# CHARACTERIZATION OF THE SURFACE GENERATED DURING THE TURNING OF ANNEALED AND AGED AISI 303, 304 AND 310 AUSTENITIC STAINLESS STEEL.

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***Abstract.*** *The most important property of austenitic stainless steels is their corrosion resistance. In some cases the absence of ferromagnetism is also important. Therefore austenitic stainless steels are used in many areas of industry such as chemical, food and electronic. Stainless steels are iron-base alloys containing at least 12%wt of chromium. They are classified as ferritic, austenitic, martensitic, duplex (ferritic-austenitic) and precipitation hardening. The most widely used type of stainless steel is the austenitic grade. However, austenitic stainless steels present low machinability as compared to low carbon steels. The main objective of this work is to characterize the surface generated during the turning of annealed and aged AISI 303, 304 and 310 austenitic stainless steels. The first set of tests carried out was the machining of the three steels in annealed condition. The results made it possible to choose the cutting speed by evaluating built up edge formation on the surface faced. The built up edge formation is often observed during austenitic stainless steels machining. The finishing (mean roughness) of the turned surfaces was measured by using a surface profilometer. The turned surface was also observed by using optical microscopy. The cutting force was measured by using a load cell connected to an acquisition board. The machinability of the three different types of austenitic stainless steels ,both in the annealed and aged condition, was compared and related to the cutting force and roughness through the surface characteristics analysis.*

***Keywords***: *Austenitic stainless steel, Cutting force, Heat treatment, Roughness, Turning.*

## 1 Introduction

The austenitic stainless steel grade is frequently used in many areas of industry such as chemical and electronic, because of their high corrosion resistance and nonmagnetism (Peckner et al., 1977; Andrade et al., 2004).

Austenitic stainless steels have excellent ductility and toughness (Peckner et al., 1977). On the other hand, they have poor machinability as compared to other classes of steels (Lacombe et al., 1993; Jang et al.; 1996 and M'Saoubi et al., 1999). The problems related to the machining of austenitic stainless steels are: tool wear, poor finishing, long and stringy chips and low cutting speed (Fang et al., 1996, Jang et al.; 1996 and M'Saoubi et al., 1999). These problems are mainly caused by their high workhardening rate, low thermal conductivity and the tendency to strain-induced martensite formation (Tessler et al., 1992; Lacombe et al., 1993 and M'Saoubi et al., 1999, Padilha et al., 2002). The workhardening is introduced in the surface during the turning as a result of residual stresses due to plastic strain of the work material ahead of the tool cutting edge (Kulkarni et al., 2003). Plastic strain in the surface causes microstructural and mechanical modifications, which increase the cutting force among other points, and poorer finishing (Machado et al., 2003).

The chemical composition of steel also influences mechanical behavior as well as its machinability. There are wide ranges of chemical composition of austenitic stainless steels. The percentages of chromium can vary from 15 to 26 wt.% whereas the percentages of nickel can vary from 3.5 to 38wt. % (Peckner et al., 1977). Steels containing higher levels of alloying elements, particularly nickel, usually have a better corrosion, oxidation resistance and a steady austenite. The machinability of some austenitic stainless steels can be improved by sulphur addition. The resulfurization decreases the cutting forces. The sulphur addition propitiates the formation of manganese sulfide inclusions that make chip breaking easier. The sulphur also works as a lubricant (Lacombe, et.al, 1993). On the other hand, the resulfurization deteriorates the surface texture, especially at lower cutting speeds in dry cutting (Akasawa, et al., 2003).

Phase transformations can occur in austenitic stainless steels during intense plastic strain and during heat treatments (Lacombe et al., 1993 and Padilha et al., 2002). Austenitic stainless steels are not susceptible to martensite formation during cooling. On the other hand, strain-induced martensite can be formed during cold work. (Lacombe et al., 1993 and Padilha et al., 2002). Precipitation of carbides and formation of intermetallic phases are expected in the range of temperatures between 600 and 900ºC. The $M_{23}C_6$ carbide precipitation, where M represents Cr, Fe, Mo and Ni, in austenitic stainless steels is predictable in the AISI 303, 304 and 310 steels. The carbon solubility in austenite decreases substantially as the temperature goes down (Padilha et al., 2002).

