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AN INVESTIGATION ABOUT THE SURFACE RESIDUAL STRESSES AFTER THE TANGENTIAL MILLING OPERATION APPLIED ON THE 15-5 PH STAINLESS STEEL WITH DIFERENT CUTTING PARAMETERS

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Abstract. *This investigation observes the surface residual stress that occurs at the surface of the workpiece when a tangential milling is produced. A set different cutting parameters combination was performed. The cutting speed and the feed per teeth were manipulated to induce different surface residual stress. The results were measured with a difractometer and the X-ray theory was fully examined. An important consideration when discussing surface stress is the need of explaining residual stress values before applying the machining operation. Wear and lubrication were not considered as dominant variables. The results measured at this investigation agree with surface residual stress behavior studied by other authors and drop-rising-stabilization profile for the residual stress can be seen in most of the results. It can also be seen at the results that cutting speed and feed per teeth do not influence equally the residual stress.*

Keywords: *Residual stress, Milling, Stainless Steel, Machining, Cutting parameters*

1. INTRODUCTION

The residual stress is an unavoidable result of the milling operation due to the severe mechanical energy applied in the raw material during the chip formation. Unfortunately, not all the mechanical energy is converted into chip. The heat generation, the acoustic emission and the residual strain and stress can be considered as secondary results of the machining processes.

The residual strain is related with the lattice defects movement and this aspect is strictly related with the cutting forces that were applied and the yield behavior of the material. The residual strain measurement is difficult and it is not enough to identify whether the surface is stressed or not. Hence, the surface can be strained but not stressed. This condition is attained when the material crystal lattice naturally relieves the stress, converting it into strain, or by the heat treatment that relieves the stress but not the strain.

The majority of the dynamic mechanical structural applications are submitted to stress during the part operation. Automotive and aerospace components are examples of this effect. The intensity and frequency of the applied loads are important aspects that justify the measurement of the residual stress in a machined part. Practical consequences of the residual stress are changes on fatigue life, wear and corrosion resistance due to compressive or tensile residual stress at the machined surface.

2. BIBLIOGRAPHY REVIEW

2.1 Residual Stress Measurement in Machining

A good amount of articles relating residual stress for hard turning can be found and the convergence among all of these researchers is the fact that the machining process is a compressive stress inducer (Xueping et al, 2009), and there is a raising tendency for the residual stress distribution as the measurement depth increases. El-Axir (2002) proposes a model which the residual stress is predominantly tensile. It is an opposite conclusion based on the majority of results observed at the literature. Tensile residual stress induced by the machining process would be prone to fatigue crack nucleation, whereas a machined surface with compressive residual stress would be resistant to such an event (Wyatt et al, 2006).

Arunachalan et al (2004) concluded that when a thermal effect is dominant the residual stress tends to be tensile. On the other hand the mechanical effect leads to compressive effect. The explanation for this effect is the different cooling time between the surface and the subsurface. Since the surface decreases its temperature faster than the core, the subsurface tends to expand while the surface contracts. At limit, the subsurface tries to expand and results in a tensile effect at the surface.

Another important observation done by Arunachalan et al (2004) is the gradient residual stress behavior as the measurement reaches the workpiece core. This observation is also related with the cooling dynamics for the billet production. The explanation for the lower residual stress is also related with the thermal gradient mentioned above.

Cutting force, workpiece temperature, and contact stress are the main aspects for the residual stress. Cutting force is severely affected by cutting edge hone (Liang et al, 2007). An understanding model of how the residual stress takes place in a particle inside a machined workpiece was suggested by Lin et al (1995). During the machining, both the mechanical and the thermal loads are dynamic and move along with the tool. Thus, if a material particle at a particular depth beneath the workpiece surface is observed, the strain field will be found to pass through the stationary particle or, if both of the loads are assumed to be fixed, as static loads, the particle is considered to flow through the strain field (Lin et al, 1995).

