# STUDY OF THE SURFACE INTEGRITY IN A SUPER DUPLEX STAINLESS STEEL AFTER TURNING

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***Abstract.*** *The purpose of this paper was to study the main effects of the turning in the surface integrity of the duplex stainless steel ASTM A890-Gr6A.The focus of the work was the finishing operations and a complete factorial planning was used, with 2 levels and 5 factors. The tests were conducted on a turning center with carbide tools and the main entrances variables were: tool material class, feed rate, cutting depth, and cutting speed. The analyzed answers were: microstructure analysis, surface roughness, cutting force measurements and the micro-hardness variation. The results showed that was not possible to find microstructural changes even when the bigger cutting parameters were used. The other answers were correlated with the cutting parameters and a good selection was founded to the best surface integrity generation, that means, that the smaller feed rate, the smaller cutting speed and the bigger cutting depth provides the best combination of the best roughness and the micro-hardness values.*

***Keywords:*** *Manufacturing and processing, machining, turning, super duplex stainless steel and surface integrity.*

## 1. INTRODUCTION

At least one in each five machining operations is turning (Chang, 1998). This process also in one of the most used in the industry, with 40% of the total time expensed in machining and 30% with relation to the operation number when compared with other processes (Tönshoff et al., 1994). Its visible the importance in the day-by-day of the industries and becomes necessary the continuous improvement of it's quality and the number of specific information that cannot be gotten during the continuous machining process. The turning also is very used in the pumps industry, that is one of the main users of the material to be studied in this work.

The super-duplex stainless steel (SDSS) presents characteristics of the ferritic and austenitic stainless steels in just one material, and in this form it has greater mechanic and corrosion resistance than the conventional austenitic stainless steels. It's characterized by a mixture structure in approximately equal parts of austenite and ferrite. Although not formally defined, it's generally accepted that the smaller phase exists in approximately 30% of the material volume. Its structure is obtained through controlled chemical analysis and balanced thermal treatment. The resistance to the corrosion of a super-duplex stainless steel is equivalent that reached by some classes of the "super-austenitic", that count 5-6% of Molybdenum (Charles, 1995).

The SDSS with relationship to the austenitic steels stainless steel, presents several advantages, being the mayor ones: larger resistance to the corrosion under clorets tension, larger resistance to the pitting corrosion and in general twice strength limit than an austenitic, with just half of the amount of nickel present in the austenitics, being less sensitive at the high costs of this element (Davidson et al., 1991 and Berglund et al., 1986). Some phase's precipitation can occur when this material is heated and cooled under certain conditions and the Fig. 1 presents a diagram "time, temperature, transformation" for this material. Between all the phases, the σ phase is one that causes greater problems in material, in its mechanical and corrosion resistance. As can bee noted, some phases can appear in some temperatures above that reached by the machining but with heating for more time than the almost instantly heating and cooling occurred by the machining, so the doubt in the beginning of this work was to know if the machining could cause some phase precipitation during the material cutting.

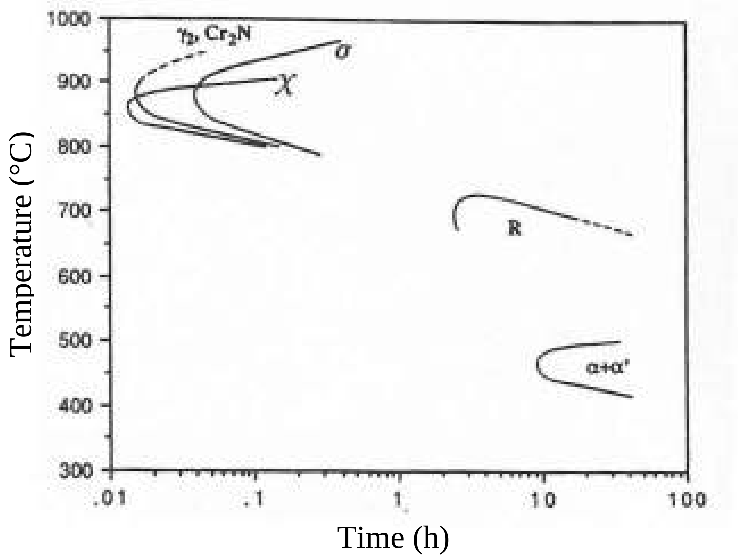

Figure 1. TTT curve for a super duplex stainless steel.