The main objective of this work is to characterize the surface generated during the turning of annealed and aged AISI 303, 304 and 310 austenitic stainless steels. The first set of tests carried out was the facing of the three steels in annealed condition. The results made it possible to choose the cutting speed by evaluating built up edge formation on the surface machined. The finishing (mean roughness) of the turned surfaces was measured by using a surface profilometer. The turned surface was also observed by using optical microscopy. The cutting force was measured by using a load cell connected to an acquisition board. The machinability of the three different types of austenitic stainless steels, in the annealed and in the aged condition, was compared and related to the cutting force and roughness through analyzing the surface characteristics.

## 2 Materials and experimental procedure.

Two types of tests were carried out to evaluate the finishing: 1. The facing of the steels in the annealed condition was carried out to evaluate the effect of the cutting speed and 2. The turning of the steels in the annealed and aged condition was carried out to evaluate their cutting forces. The materials and experimental procedure are described as follows: 2.1 Materials, 2.2 Machining and 2.3 Turning.

### 2.1 Materials

The materials used in this study were an AISI 304 austenitic stainless steel rolling bar if about 50 mm in diameter and AISI 303, 304 and 310 austenitic stainless steels rolling bars of about 25 mm in diameter. The chemical compositions of the steels studied are showed in table 1. The samples used in the tests were about 100 mm long.

Table 1 – Chemical compositions (wt%) of AISI 303, 304 and 310 austenitic stainless steels and Mn/S ratio.

| Steel | %Cr | %Ni | %C | %Mn | %Si | %S | %P | Mn/S |
|---|---|---|---|---|---|---|---|---|
| 303 | 17.2 | 8.21 | 0.050 | 1.88 | 0.48 | 0.200 | 0.036 | 10 |
| 304 | 18.1 | 8.54 | 0.055 | 1.80 | 0.58 | 0.030 | 0.037 | 60 |
| 310 | 24.2 | 19.6 | 0.069 | 2.00 | 0.62 | 0.019 | 0.036 | 105 |

The materials were received in the annealed condition. The aging heat treatments were carried out at 800ºC for 5 hours. The sample was heated and cooled inside the muffle. The heating rate of the muffle was about 10ºC/minute and the cooling hate was about 1ºC/minute.

### 2.2 Machining (Facing)

The steels samples, which were of about 25 and 50 mm in diameter and 100 mm in lenght, were machined in different conditions. The feed of 0.054 mm/rotation and the cutting depth of 0.1 mm were the machining parameters of the tests. Four different rotations were used: 400, 1000, 1600 and 2500 rpm.

The facing seems to be an interesting method to evaluate the effect of the cutting speed on the machined surface. The samples were fixed in three-jaw chucks. The tool utilized was hard-metal tool. The side cutting edge angle utilized was 16º, the rake angle used was +6º and relief angle was 8º. No cutting fluid was used. A universal lathe was used in the materials machining.

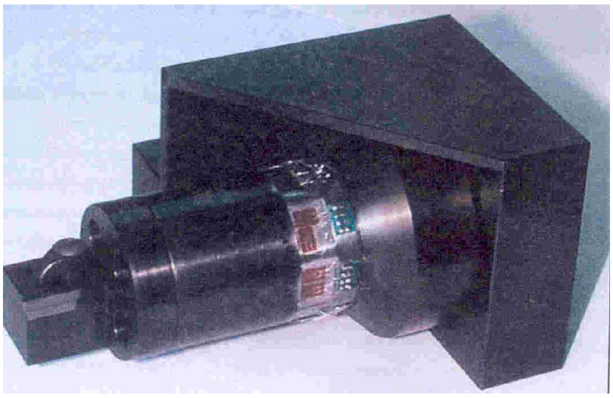
### 2.3 Turning

A universal lathe was used in turning of the samples of the steels of about 25 mm in diameter and 100 mm in length. The feed of 0.104 mm/rotation, the cutting depth of 0.5 mm and the cutting speed of about of 90 m/minute were the machining parameters of the tests. The toolholder equipped with a load cell (figure 1(a)) made it possible to measure the cutting forces. The samples were fixed in three-jaw chucks without using a tailstock. The tool utilized was TCMT160304 type, TiN coated. The side cutting edge angle utilized was 0º, the rake angle used was +4º and relief angle was 7º. No cutting fluid was used. The experimental equipment is shown in figure 1(b).