It is possible to affirm that the electrolytic polishing time influences severely the residual stress measurement. And this important information is not given by many authors. This influence is related with the depth and the real roughness profile that is being focused by the X-ray beam. Tang et al (2009) indicates that the highest residual stress takes place at 15-25μm beneath the surface but do not mention the time spent by the electrolytic polishing to achieve this depth. El-Axir (2002) indicates the same depth removal for a good residual stress evaluation.

The depth of the induced residual stress penetration is not a common value among the researchers. This very small scale is about 10μm. Nanoidentation can fit this scale in the case of a physical and not a wave lenght measurement (Warren, 2006). The same authors do not consider the influence of surface roughness for the residual stress measurement.

2.2 The Tangential Milling Operation

The tangential milling operation is markedly applied for those profiles where the cutting depth (a_p) overcomes the cutting width (a_e) in 6 to 10 times at least. The tangential cutter can also produce secondarily a flat surface orthogonal to the center line of the machine spindle but its major duty is producing a wall at the workpiece.

The use of a tangential cutter may allow a wall to be produced inside or outside of a workpiece (figure 1), but in these cases a regular milling cutter with cutting edges at its top and periphery must be used. All those cases which the wall produced is an outside outline a tangential cutter is enough and suggested. The corner radius is not a major detail at the design of a tangential milling cutter. The tangential cutting edge length is the main detail because the wall to be produced must be aligned and free of shattering marks along the machined wall. The power consumption is higher than the face milling due to the higher cutting contact area. The helical profile of the majority of the solid or exchangeable tangential milling cutter takes into account all of those aspects for defining the cutting contact. It means that all the surface and angles are composed in order to increase stability along the machining operation and not only the macro details are important for results of the residual stress, but also the micro profile specifically defined by the tool edge radii.

Figure 1 – Tangential milling cutter contact and the machined surface

2.3 Physical metallurgy of the residual stress and strain

A crystal may be defined as a solid composed of atoms arranged in a three dimensional periodic pattern. Ideally, the crystal or the unity cell is a set of parallel and equally spaced planes. The intersections of these planes are straight lines which are connected at the corner of each unit cell with the cited arrangement. A set of points constitutes a lattice point, which is defined as an array of points in space arranged in way that each point has identical surroundings. Serruys (1988) complements that it is necessary to understand the elastic behavior of a single crystal in a polycrystalline material in order to understand the problem with the X-ray elastic constants.

The Bravais lattices based on real crystals exhibit several types of symmetry. The symmetry leads to macroscopic symmetric operations at a unit cell. Reflection, rotation, inversion and rotation inversion are the macroscopic symmetric operation possibilities.

A unit cell has a relation with a primitive cell for a specific geometrical condition which arises from the real point cell distribution. The figure 2 shows a face centered cubic point lattice cell referred to cubic and rhombohedral cell. According to the figure 2, a particular condition of the rhombohedral cell results in a cubic cell. Lattice directions and planes also change according to real crystal arrangement. The plane orientation is represented symbolically by the Miller indices, which are defined as the reciprocals of the fractional intercepts which the plane makes with the crystallographic axes. The elastic constants related with Miller indices are presented by Serruys (1988) and also a relation between the two prediction models for the residual stress. These two models are based on constant stress and constant strain respectively.

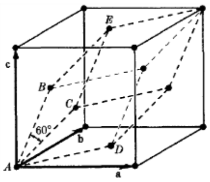


Figure 2 - Centered cubic point lattice cell referred to cubic and rhombohedral cell (Cullity, 1978).

The complete understanding of the X-ray diffraction technique for residual stress measurement is related with the slope angle which is formed after a compressive or tensile effort imposed against the unit cell. It is supposed that a unit cell has a natural diffractory behavior when the lattice is subjected to any thermo-mechanical effort (machining, heat treatment, hot rolling). When an X-ray is applied to an unstressed unit cell, the diffractory peak counting tends to be centralized, indicating that the discordance movement, the vacancies or any other disarrangement of the deforming planes are not disturbing the original diffractory behavior. After any thermo-mechanical deformation, the unit cell has its planes in a different orientation when compared to a Miller standardized sequence of parallel planes. The formation of residual stresses is a thermo-mechanical coupled effect.