The machining of stainless steels is in general different, when compared with other steels. It’s mainly characterized for: High strain rates that induce mechanical modifications and heterogeneous behavior in the generated surfaces, and that take to the unstable chip formation and vibrations (Saoubi et al., 1999); Low thermal conductivity (Dolinsek et al., 2003) because the conduction of heat corresponds approximately ¼ of the founded value in the machining of a common steel, and in this way the heat is less transferred for the work material or the chip and it’s concentrated more on the tool edges; High fracture resistance, resulting in high temperatures, difficult chip break and consequently low surface quality (Jang et al., 1996); High values of mechanical resistance and ductibility (Chang, 1996); BUE formation, and in a different way from the conventional steels, it can appear in higher speeds; High wear of the tools, due to the high cutting forces, and frequently small material pieces are removed from the tool, due to the high adhesion in the rake surface; High thermal dilation coefficient, what difficult the maintenance of small tolerances and high friction coefficient, that has as consequence, the increase of the cutting forces and the generated heat.

In spite of the main characteristics presented, it’s noted that the machining of stainless steels cannot be totally generalized. Due to the great variety, the machining can be worse, or better, in agreement with the microstructure, hardness and elements content league, being known that the microstructure affects the machining in larger scale than the hardness. As example, Bletton et al., (1990) mention that the two-phase structure of the duplex stainless steels, contribute to induce vibrations during the cutting, increasing the problems mentioned until the moment and contributing to the tool life decrease.

The difficulties in the machining of SDSS tend to increase, therefore the machining of this material frequently is compared with its PRE (pitting resistance equivalent) (Jiang, 1996). Due to the great amount of austenite, nitrogen and alloy elements, the machining of this material tends to decrease quickly. Another factor that contributes to the difficulties in the machining and in the study of this material is the fact that, it’s biphasic, as previously mentioned. Each phase is random distributed, and contains different characteristics and properties, and each one contributes in a different way to the chip formation and material cutting during the machining.

Some studies, many of them recent, were conducted in the metallurgy area and in the material properties, but there are not many researches about the machining of this material. It’s very clear the necessity of studies for the SDSS in this area.

The surface integrity is a measure of the machined surfaces quality, interpreted in function of elements that describe the structure of the surface and the substratum of the material. Generally it is defined by the metallurgic, chemical and topological properties of the surfaces, as surface roughness, microstructure, micro-hardness variations and changes in the residual stresses (Jang et al., 1996 and Matsumoto, 1986). These characteristics become still more important in the machining of a material of an expensive cost, as the case in this work. Some studies of previous decades have studied this subject for many materials, however not specific for the super-duplex stainless steel, that is more recent and its utilization is growing nowadays.

To accomplish the established objectives of this work, some tests were made by a factorial design and the mainly analyzed answers were: surface roughness, microstructural changes, cutting forces, and micro-hardness variation. The objective of this work is to characterize the main effects caused in the material surface integrity by the machining through the turning operation and to establish correlations between the cutting parameters and it’s consequences, since the adequate choice of the cutting parameters is basic to get products with the surface qualities required [Thomas et al., 2003 and Lee et al., 2000].

## 2. EXPERIMENTAL PROCEDURE

The tests were conducted in a turning center OKUMA LB300, and the used cutting fluid was the Castrol PS04002 with 6% of emulsion in water, in abundance.

The Fig. 2 shows an example for the used specimens.

The material was the super duplex stainless steel ASTM A890GR6A (0.02 C, 24.8 Cr, 7.49 Ni, 0.65 Mn, 0.8 Si, 3.37 Mo, 0.006 S, 0.025 P, 0.8 Cu, 0.059 Zr, 0.79 W, 0.24 N, <0.001 Nb, <0.001 Al, 0.044 Co, 0.03 V, 0.006 Ti, 0.0009 Pb, 0.082 Sn, Fe).