The Vickers hardness was measured the use of 196 N load (HV 20) in all the austenitic stainless steels studied. Three measurements were carried out in each sample. The average hardness and standard deviation were calculated.

A surface profilometer Mitutoyo SJ-201P was used to measure the roughness of the turned surfaces. The cutoff (lc) utilized was the one recommended in ASTM 95 (0.8 mm or 2.5 mm selected based on mean roughness). The roughness was measured twice in each turned sample to confirm the results. Only one measure of each sample was chosen to be shown in this work. The turned surface was also observed by using optical microscopy.

During the turning, the cutting force was measured. The cutting force was measured by using a load cell connected to an acquisition board with a power source, an amplifier and a low pass filter. The load cell was calibrated by applying force in a spindle linked to a mechanical dynamometer. A calibration constant was obtained to set the tests. During the turning test, the sample rate utilized was 5000Hz. The results were acquired during 60-second tests.



(a)

(b)

Figure 1. (a) The toolholder equipped with a load cell and (b) experimental equipment used to measure cutting forces during turning: lathe, acquisition system and a microcomputer.

## 3 Results and discussion

Results and discussion will be presented in different sections as follows: 3.1 Vickers hardness, 3.2 Machining and 3.3 Turning.

### 3.1 Vickers hardness

Vickers hardness of the AISI 303, 304 and 310 austenitic stainless steels studied are displayed in table 2. The hardness of the different steels are similar. The results did not show a significant change in hardness due to heat treatment.

Table 2 - Vickers hardness HV 20, 196 N load, of AISI 303, 304 and 310 austenitic stainless steels in the annealed and in the aged condition.

| Steel | AISI 303 annealed | AISI 303 aged | AISI 304 annealed | AISI 304 aged | AISI 310 annealed | AISI 310 aged |
|---|---|---|---|---|---|---|
| Microhardness | 171±3 | 168±4 | 189±7 | 174±3 | 193±2 | 197±2 |

### 3.2 Machining

The motivation to carry out this type of experiments (facing) was to evaluate the behavior of the AISI 304 steel at variable cutting speeds. The cutting speeds varied from near 0 to 400 m/minute. At 25 mm from center the sample the cutting speed were about 65, 160 and 400 m/minute for rotation of 400, 1000 and 2500 rpm, respectively. The machining experiments began testing the samples of the AISI 304 steel of about 50 mm in diameter and 100 mm in length. The rotation used was 400 rpm. The surface machined was observed after machining by using optical microscopy. The formation of built up edge was observed when the cutting speed was about 25 m/minute. Therefore, the finishing quality was affected. This speed was reached at 10 mm from the center of the sample. A different behavior was observed during tests carried out higher rotations (1000 and 2500 rpm) because the built up edge was expected to form very close to the center of the sample in these cutting conditions. In these tests, the surface quality was affected only when low cutting speeds were used.

After the tests described above, some experiments were carried out to evaluate the cutting speeds in the other steels. The AISI 303, 304 and 310 steels samples of about 25 mm in diameter and 100 mm in length were tested. In this type of tests the rotations used were 1600 and 2500 rpm. The cutting speeds at 12.5 mm from the center of the samples were about 125 and 200 m/minute for rotation of 1600 and 2500 rpm, respectively. The region near the center of the sample was not evaluated. A centering hole was drilled to avoid tools broken during the tests. Figures 2, 3, 4 and 5 show the machined surfaces as the result of the machining (facing). No cutting fluid was used during the machining. However, a jet of compressed air was used during the machining of AISI 310 steel because of long and stringy chips formed, which caused some damage in the machined surface.