The thermal aspect can also be observed by the phase transformation behavior. Induced temperatures at the surface region may lead to phase transformation. The transformation may induce the white layer formation. Phase transformation is the third aspect to affect machined surface integrity.

Stress can be observed as micro or macro level in nature. Micro-level residual stresses are those stresses within the crystal lattice which cover distances that are less than the size of the grain. Only stress in one phase is measured by the X-ray method, according to Serruys (1988).

Outeiro et al (2006) simplifies a very important aspect during the residual stress measurement. Despite the residual stress is a second order tensor with nine orthogonal components, the residual stress must be understood as a triaxial state of stress. On the other hand, the normal surface component σ_z is taken as zero despite a low depth penetration of the X-ray beam. As a consequence of σ_z the shear components τ_{xz} and τ_{yz} will be null. This analysis justifies the biaxial state of stress.

2.4 The Precipation Hardening Stainless Steel

This is a martensitic, precipitation hardening, chromium-nickel-copper stainless steel. The main applications of this material are: aircraft components, fabricated parts in high pressure corrosive environments including valves, shafts, fasteners, fittings and gears.

It´s a very sensitive material because of the precipitation hardening profile. The table 1 presents the mechanical properties as function of solution heat treatment temperature. This grade of stainless steel is also produced by ESR or VAR foundry process.

Table 1. Mechanical properties as a function of the solution heat treating temperature, according UNS 15500.

Solution temperature	*Tensile Strenght*	*Elongation (%)*		*Reduction of area (%)*		*Hardness*	
(F)	(MPa)	Min		Min		(HB)	
		Long.	Trans	Long.	Trans	Min	Max
900	1310	10	6	35	20	388	444
1000	1172	10	7	38	25	375	429
1025	1069	12	8	45	32	331	401
1050	1000	13	9	45	33	311	375
1100	965	14	10	45	34	302	363
1150	931	16	11	50	35	277	352

The elasticity modulus is about 200 GPa. The precipitation hardening (PH) profile is a hardening mechanism also called age hardening or dispersion hardening. The central idea of this characteristic is to provide fine particles of controlled impurities phases which constrain the movement of dislocation or defects in the crystal´s lattice. Since the dislocation are the main aspect in the plasticity behavior, this constrains induces hardening changes. The solution heat treating involves the formation of single-phase via solid solution.

3. EXPERIMENTAL PROCEDURE

3.1 Materials and Set Up

The following itens were applied at the machining operation:

Machine Tool: Romi Milling Center D540 with 15kW spindle power

Cutting Tool: Mitsubishi exchangeable milling cutter with 6 teeth and 80mm diameter. The tool insert is XDGT1550PDER-G30 VP15TF. The tool edge was a sharp intersection without honing and the surface coating was TiAlN.

Workpiece samples: Six blocks (140 x 120 x 200 mm) made with 15-5PH stainless steel. The average surface hardness is 321HB. The Sulfur content is about 10PPM. The samples of stainless steel was processed at regular arc continuous casting and also a vacuum arc remelting procedure. The billet was hot rolled into a bar shape. The samples were sewed at the transversal direction and the stress observed at the raw material before the machining procedure was -1124,56 (+/- 428,55) MPa, compression predominantly.

Measurement: The residual stress was measured with a Rigaku MSF – 3M X-Ray Difractometer. The roughness was measured with a Taylor Hobson Talysurf PGI Perfilometer.

Fixture: The tool drive was a DIN 69871 SK40 tool holder. The workpiece was mechanically clamped providing an exposed side of the sample block for applying the tangential milling.

Coolant: A single jet with 20 l/min flow of a semi synthetic water base emulsion with 8% concentration of HOCUT 795.

3.2 Experimental Method

The complete experimental planning is presented at table 1. The experiments were carried out at the arrangement cited at 3.1 and the governing variables manipulated are the cutting speed (v_c), the feed per teeth (f_z) the milling strategy (up milling or down milling) and the electrolytic etching time (t). The etching time results in the measurement depth.