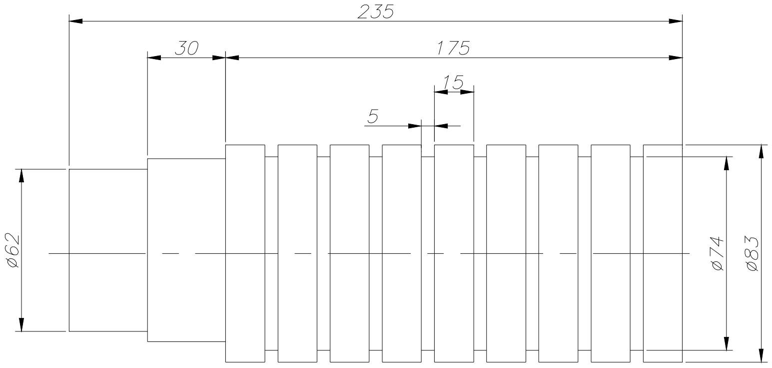

Figure 2. An example of a specimen used.

After the casting made especially for this work with dimensions ∅90x400mm, the material was annealed. Each part of the specimens (piece of 15mm as illustrated in Fig. 2) were machined by different cutting parameters, as will be showed at next. The left part of the the specimens was used to fix it on the turning center machine.

The used design of experiments was the complete factorial, with 2 levels, 4 factors and 2 replicates. This design was used because it's the unique that can study the interactions between the factors (Calado et al., 2003 and Montgomery, 1976). The used cutting parameters were: cutting speed (110 and 150 m/min), feed rate (0.1 and 0.2 mm/r) and cutting depth (0.25 and 0.5 mm).

Every one of the used insert carbide tools doesn't have been utilized for more than 2 segments of the specimen and in this way, was considered that only new tools were used on the work. The inserts carbides used were: VNMG 160404-MF–1025 with PVD TiAlN coating and VNMG 160404-MF–2015 with CVD TiCN-Al2O3-TiN coating.

For the cutting measurements the mainly used instruments were: piezoelectric dynamometer with a PCB Piezotronics cell, model 260A01, software Catman release 3.1, signal conditioning Spyder 8 from Hottinger Baldwin Messtechnik (HBM) and a personal computer.

For the surface roughness measurements: Roughness surface tester Mitutoyo Surftest SJ201.

The investigation on precipitated phases was made by x-ray difractometer RIGAKU, model Multiflex and optical microscopy Olympus BX60MFS, with digital camera Sony CCD-IRIS.

The micro-hardness measurements were conducted by micro-hardness tester HMV – Shimadzu (HMV-2 344-04152-02), with 50g of load, during 15s for all the measurements. The Fig. 3 shows how the pieces were separated from the initial specimen to the micro-hardness measurements and microstructure analysis. After the cutting made in a cut-off machine with abrasive disc and water fluid in abundance the samples were prepared using standard metallographic techniques.

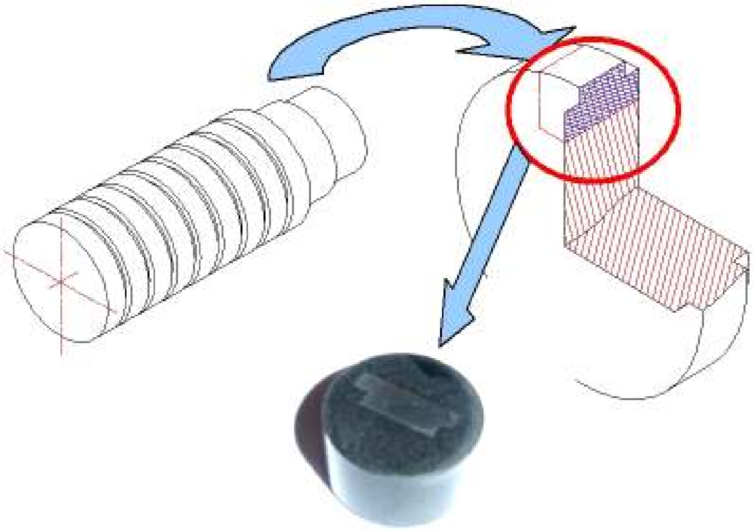

Figure 3. Cutting from the specimen for the micro-hardness measurements

The KOH (Heated Potassium Hydroxide) etch by electrolytic immersion during 50 s with 2 V was used for distinguishes the both phases before the micro-hardness measurements.

