Tribological Approach and Surface Quality Analysis of Stainless Steel for Cutlery Applications after Surface Grinding

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Abstract: In precision machining processes such as grinding, for example, analysis of machined surface is important one of most parameters to evaluate process performance. Equally important is to perform tribological analysis to understand chip formation and abrasive wheel wear, thus enabling manufacturing of components free of thermal damages. In grinding, due to high hardness of abrasive grains that remove material from workpiece in chip form and very low values of radial depth of cut, combination of low roughness values and tight dimensional tolerances is attained. Accordingly, the parameters involved in this process are determinant in surface quality that is primarily evaluated in terms of surface roughness and workpiece functionality. In this work, surface roughness (Rt parameter) and scanning electron microscope (SEM) images of ground surfaces of the AISI 420 martensitic stainless steel samples were evaluated. Tests were carried out in surface grinding with a white aluminum oxide wheel and an environmentally-friendly semisynthetic water-soluble coolant. Two values of radial depth of cut (10 µm and 25 µm) were tested. The results showed that the highest roughness values, deeper grooves on the machined surfaces as well as poorer surface quality were obtained after grinding under the severest cutting conditions.

Key words: Grinding, AISI 420 martensitic stainless steel, trigological analysis, depth of cut, surface roughness, SEM images.

Nomenclature

| Symbol | Description       |
|--------|-------------------|
| ad     | dressing depth    |
| Ud     | dressing overlap ratio |
| ae     | radial depth of cut |
| Vs     | cutting speed     |
| Vw     | work speed        |

1. Introduction

Grinding can be assessed as a tribological process of two body abrasions due to the interaction between grinding wheel and workpiece. In this case, relative motion is defined by abrasive grains sliding against workpiece surface, thus yielding oriented grooves [1].

From this interaction between abrasive grains and workpiece surface a high amount of heat is generated in the contact zone, usually causing thermal damages which compromise surface quality [2]. Therefore, the proper selection of machining parameters is essential to fulfil required dimensional and form tolerances to ground surfaces [3].

This approach is fundamental during machining of hard grindability materials such as stainless steels that are composed by several chemical elements. These components ensure high corrosion, wear and oxidation resistance to steels, but compromise their machinability by reducing thermal conductivity and increasing hardening rate as well as mechanical hardness [4].

Stainless steel is defined as iron-base alloys which have a minimum percentage of chromium equivalent to 11%. Besides, other chemical elements are common such as sulfur, manganese, vanadium, molybdenum among others. These steels are commonly used in...
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According to the main microstructure or heat treatment that they are subjected, stainless steel is classified into five ranks, namely: austenitic, ferritic, martensitic, duplex and precipitation hardened. Within the martensitic class, AISI 420 steel stands out due to its wide range of applications in metalworking industry, in the manufacturing of molds, dies and measuring instruments as well as in cutlery items, such as knives and spoons for example [6, 7].

Although the understanding of grinding of hardened carbon steels has already been consolidated, data about grindability of stainless steels are still few on available literature until the date of preparation of this work. A research developed by Manimaran and Kumar [8] evaluated AISI 316 austenitic stainless steel after grinding with sol-gel alumina (SG) wheel. The authors observed that cryogenic cooling delivered an improvement of 30-49% in surface roughness and fewer surface defects in workpieces compared to dry and wet cooling conditions. After grinding the 2304 duplex stainless steel with different grit sizes and a synthetic fluid, Zhou et al. [9] evaluated the surface integrity in terms of surface roughness and scanning electron microscope (SEM) images and reported that fine grit sizes (#100) provided the lowest roughness values ($Ra$) and the smallest number of surface defects.

In this context, this work aimed to evaluate tribological effects generated by peripheral surface grinding on AISI 420 martensitic stainless steel in terms of surface roughness ($Rt$) and SEM ground surface images. During grinding tests, a conventional white alumina wheel, a semi synthetic cutting fluid and two radial depth of cut were employed.

2. Experimental Setup

Experimental trials were carried out on a semi-automatic peripheral surface grinder, P36 model, with a $z$-axis resolution of 5 µm from MELLO S.A. manufacturer. The material tested was the AISI 420 stainless steel, quenched and tempered, which was prepared with dimensions: 60 mm length $\times$ 10 mm width $\times$ 23 mm height. This steel is widely employed in household utensils and cutlery items. Chemical compositions such as physical and mechanical properties of this steel are listed on Table 1. In Fig. 1 is shown the microstructure of AISI 420 stainless steel. A conventional white alumina grinding wheel was used with the following dimensions: 300 mm external diameter $\times$ 25 mm width $\times$ 127 mm internal diameter, from Saint-Gobain manufacturer.

Throughout grinding tests, each sample was fixed in a precision bench vise to guarantee the parallelism between workpiece surface and machine table (Fig. 2).