The tangential milling experiments were divided in groups of three tests for each sample. The cutting depth for every test was 10mm and the cutting width was 2mm. A gap of 1mm was produced among each test in every blocks in order to separate the areas where each cutting condition was applied. The sample fixture provided enough rigidity because a workpiece overhang could impose differences at the cutting width. Chip morphology were not observed and the cutting tool was replaced to every set of three experiments.

Table 1 - Experimental planning

Test	Sample number	Cutting speed (v_c) [m/min]	Rotation (n) [1/min]	Feed per teeth (f_z) [mm/teeth]	Table speed (v_f) [mm/min]	Strategy	Cutting fluid	Etching time (t)[s]
1	1	60	238,73	0,1	143,23	Up milling	Yes	0; 15; 30; 60
2		90	358,10		214,85			
3		120	477,46		286,47			
4	2	60	238,73	0,125	143,23			
5		90	358,10		214,85			
6		120	477,46		286,47			
7	3	60	238,73	0,15	143,23			
8		90	358,10		214,85			
9		120	477,46		286,47			
10	4	60	238,73	0,1	143,23	Down milling		
11		90	358,10		214,85			
12		120	477,46		286,47			
13	5	60	238,73	0,125	143,23			
14		90	358,10		214,85			
15		120	477,46		286,47			
16	6	60	238,73	0,15	143,23			
17		90	358,10		214,85			
18		120	477,46		286,47			

The residual stress measurement details are presented at table 2. All the machined surfaces produced according to table 1 were submitted to residual stress measurement with four conditions of electrolytic etching time. All the residual stress measurement were taken in the feed direction.

The roughness was measured with the perfilometer in order to understand the surface profile for every etching time condition.

Table 2 - Ray Setting variables for the residual stress measurement

Item	Value	Item	value
Wave length radiation	Cr-K / alpha com λ = 2.28970 ⊕	Inclination angle (Ψ)	0°, 18,40°, 26,60°, 33,20°, 39,20° e 45°
X – Ray tube Voltage	30 KV	Method for peak identification	FWHM
X – Ray tube current	10mA	Young modulus (E)	223,3 GPa
Measurement widht	140 a 169,69° (peak at 156,40°)	Poison rate	0,28
Direction of lattice plan measurement	2 – 2 – 2	Strees / Inclination rate	-318,00 MPa / deg.
Incidence angle (2θ)	156,016		

4. RESULTS AND DISCUSSION

The variable etching time results in different surface roughness mean line depth where the residual stress is measured. This fact indicates the importance of a relation between these variables and it can be seen at figure 3. The results compiled further considered the roughness mean line depth measured with a perfilometer. It is important to consider that deeper roughness mean line will distort the profile by the chemical metal removal contact. It is possible to suggest that from 0 up to 60 seconds the mean line reduces linearly. The figure 4 presents the roughness profile as a function of the electrolytic etching time.