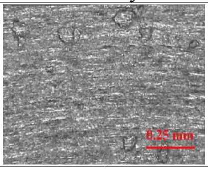
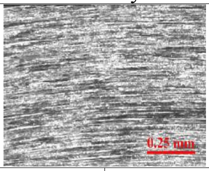
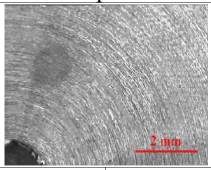
| Machining Parameters | | | Surface | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 303 dry | | 304 dry | | 310 compressed air | |
| Rotation | 1600 | rpm |  | |  | |  | |
| Diameter | 12 | mm | | | | | | |
| Cutting Speed | 60 | m/min | | | | | | |
| depth | 0.1 | mm | | | | | | |
| feed | 0.054 | mm/n | | | | | | |
| Tool | | | | | | | | |
| Hard Metal BA55 Brassinter | | | Ra [µm] | 1.28 | Ra [µm] | 0.29 | Ra [µm] | 0.45 |
| | | | Ry [µm] | 6.98 | Ry [µm] | 2.18 | Ry [µm] | 3.01 |
| | | | Rz [µm] | 6.98 | Rz [µm] | 2.18 | Rz [µm] | 3.01 |
| | | | Rq [µm] | 1.63 | Rq [µm] | 0.37 | Rq [µm] | 0.56 |
| | | | Rt [µm] | 11.21 | Rt [µm] | 2.64 | Rt [µm] | 3.29 |
| | | | Rp [µm] | 3.85 | Rp [µm] | 0.98 | Rp [µm] | 1.75 |

Figure 2. Machined surfaces of AISI 303, 304 and 310 steels. Average cutting speed was about 60 m/minutes. n represents rotation. The machining parameters are described in the figure. Ra, Ry, Rz, Rq, Ry and Rp represent arithmetic mean roughness, maximum height, maximum height, root-mean-square roughness, total height, peak height, respectively.

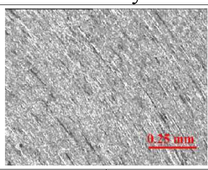
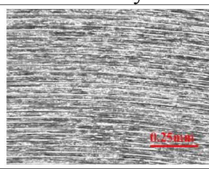
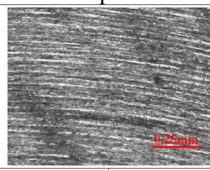
| Machining Parameters | | | Surface | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 303 dry | | 304 dry | | 310 compressed air | |
| Rotation | 2500 | rpm |  | |  | |  | |
| Diameter | 12 | mm | | | | | | |
| Cutting Speed | 94 | m/min | | | | | | |
| depht | 0.1 | mm | | | | | | |
| feed | 0.054 | mm/n | | | | | | |
| Tool | | | | | | | | |
| Hard Metal BA55 Brassinter | | | Ra [µm] | 0.64 | Ra [µm] | 0.85 | Ra [µm] | 0.59 |
| | | | Ry [µm] | 4.47 | Ry [µm] | 5.30 | Ry [µm] | 3.25 |
| | | | Rz [µm] | 4.47 | Rz [µm] | 5.30 | Rz [µm] | 3.25 |
| | | | Rq [µm] | 0.81 | Rq [µm] | 1.07 | Rq [µm] | 0.75 |
| | | | Rt [µm] | 6.19 | Rt [µm] | 5.93 | Rt [µm] | 4.96 |
| | | | Rp [µm] | 2.09 | Rp [µm] | 2.94 | Rp [µm] | 1.96 |

Figure 3. Machined surfaces of AISI 303, 304 and 310 steels. Average cutting speed was about 94 m/minutes. n represents rotation. The machining parameters are described in the figure. Ra, Ry, Rz, Rq, Ry and Rp represent arithmetic mean roughness, maximum height, maximum height, root-mean-square roughness, total height, peak height, respectively.