For the optical metallographic analysis more 2 etches were made to study the precipitation phases on the material: Oxalic 10%, with immersion in an electrolytic solution during 1.5 min with 3.5V according ASTM A262 and modified Behara that consists in 5 parts of $H_2O$ for 1 of concentrated HCl, with 0.3 g of metabisulfite of Potassium, for 100 ml of solution, for indeterminate immersion time.

## 3. RESULTS AND DISCUSSIONS

During the machining, the cutting temperature can reach at 1000° C or more, but in a short period of time. Precipitations diagrams of super duplex stainless steels showed that in smaller temperatures than this, many micro structural changes can occur, in according with Fig. 1 (Davidson et al., 1991 and Berglund et al., 1986). The optical metallographic analysis does not show any change in the microstructure of the material in any one of the 3 etches conducted. The Fig. 4 shows an example of one specimen etched by modified Behara. In the same way, the x-ray diffraction also reveals that used the cutting parameters don’t affected the surface and the substrate of the material. So, the doubt was solved with this preliminary analysis, remembering that for some phases precipitation this analysis weren’t sufficient to make this affirmation, but for the mainly that can affect the reliability of the material in service, as example, sigma phase could be detected in this case.

The Table 1 presents all the obtained results for the measurements.

The surface roughness analysis is illustrated in the Fig. 5. Each one of the plotted points is the mean value of 3 measurements for each test, of 3 replicates, that means 9 measurements in the total. The confidence level used on the work was 95%.

The results show great influence of feed rate on the analysis, as expected, considering that the surface roughness is geometrical dependent of this parameter. The cutting depth practically does not make influence on the surface roughness. The cutting fluid when used, improves the tribological phenomenon in the machining by the cutting lubrification and better surface roughness values were obtained. Bigger cutting speed decreases the BUE (Build-up edge) tendency formation (critical in this material), and decreases the tool-piece contact area, decreasing in this way the deformations and consequently the surface roughness (Bouzid Saï et al., 2001). The insert class 1025 with PVD coating provides smaller surface roughness values.

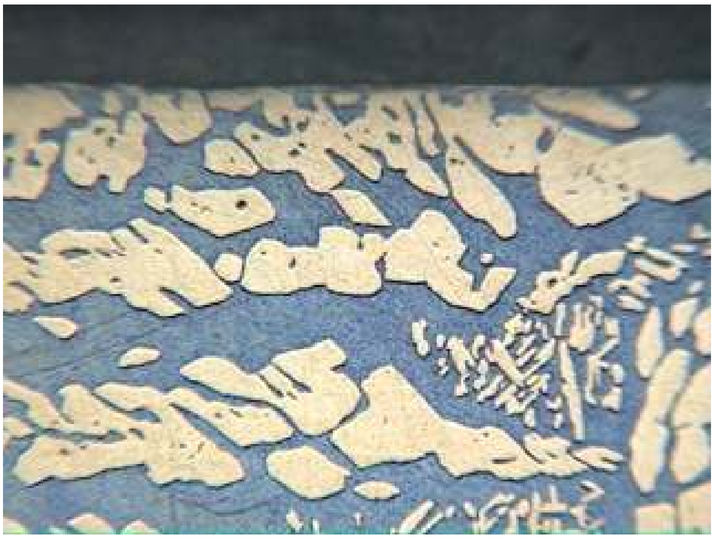

Figure 4. Optical analysis of a specimen (Cutting speed = 80 m/min; feed rate = 0.25 mm/r; cutting depth = 2 mm; with cutting fluid; carbide insert class 2015) etched by modified Behara