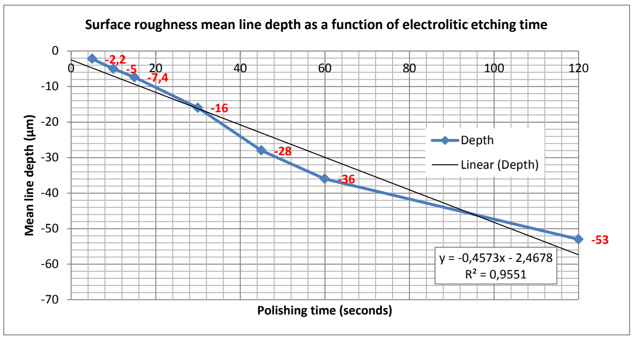


Figure 3

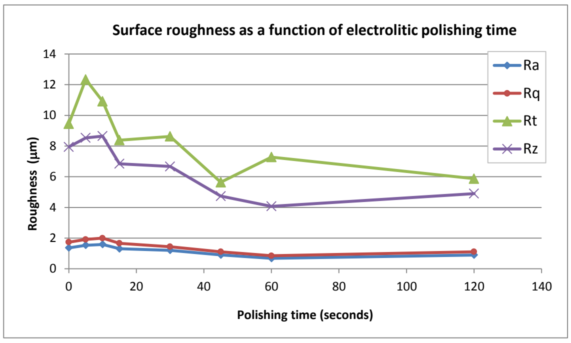


Figure 4

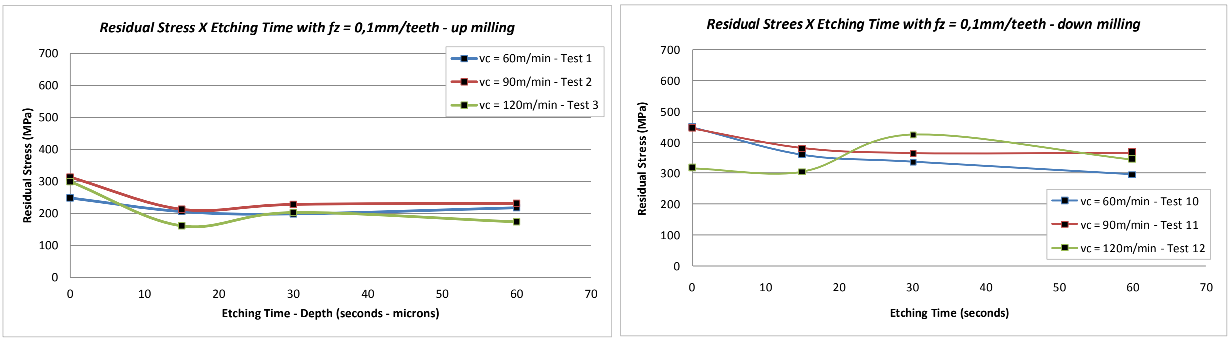
An important point that is necessary to relate with the residual stress measurement is the influence of the roughness. As the mean line depth changes, all the profile changes and the influence of the roughness decreases. The reason for that is metal removal that attenuates the peak-to-valley profile. Thus all the roughness is not completely removed but on the other hand and a different roughness pattern emerges from the chemical metal removed.

It is possible to affirm based on figure 3 and figure 4 that the roughness mean line decreases but the values Ra and Rq are possibly round a mean value that remains the same even with the decrease of the mean line. Another important point that must be related is the approximate point where the surface roughness does not influence the surface residual stress measurement. The maximum roughness parameter Rt is overcome by the roughness mean line at 30 seconds of etching time. It means that the chemical metal removal is deeper than the maximum peak-to-valley value observed. So, this investigation is based on the influence of the surface roughness from 0 up to 30 seconds of etching time and all the values over 30 seconds are free of the surface roughness influence.

The results according to the table 1 were divided in two set of graphics which the first set (figures 5 to 7) of analysis occurred with the value of feed per teeth taken as constant. The second set (figures 8 to 10) of graphics presents the same results but considering the cutting speed as a constant value. This division was suggested in order to simplify the observation whether a major variable is explicitly identified.

The workpiece material samples were obtained from a hot rolled long bar. This bar was sewed and all the surfaces where the machining tests took place were submitted to compression. It means that the signal is minus for the initial stress considered at the workpiece material. Some authors studied the residual stress as an effect that the previous manufacturing process is disregarded. This investigation considered the previous stress at the workpiece as the reference value and all the comparisons took this value as the initial. It means that a result for the residual stress is a sum between the previous state of stress and the amount of stress imposed by the system under observation.