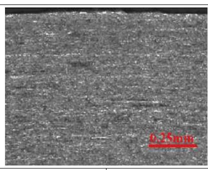
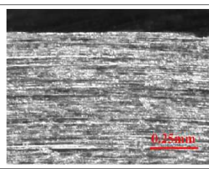
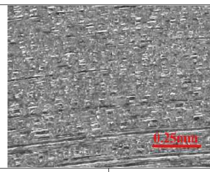
| Machining Parameters | | | Surface | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 303 dry | | 304 dry | | 310 compressed air | |
| Rotation | 1600 | rpm |  | |  | |  | |
| Diameter | 25 | mm | | | | | | |
| Cutting Speed | 126 | m/min | | | | | | |
| depht | 0.1 | mm | | | | | | |
| feed | 0.054 | mm/n | | | | | | |
| Tool | | | | | | | | |
| Hard Metal BA55 Brassinter | | | Ra [µm] | 1.30 | Ra [µm] | 0.32 | Ra [µm] | 0.74 |
| | | | Ry [µm] | 6.68 | Ry [µm] | 2.05 | Ry [µm] | 4.05 |
| | | | Rz [µm] | 6.68 | Rz [µm] | 2.05 | Rz [µm] | 4.05 |
| | | | Rq [µm] | 1.65 | Rq [µm] | 0.39 | Rq [µm] | 0.93 |
| | | | Rt [µm] | 12.55 | Rt [µm] | 2.45 | Rt [µm] | 6.12 |
| | | | Rp [µm] | 4.02 | Rp [µm] | 1.00 | Rp [µm] | 2.29 |

Figure 4. Machined surfaces of AISI 303, 304 and 310 steels. Average cutting speed was about 126 m/minutes. n represents rotation. The machining parameters are described in the figure. Ra, Ry, Rz, Rq, Ry and Rp represent arithmetic mean roughness, maximum height, maximum height, root-mean-square roughness, total height, peak height, respectively.

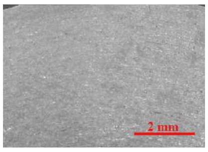
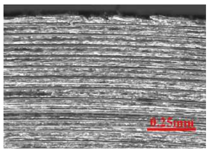
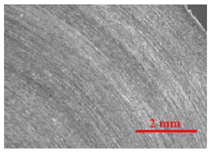
| Machining Parameters | | | Surface | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 303 dry | | 304 dry | | 310 compressed air | |
| Rotation | 2500 | rpm |  | |  | |  | |
| Diameter | 25 | mm | | | | | | |
| Cutting Speed | 196 | m/min | | | | | | |
| depht | 0.1 | mm | | | | | | |
| feed | 0.054 | mm/n | | | | | | |
| Tool | | | | | | | | |
| Hard Metal BA55 Brassinter | | | Ra [μm] | 1.09 | Ra [μm] | 0.77 | Ra [μm] | 0.35 |
| | | | Ry [μm] | 7.76 | Ry [μm] | 3.93 | Ry [μm] | 2.13 |
| | | | Rz [μm] | 7.76 | Rz [μm] | 3.93 | Rz [μm] | 2.13 |
| | | | Rq [μm] | 4.67 | Rq [μm] | 0.92 | Rq [μm] | 0.45 |
| | | | Rt [μm] | 9.66 | Rt [μm] | 5.14 | Rt [μm] | 3.11 |
| | | | Rp [μm] | 5.13 | Rp [μm] | 2.03 | Rp [μm] | 1.12 |

Figure 5. Machined surfaces of AISI 303, 304 and 310 steels. Average cutting speed was about 196 m/minutes. n represents rotation. The machining parameters are described in the figure. Ra, Ry, Rz, Rq, Ry and Rp represent arithmetic mean roughness, maximum height, maximum height, root-mean-square roughness, total height, peak height, respectively.

