consumption of the process (Fig. 1). Therefore, understanding the cutting forces in manual finishing operations is challenging and has an open scope for research.

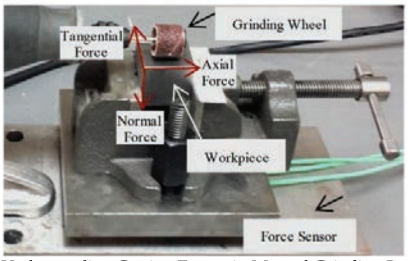

Fig. 1. Understanding Cutting Forces in Manual Grinding Processes

Compared to other conventional cutting processes, the abrasive finishing operations consume higher specific energy under small chip thickness [4]. In addition, most of the manual abrasive finishing operations are running under dry cutting conditions. Therefore, due to these 3-dimensional force variations, high specific energy consumption, and dry cutting conditions, the manual grinding operations produce high thermal effect and affect on surface integrity of the workpiece. Hence, the tradeoff between thermal effect and desired surface properties for manual grinding operations requires a closer investigation.

However, although dry cutting conditions increase the possibility of thermal damages during machining processes, the process has some added advantages over lubricated conditions. The cutting fluids have adverse health impact on workers and on the environment like chest bronchitis, skin disorder, expensive and harmful recycling processes, etc. Whereas, dry machining is eco-friendly, nullifies lubrication cost, and makes it easier to collect chips for recycling purposes [7].

In order to optimize the generated surface properties, it is very important to analyze the resource usage, costs, and sustainability of the overall process [5]. Fig. 2 shows the input-output diagram for the manual grinding operations.

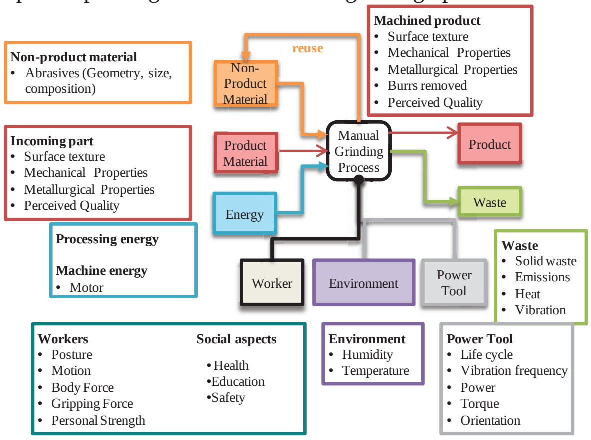

Fig. 2. Comprehensive Input-Output Diagram of Manual Grinding Process

By analyzing the process level of manual grinding operations, the correlation between different process parameters can be depicted in the following way (Fig. 3):

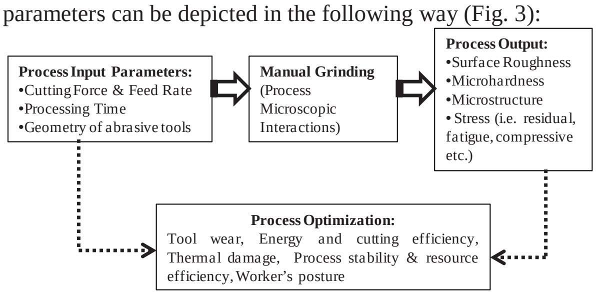

Fig. 3. Correlation between Different Process Parameters in Grinding

The process output in Fig. 3 controls the surface integrity (SI) of the machined surface. SI generally controls the mechanical, metallurgical properties of the surfaces (i.e. hardness, friction behavior, microstructure, etc.) and geometry of the machined surface (i.e. roughness and waviness) [6].

3. Experiment

In this section, we have described the experimental setup and procedure for our manual grinding experiment.

3.1 Set-up and Procedure

For the purpose of studying the effect of grinding parameters (i.e. force ratio, specific energy, material removal rate) over the SI of machined surfaces (i.e. microhardness, microstructure), one subject was used throughout the experiment to improve consistency of manual applied forces on the workpiece. Three trials were performed to make the process statistically significant. The subject was used to grind the material for a duration of about 1 min 25 sec. Both the abrasive wheel and the grinding samples were replaced for each trial.

The material used in this study was grade 304 annealed stainless steel with dimensions of 4.5cm x 1.5cm x 2cm. The ground surfaces were prepared by Dremel 4000 hand held power tool using alumina sanding bands of two different grit sizes (60 grit and 240 grit, ¼ inch diameter). The constant rotational speed of the power tool was 5000 rpm. All grinding operations were conducted under dry cutting conditions.