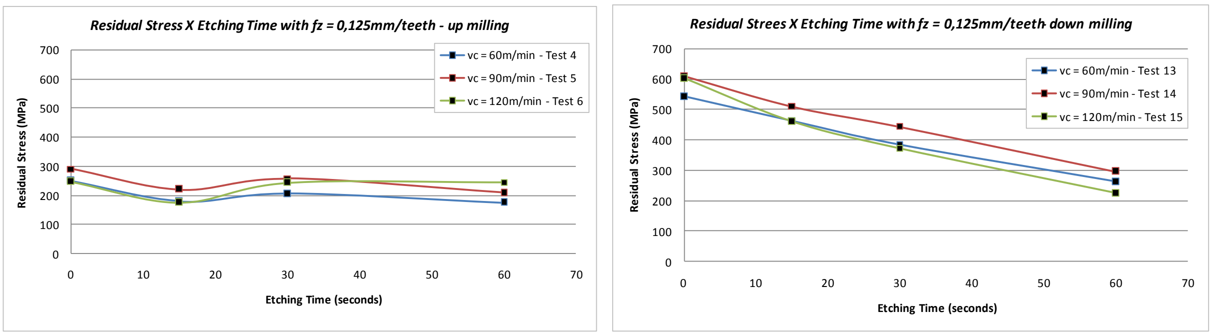
The figure 5, (a) and (b) presents the results for the residual stress according to table 1 for the tests with feed per teeth equals to 0,1mm/teeth.



(a) (b)

Figure 4

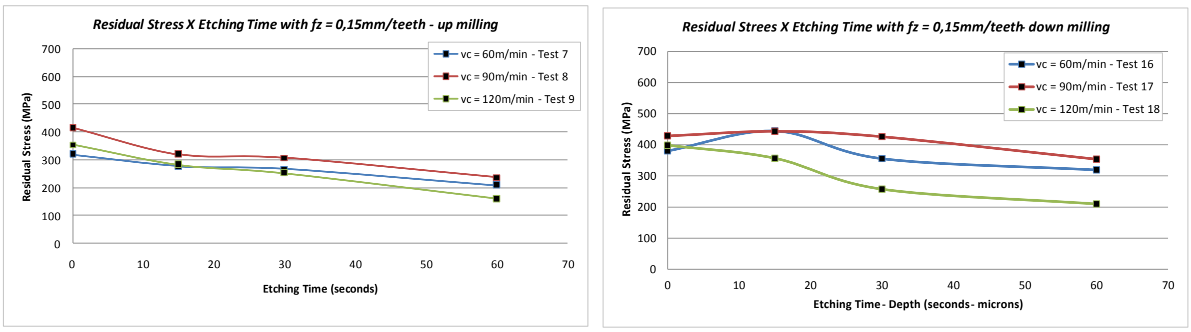
The figure 6, (a) and (b) presents the results for the residual stress according to table 1 for the tests with feed per teeth equals to 0,125mm/teeth.



(a) (b)

Figure 5

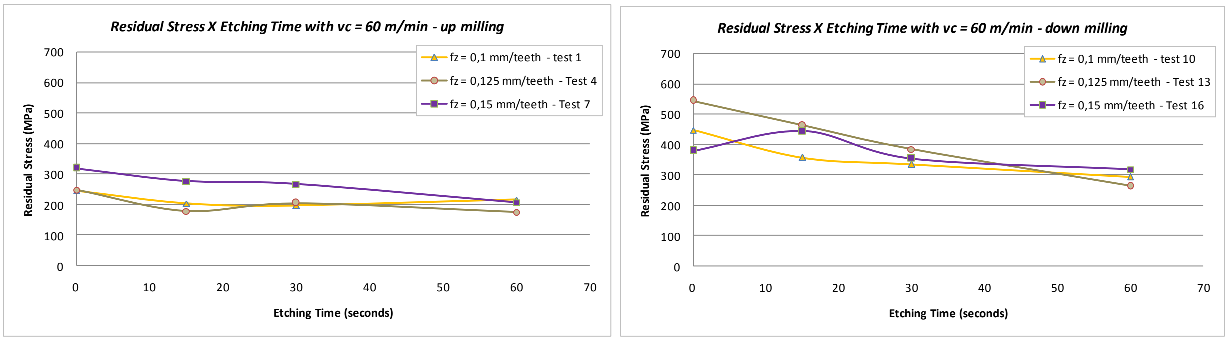
The figure 6, (a) and (b) presents the results for the residual stress according to table 1 for the tests with feed per teeth equals to 0,15mm/teeth.