The AISI 310 steel showed no tendency for strain-induced martensite formation (Machado et al., 2005). Neither on machined sample nor in the chip was magnetism recorded. On the other hand, the formation of strain-induced martensite was observed in the AISI 303 and 304 steels, mainly in the chips. This phase transformation is usually undesirable. However, the formation of strain-induced martensite might cause the AISI 304 steel chip to be broken of. In the AISI 303 inclusions facilitated chip breaking.

The surface roughness measurements did not present significant differences in the steels studied. The effect machining parameters affect the surface finishing in a different way. For instance, the lowest value of Ra (arithmetic mean roughness) was obtained at different cutting speeds: 94 m/minute in AISI 303 steel; 60 m/minute in AISI 304 steel and 196m/minute in AISI 310 steel. However, the results made it possible to choose the appropriate cutting speed for the other tests. A similar behavior was observed in the steels machined at the cutting speed of about 90 m/minute as shown in figure 6.

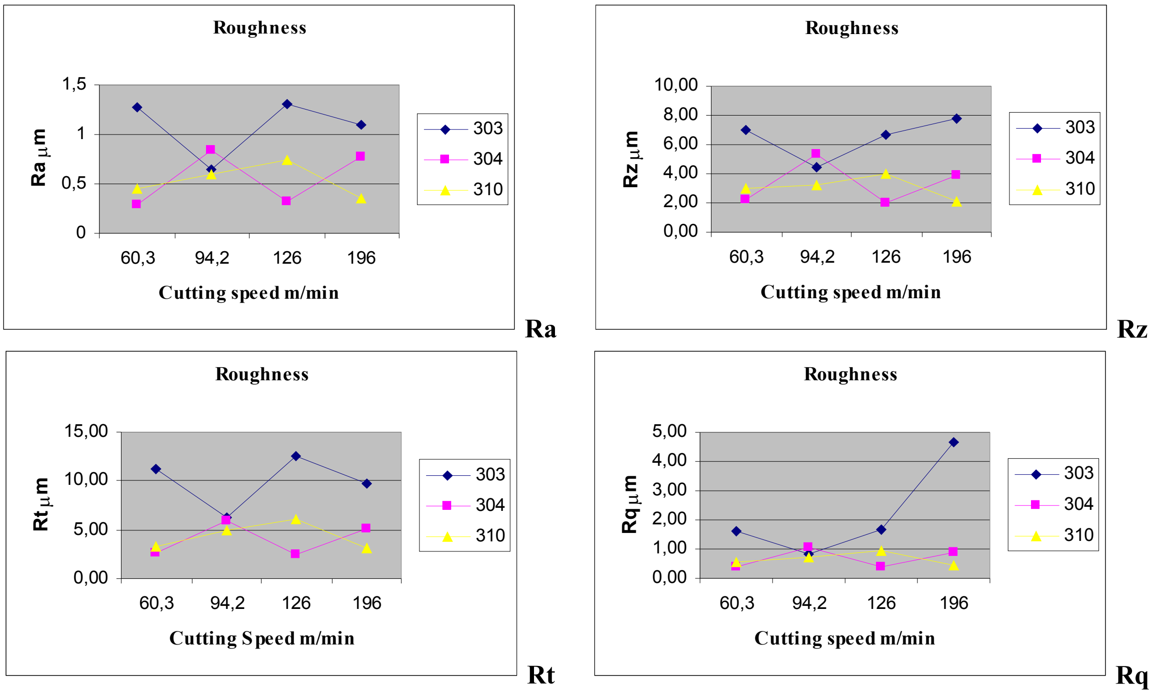



Figure 6. Roughness of machined surfaces versus cutting speed of AISI 303, 304 and 310 steels. The machining parameters are described in the figure. Ra, Rz, Rq, and Ry represent arithmetic mean roughness, maximum height, root-mean-square roughness, total height, respectively.