3.2 Data Processing Methods

The manual grinding operation causes force variation in tangential, normal and axial direction. The cutting forces were measured by a piezo-electric transducer based load cell (Kistler 9252A) and was mounted under the workpiece during machining. Two vises were used to clamp the workpiece to the sensor. The force data were sampled at the frequency rate of 1000 Hz using a National Instrument data acquisition board and LabVIEW software.

A Mitutoyo SJ-210 surface profilometer and FX500i balance were used to measure the surface roughness and material removal volume respectively. The microhardness measurements were performed on a Buehler OMNIMET microhardness tester using a Vickers diamond pyramid indenter with a load of 10 gram force (gf) and a test time of 10 sec. The ground samples were polished for microstructure observation using ECOMET and aqua regia etchant.

4. Results and Discussion

The average roughness (Ra) and depth of core roughness profile (Rk) behaviors were observed under different grit sizes (60 grit and 240 grit) (Fig. 6). These roughness parameters are based on ISO standards 13565-2:1996. Fig. 4 shows that lower grit size leads to higher surface roughness. The results show that every process has two phases i.e. active phase (phase I) and dying phase (phase II). During phase I, the process becomes very efficient and able to achieve better surface properties within a shorter period of time. Depending on the grit sizes, tool wear accelerates during the process and phase II starts to make the process saturated and no noticeable surface improvement can be seen during this dying phase. The saturation point is different for different roughness parameters. For example, for same grit size (240 grit), Ra has been saturated within 35 sec but the Rk parameter has not been saturated at the same time for the same grit size.

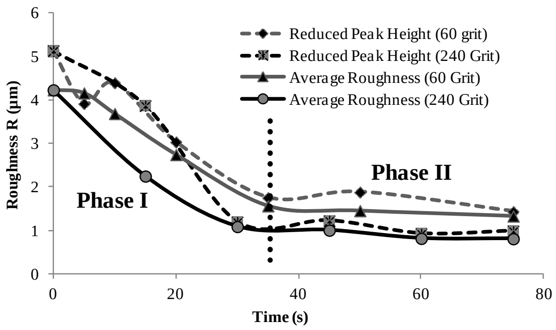

Fig. 4. Relationship between Roughness, Grit Sizes, and Saturation Point

The grinding process is hard to observe directly due to its short contact time and small contact zone. Therefore, analyzing cutting forces and chip formation mechanisms can help to understand the grinding process better. The topography of abrasive material and kinematic motion between wheel-workpiece interfaces control the cutting forces. The cutting forces influence the penetration depth, material removal rate, and surface roughness of the machined surfaces [8]. High grinding forces can cause subsurface damage, workpiece deformation, tool wear, and high coolant usage. Ways to reduce grinding forces include a smaller depth of cut, higher cutting speed, in-process dressing, and better lubrication. Therefore, for dry cutting condition, material removal rate (Q_w) and specific energy (e_c) play an important role to measure grinding efficiency.

The specific grinding energy, e_c can be calculated by using the following equation (1), where F_t stands for tangential force, v_c for the cutting speed, Q_w for the material removal rate.

$$e_c = \frac{F_t * v_c}{Q_w} \quad (1)$$

The experimental result shows that, under dry cutting condition, the manual grinding process consumes lower specific energy while increasing the material removal rate for a certain volume of material (Fig 5), which satisfies the results shown by Malkin and Guo for other conventional cutting process [8].

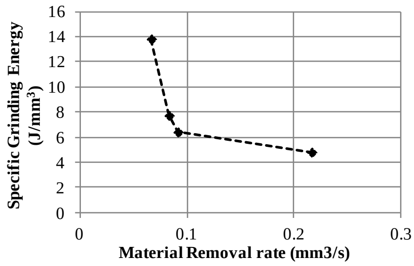

Fig.5. Relationship between Specific Energy with Material Removal rate

At the beginning of the cutting process, many active cutting edges are involved and result in higher chip thickness, higher friction, and higher material removal rate. By increasing the processing time, tool wear accelerates. This has a direct impact on the force ratio ($\mu = F_t/F_n$), reduces chip thickness and material removal rate, and saturates the cutting process as shown in Fig 1. As a consequence of the effect, no noticeable improvement in the process parameters can be observed after that (Fig.6).