Table 1. Measurements results for the roughness, cutting forces and micro-hardness

| Cutting speed (m/min) | Feed rate (mm/r) | Cutting depth (mm) | Insert class | Feed rate force (N) | Penetration force (N) | Cutting force (N) | Roughness Ra (um) | Micro-hardness (HV0.05) |
|---|---|---|---|---|---|---|---|---|
| 110 | 0,1 | 0,25 | 2015 | 42,9 | 74,68 | 84,84 | 0,867 | 402,5 |
| 150 | 0,1 | 0,25 | 2015 | 45,92 | 84,36 | 86,78 | 0,818 | 445,5 |
| 110 | 0,2 | 0,25 | 2015 | 68,23 | 135,76 | 158,21 | 2,593 | 478,5 |
| 150 | 0,2 | 0,25 | 2015 | 65,03 | 141,06 | 153,37 | 2,857 | 464,25 |
| 110 | 0,1 | 0,5 | 2015 | 115,05 | 126,2 | 170,05 | 1,187 | 458,5 |
| 150 | 0,1 | 0,5 | 2015 | 92,35 | 103,03 | 156,27 | 1,157 | 446,5 |
| 110 | 0,2 | 0,5 | 2015 | 156,6 | 197,07 | 304,75 | 2,95 | 417,25 |
| 150 | 0,2 | 0,5 | 2015 | 163,72 | 212,98 | 310,01 | 3,333 | 459,75 |
| 110 | 0,1 | 0,25 | 1025 | 35,21 | 67,07 | 74,15 | 2,223 | 394,25 |
| 150 | 0,1 | 0,25 | 1025 | 36,94 | 73,3 | 79,89 | 1,162 | 435,5 |
| 110 | 0,2 | 0,25 | 1025 | 62,72 | 122,39 | 149,38 | 2,42 | 458 |
| 150 | 0,2 | 0,25 | 1025 | 44,25 | 93,35 | 114,39 | 3,477 | 432,5 |
| 110 | 0,1 | 0,5 | 1025 | 95,91 | 95,79 | 151,2 | 0,858 | 468,5 |
| 150 | 0,1 | 0,5 | 1025 | 53,09 | 78,13 | 104 | 0,923 | 387,75 |
| 110 | 0,2 | 0,5 | 1025 | 145,8 | 183,25 | 303,65 | 2,763 | 458,25 |
| 150 | 0,2 | 0,5 | 1025 | 135,42 | 158 | 285,67 | 2,732 | 479,5 |

The cutting forces measurements showed that the cutting force was the bigger, followed up by the penetration cutting force and the feed rate cutting force. This is a common behavior in ductile materials, but changing the position angle tool and rake angle this order could be affected. The feed rate and the cutting depth were the mainly parameters that influenced the forces, since they are responsible for the cutting section. The bigger cutting velocities, the smaller feed rate and cutting depth, the dry cutting and the insert class 1025 makes minor forces in it’s 3 components. The feed rate and cutting depth influences geometrically the cutting section and this behavior was expected. The bigger cutting speed and the dry cutting, decrease the shear stress, due to decrease in plastic deformation, in the chip hardness and in the friction coefficient, due to the increase in cutting temperature. The insert class also makes influences in all the cutting forces, due to the changes in tribological contact tool-piece, that the PVD TiAlN coating introduce on the cutting.

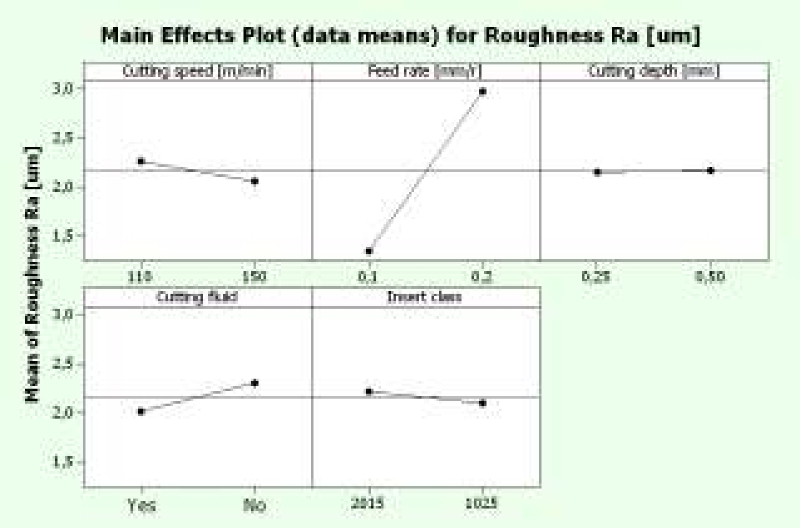

Figure 5. Main effects plot for surface roughness analysis

The micro-hardness measurements showed different values for the austenitic and ferritic phases. The ferritic were the bigger, and for the both, the values were dropped as soon as the depth from the surface of the cutting became bigger. The Fig. 6 shows the graph for one specimen. In most of all the measurements, below the 0.1 mm of depth the values do not change significantly, staying similar to the material center.