(a) (b)

Figure 6

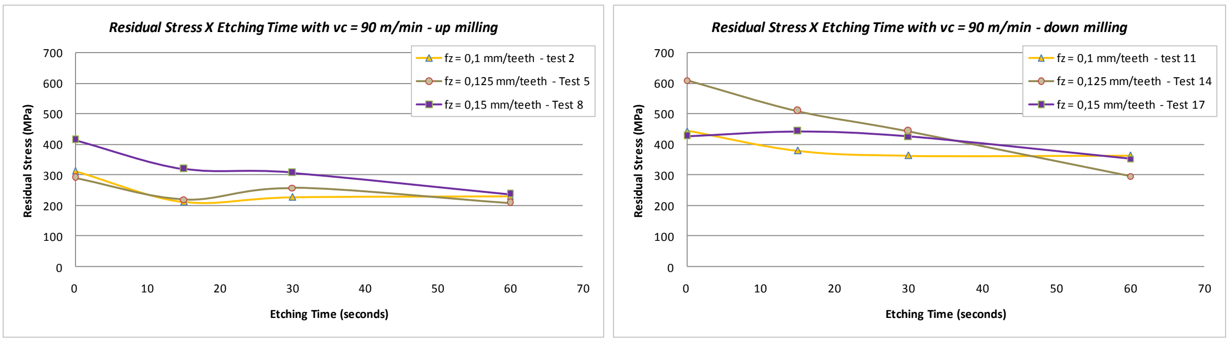
The figure 7, (a) and (b) presents the results for the residual stress according to table 1 for the tests with cutting speed equals to 60 m/min.



(a) (b)

Figure 7

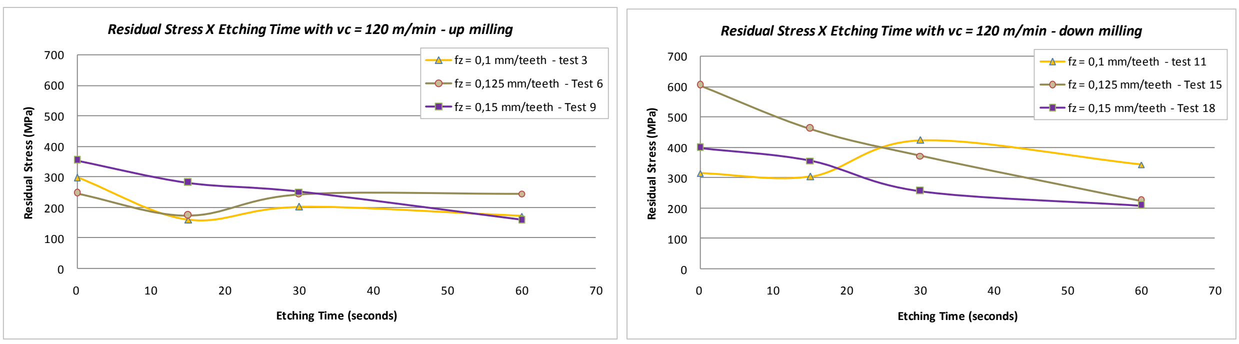
The figure (a) and (b) presents the results for the residual stress according to table 1 for the tests with cutting speed equals to 90 m/min.



(a) (b)

Figure 8

The figure 9, (a) and (b) presents the results for the residual stress according to table 1 for the tests with cutting speed equals to 120 m/min.



(a) (b)

Figure 9

The following paragraphs present the discussion for each parameter which allows a reasonable comparison.

- *Milling strategy*: The milling strategy with lower residual stress values is the up milling. It can be seen as a comparison between (a) and (b) to figures 4 to 9. The up milling presented a more controlled distribution of the values when compared with the values for the down milling.
- *Feed per teeth:* The increase in the feed per teeth resulted in convergent results at higher etching time (close to 60 seconds). All the results presented a decreasing value of the residual stress. However the up milling showed a very regular behavior to three values of the cutting speed. It means that for 60, 90 or 120m/min the feed per teeth had the same influence and the higher residual stress was measured to the higher feed per teeth. Even though the results for the down milling strategy are not regular as seen at the up milling, a singularity was seen and the medium feed per teeth. The residual stress is higher for the medium feed per teeth to every cutting speed at the down milling behaviour.