Table 1 Chemical composition, mechanical and physical properties of AISI 420 stainless steel [10].

| Chemical composition (wt.%) | Cr       | Fe | C    | Si | V
|---------------------------|---------|----|------|----|----|
| Cr                        | 13.97   | 51.182 | 0.388 | 0.138 | 0.200 |
| Mn                        | 0.451   | 0.275 | 0.245 | 0.683 | 0.103 |

| Mechanical properties     | Down point (MPa) | 1,344 |
|----------------------------|------------------|--------|
| Tensile strength (MPa)     | 1,586            |
| Elongation (%)              | 8                |
| Hardness (HRC)             | 51               |

| Physical properties        | Density (g·cm$^{-3}$) | 7.78  |
|----------------------------|-----------------------|-------|
| Stretching modulus (GPa)   | 81                    |
| Thermal conductivity (W/mK)| 24.9                  |
| Melting range (K)          | 1,727-1,783          |

![Fig. 1 AISI 420 stainless steel quenched and tempered microstructure.](image)
Grinding tests were performed with a VASCO 7000 semi synthetic fluid (vegetable based) diluted in water at a ratio of 1:19, equivalent to a BRIX of 3.2%. Its concentration was verified by a N1-ATAGO refractometer. The coolant was delivered at a flow rate of 11 L/min via a nozzle shoe positioned at horizontal and vertical distances of 82 mm and 103 mm, respectively, from the center grinding wheel to ensure that coolant jet reaches properly the workpiece-grinding wheel interface.

Prior to experimental tests, the grinding wheel was subjected to a dressing operation with a fliesen stationary diamond in two consecutive passes at a dressing depth ($a_d$) of 20 µm to ensure a dressing overlap ratio $U_d$ equals to 6. As grinding parameters two radial depths of cut $a_e$ (10 µm and 25 µm), a cutting speed ($V_s$) of 37 m/s and a work speed ($V_w$) of 10 m/min were used.

After experimental tests, surface roughness parameter $R_t$ and SEM ground surface images were evaluated. Roughness parameter $R_t$ was measured after each grinding test at the Metrology Laboratory of Dimensional Metrology (FEMEC-UFU) under controlled temperature conditions (20 ± 1 °C) using a portable perfilometer model Surtronic S-100 with resolution of 0.01 µm and tip radio of profile of 2 µm.

A cut off wavelength of 0.08 mm and an evaluation length of 4.0 mm were adopted. Measurements were made transversally to grinding direction into five different and equal spaced regions of ground surfaces. Ground surfaces were analyzed through SEM model TM 3000 from Hitachi (1,500×).

3. Experimental Results

3.1 Surface Roughness

The results obtained in terms of the parameter $R_t$ as a function of radial depth of cut $a_e$ are presented in Fig. 3.

On average, an increase on radial depth of cut $a_e$ from 10 µm to 25 µm provided an increase of $R_t$ roughness. According to Klocke [11], this phenomenon can be explained by the fact that an increase on radial depth of cut allows higher material removal rate, due to an increase on contact area between grinding wheel and workpiece surface. Consequently, a great number of abrasive grains act on surface generating deeper grooves and a greater material displacement, which is reflected by an increase on surface roughness $R_t$, i.e., surface finish deterioration.

A similar behavior was observed by Fredj et al. [12] on grinding of AISI 304 austenitic stainless steel with alumina wheel. According to the authors, machining at the highest radial depth of cut $a_e = 30$ µm, roughness ($Ra$) was 2.7 µm, whereas $Ra = 1.5$ µm was recorded at the radial depth of cut $a_e = 3$ µm, i.e., a reduction in $a_e$ provided superior surface finish.

![Surface roughness ($R_t$) versus radial depth of cut ($a_e$) of AISI 420 stainless steel ground surfaces.](image)
Manimaran et al. [13] carried out experimental tests on grinding of AISI 316 austenitic stainless steel with alumina oxide wheel and observed that an increase on radial depth of cut from \( a_e = 10 \, \mu m \) to \( a_e = 40 \, \mu m \) resulted in an increase on \( Ra \) roughness value from 0.3 \( \mu m \) to 1.8 \( \mu m \).

3.2 SEM Images

SEM images of AISI 420 martensitic stainless steel obtained after grinding tests are shown in Fig. 4. From Fig. 4a, one notes that oriented grooves on the ground surfaces that are a phenomenon typically from grinding process, and material side flow were observed after grinding under mild conditions. Nevertheless, deeper grooves, burr and peeling of material were observed after grinding under the severest grinding condition, with \( a_e = 25 \, m \).

According to Malkin and Guo [3], the higher radial depth of cut \( a_e \), the greater thermal damages on the ground surface, as a greater amount of abrasive grains come into contact with the workpiece, thereby increasing the temperature in the contact zone and the amount of material removal, which adversely affects the surface quality. Manimaran and Kumar [8] reported that an increase on radial depth of cut from 20 \( \mu m \) to 40 \( \mu m \) resulted in deeper grooves and burn marks on surfaces of AISI 316 stainless steel after grinding with alumina grinding wheel.

A similar behavior was observed by Fredj et al. [12] on grinding the AISI 304 austenitic stainless steel with alumina grinding wheel and several values of depth of cut values. These authors reported that material side flow, tearing and grinding burns were more evident when machining with higher radial depth of cut \( (a_e = 30 \, \mu m) \).

These results suggest that materials are highly susceptible to work hardening during grinding and with low thermal conductivity, like stainless steels and superalloys, and are more susceptible to tribological events generated on the ground surfaces when machining at higher radial depth of cut values that adversely affect surface quality.

4. Conclusions

The following conclusions can be drawn:

- An increase on radial depth of cut \( (a_e) \) from 10 \( \mu m \) to 25 \( \mu m \) resulted in greater material removal and deeper grooves, which adversely affected the surface finish (increase in the \( Rt \) roughness parameter).
- Occurrence of burr and peeling of workpiece material were observed after grinding under the severest grinding condition, demonstrating that stainless steel experiences more tribological events, which are undesirable for cutlery products.

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