### 3.3 Turning

The results of the feed force and the cutting force are shown in table 3. The AISI 310 steel showed the highest values of machining forces. This behavior can be associated to high workhardening of this material. The AISI 303 steel showed the lowest values of machining forces, which is widely known for its better machinability. The MnS inclusions improve chip breaking. The difference between the cutting force of AISI 304 and AISI 310 steel in the annealed condition was not significant. However, the difference between the cutting forces of these steels in the aged condition was higher. This behavior is probably related to higher contents of alloying elements of AISI 310 steel. The relationship between the cutting force and the austenitic steels studied showed the same pattern of previous work (Machado et al., 2005). The results of this work confirm the effect of materials mechanical behavior on the cutting force. The feed forces measured during all tests varied between 75 and 80% of the cutting force. Another interesting result is related to hardness. The hardness of the materials did not change very much with heat treatment. As a conclusion, in this work, the hardness cannot be related to the cutting forces.

Table 3 – Cutting forces of AISI 303, 304 and 310 steels in the annealed and in the aged conditions. The feed of 0.104 mm/rotation, the cutting depth of 0.5 mm and the cutting speed of about of 90 m/minute were the machining parameters of the tests.

| **Steel** | **Cutting force** | **Feed force** |
|---|---|---|
| AISI 303 annealed | 158 N | 117 N |
| AISI 303 aged | 194 N | 147 N |
| AISI 304 annealed | 194 N | 156 N |
| AISI 304 aged | 182 N | 144 N |
| AISI 310 annealed | 196 N | 147 N |
| AISI 310 Aged | 232 N | 176 N |

The geometrical values of roughness were calculated and compared to Rt (maximum roughness) (Ferraresi, 1977). The feed of 0.104 resulted in geometrical roughness of 3.38 μm. Table 3 shows the roughness of the machined surface of different steels. No significant difference was observed in roughness of the materials studied. The roughness measured was higher than previous calculated (geometrical roughness). The roughness is influenced by tool wear, vibrations and plastic strain that occurs due to chip formation. Hence these results were expected.

Table 3 - Roughness of the machined surface of AISI 303, 304 and 310 steels. Ra, Ry, Rz, Rq, Ry and Rp represent arithmetic mean roughness, maximum height, maximum height, root-mean-square roughness, total height, peak height, respectively.

| Steel | Ra μm | Ry μm | Rz μm | Rq μm | Rt μm | Rp μm |
|---|---|---|---|---|---|---|
| AISI 303 annealed | 1.97 | 14.39 | 14.39 | 2.60 | 17.97 | 7.99 |
| AISI 303 aged | 2.03 | 13.64 | 13.64 | 2.66 | 16.32 | 6.07 |
| AISI 304 annealed | 2.36 | 15.19 | 15.19 | 3.02 | 17.73 | 8.89 |
| AISI 304 aged | 1.55 | 10.25 | 10.25 | 1.97 | 11.68 | 6.67 |
| AISI 310 annealed | 2.09 | 15.96 | 15.96 | 2.95 | 21.37 | 11.14 |
| AISI 310 aged | 2.82 | 18.23 | 18.23 | 3.71 | 20.62 | 10.43 |

### 4 Conclusions

The following conclusions are based on the results presented in this study:

1. No significant difference was observed in roughness of the materials machined.
2. The effect machining parameters affect the surface finishing in a different way. For instance, the lowest value of Ra (arithmetic mean roughness) was obtained at different cutting speeds: 94 m/minute in AISI 303 steel; 60 m/minute in AISI 304 steel and 196m/minute in AISI 310 steel. However, the results made it possible to choose the appropriate cutting speed for the other tests. A similar behavior was observed in the steels machined at the cutting speed of about 90 m/minute.
3. The AISI 310 steel showed the highest values of machining forces. This behavior can be associated to high workhardening of this material. The AISI 303 steel showed the lowest values of machining forces, which is widely known for its better machinability. The MnS inclusions improve chip breaking. The difference between the cutting force of AISI 304 and AISI 310 steel in the annealed condition was not significant. However, the difference between the cutting forces of these steels in the aged condition was higher. This behavior is probably

related to higher contents of alloying elements of AISI 310 steel. condition was higher. This behavior probably is related to higher contents of alloying elements of AISI 310 steel.
4. In this work, the hardness of the materials cannot be related to the cutting forces.

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