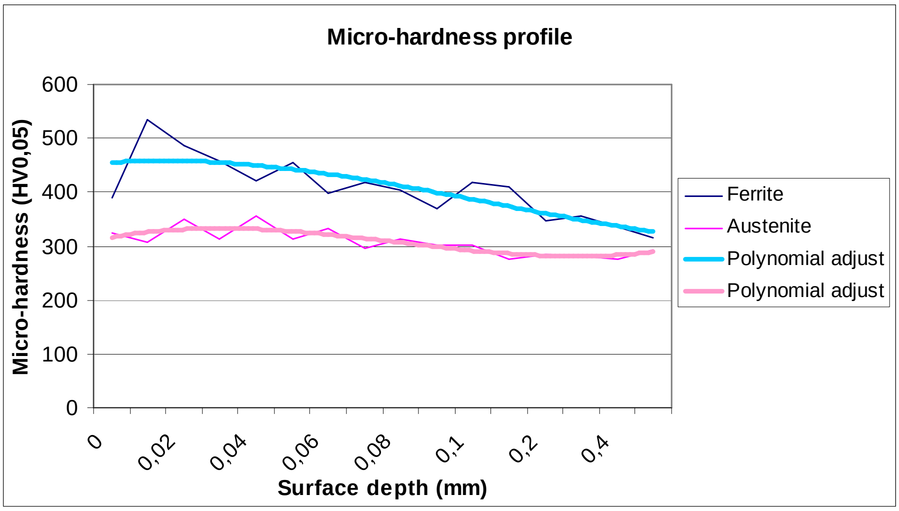

Figure 6. Micro-hardness example profile for a specimen (cutting speed=150 m/min; feed rate=0.1 mm/r; cutting depth=0,25 mm)

The deformation process of the austenite occurs by grain contours rearrangement and has a viscous character. Its rearrangement is more time dependent than the slip occurred in the ferritic phases, and for this its more dependent of the deformation rates imposed on the machining (Shaw, 2005 and Lee et al., 2000). The Fig. 7 can prove this, which for the finishing operations due to the small differences between the cutting parameters, the ferrite and austenite values didn’t change and all measurements were similar to the Fig. 6. For some rough operations conducted, due to the great differences between the cutting depth and feed rate, this phenomenon could be observed easily, and the austenite values were bigger than the ferrite values near to the surface, and when the depth from the surface was increasing, the values were inversed, according to the graph.

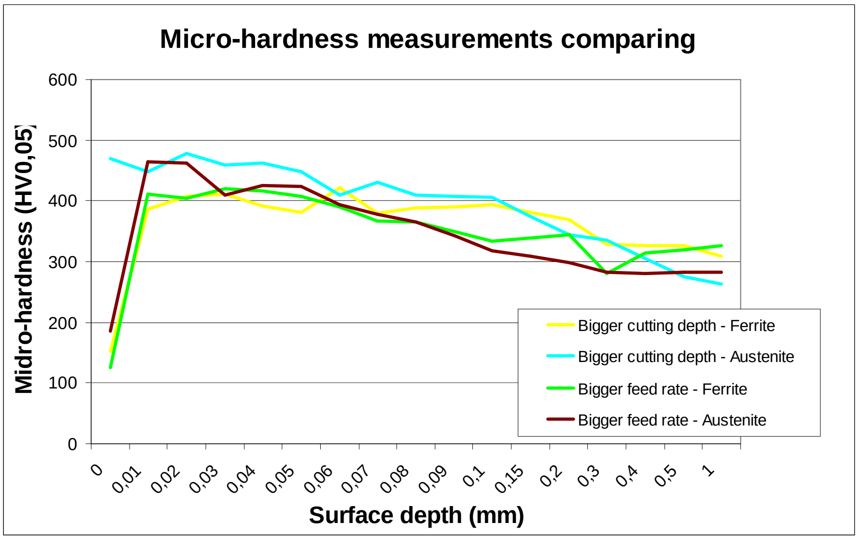

Figure 7. Micro-hardness comparing for bigger cutting depth and feed rate in rough operations