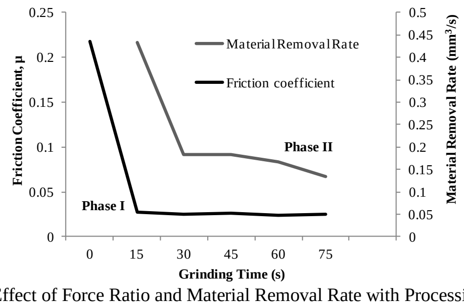

Fig.6. Effect of Force Ratio and Material Removal Rate with Processing Time

3.2 Surface Layer Properties of Machined Surfaces

The dry cutting condition caused plastic deformation in the surface and subsurface region in the grinding direction due to the localized heat generation on the workpiece. Because of the thermal damage, the metallurgical properties of machined surfaces (e.g. microstructure, microhardness) become affected mostly in the grinding direction (Fig 7).

From Fig 7 & 8, compared to the control sample, smaller grain structure and higher hardness throughout the surface can be observed in the grinding direction, which indicates the process of recrystallization. Due to higher contact area and heat transfer gradient, the longitudinal direction exhibits higher grain deformation and hardness variation up to 240 µm from the edge compared to transverse direction (variation continues only up to 50 µm).

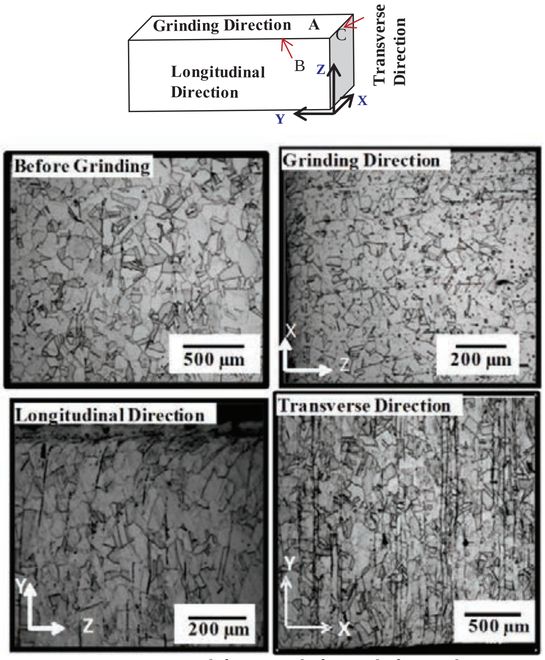

Fig. 7. Microstructure deformation before and after machining

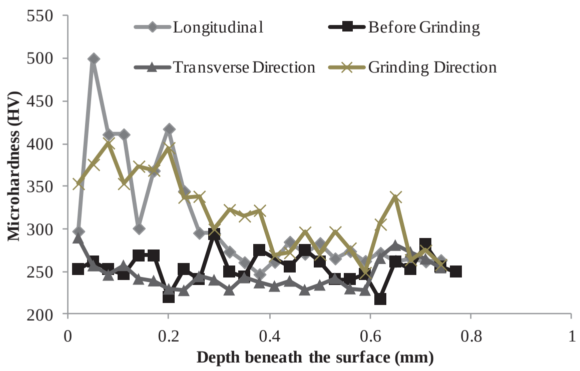

Fig. 8. Micro hardness variation before and after the machining

Summary and Future Work

The future goal of this research is to develop an energy efficient and ergonomic friendly surface generation by manual grinding operation. As steps towards this goal, this paper discusses the influencing factors for manual grinding operations. The summary of the paper can be concluded as follows:

1. The geometry of the abrasive wheel controls the surface roughness. Due to tool wear, every process can be separated into active and dying phase. It is important to find the optimum time for different process parameters like roughness, force ratio, material removal rate, and specific energy in order to increase the sustainability of the grinding process.
2. Higher grain deformation and hardness variation has been observed throughout the surface in grinding direction compared to transverse and longitudinal area of contact due to the high heat transfer gradient.

Future work will be focused on the variation of workers' skill, study sustainability aspects and define new sustainability indicators for manual grinding operations. Moreover, surface roughness was used as an index of process control stability but not as an index of product performance. Defining the most promising roughness parameter as a sustainability indicator might open up a new window for assessing product quality [9]. Moreover, since the success of manual finishing operations is largely depend on workers' skill; the future goal is to develop a smart platform for efficient transfer of knowledge to enhance the process reliability.

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