Can be noted by the figures that the most important variable to be studied is the feed rate, considering it's fundamental mechanical contribution during the machining in the strain hardening of the steels. These results were the same as the founded by Jiang et al. (1996) during milling operations. One more time, the insert carbide class show it's importance in the analysis. Bouzid Saï et al., (2001) also confirm this hypothesis and says that the increase in the tool-piece contact area and in the chip thickness, beyond the thermal effects that the feed rate improve make bigger values for the micro-hardness as well as the increase in the cutting speed and consequently the augment in the temperature.

The Fig. 8 shows the influence of the cutting parameters on the micro-hardness values. The considered values were the mean values of ferritic and austenitic phases, considering that this is the most important value for micro structural analysis, and that the sub-surface must be all analyzed and not only one or other single phase.

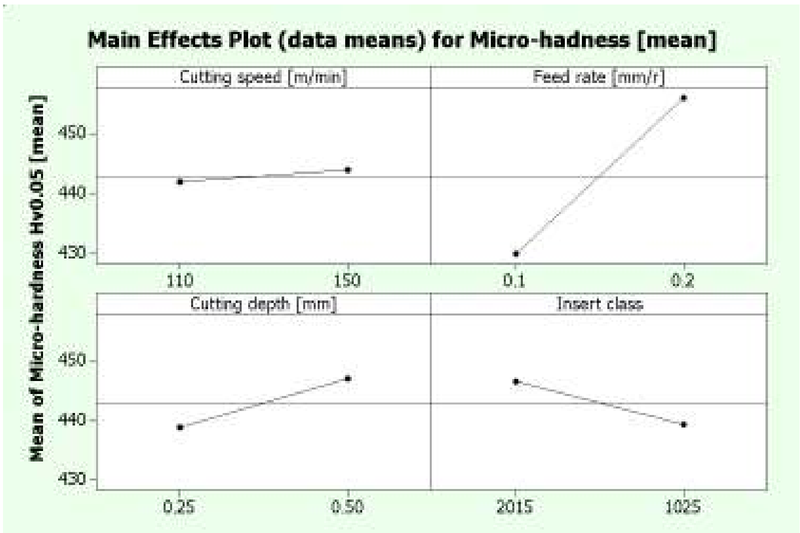

Figure 8. Factorial analysis for micro-hardness

The Fig. 8 shows the cutting parameters influence in the micro-hardness values. The cutting speed practically doesn’t affect the micro-hardness variation. The feed rate and the cutting depth (the most responsible for the cutting deformation process) are the most responsible for the changing in the values, where the bigger feed rate and the bigger cutting depth makes the greater values for the micro-hardness, as well as the 2015 insert class.

A correlation between all the answers was tried to be established, but it was not possible since each one of the factors influence the answers in a different way. For some data group this correlation can be made, for example, between the roughness and the cutting forces, but was not possible to correlate these two with the micro-hardness.

## 5. CONCLUSIONS

- ✓ There were not identified micro structural changes in any one of the specimens, even when the greater cutting parameters in rough parameters were used;
- ✓ The feed rate and the cutting speed were the mayor influence factors in the roughness analysis, where the smaller feed rate and the bigger cutting speed provides smaller roughness;
- ✓ The cutting force analysis shows that the cutting depth and feed rate were the most important factors in this analysis and the cutting speed was bigger than the feed rate and the penetration forces;
- ✓ The austenitic phases is more sensible to the deformation process in the machining than the ferritic;
- ✓ A correlation between all the factors cannot be made, because each factor influence in a different way the answers, but the combination between the smaller feed rate (0.1mm/r), the smaller cutting speed (110m/min) and the bigger cutting depth (0.5mm) makes the best values for the analyzed answers (smaller roughness and great micro-hardness);

### *Acknowledgements*

The authors would like to thank the Sandvik Coromant, the Sulzer Pumps and the Mauá Institute of Technology for the great help during this work.

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