- *Cutting speed:* The increase of the cutting speed results in the increase of the residual stress for the up milling in a controlled manner. The increase at the cutting speed at the down milling strategy offers also an increase at the residual stress but the higher cutting speed does not represent the higher residual stress.

An important observation before searching for any other conclusion is the fact that an increase at the cutting speed has the major influence to the residual stress behavior. It can be affirmed after comparing the graphs above where the inclination of all curves are easily identified and all of them extracted from the figure 7 to figure 9 are shaper than those observed at figure 4 to figure 6.

The historical stress behavior of the material must be taken into account of the result that concludes the investigation by the fact that all the effect which is read at the graphs above are a sum of effects. The stress effects before the machining must be considered and the metallurgical homogeneity or heterogeneity play a role in the final result of the stressed component. All the results from figure 4 to figure 9 are tensile. But the previous value of the stress resulted from the hot rolling process is compression, -1124,56 (+/- 428,55) MPa. The figure 10 presents the result of final residual stress minus the reference value at the surface without etching time and after 60 seconds of etching time when the surface roughness can disregarded.

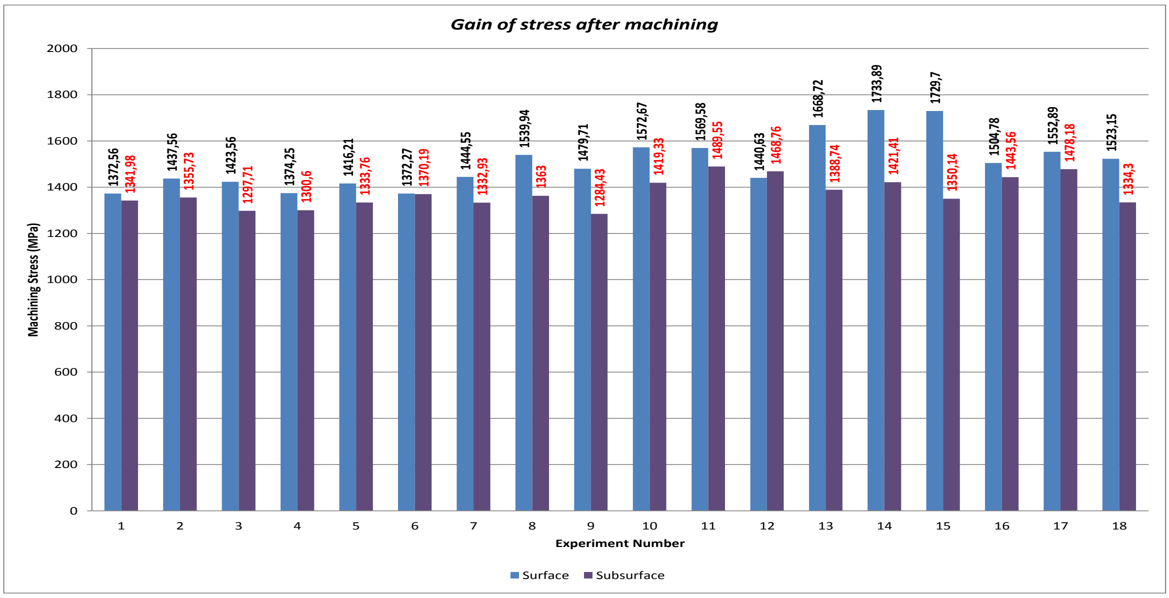


Figure 10

5. CONCLUSION

A mean line for the complete set of values which compose the figure 10 is not a correct analysis because an inferred comparison among very different cutting conditions can lead to incorrect and confused conclusions by the conditions analysis that must be understood monotonically and not composed by a simple mean or standard deviation altogether. But dividing the results into for groups which the milling strategy and the etching time are the considered variables, it´s observed the results presented at Table 3.

Table 3

Region	Mean (Mpa)	Standard Deviation	Variation (%)
Surface up Milling	1428,96	55,66	3,89
Surface down Milling	1588,45	101,57	6,39
Subsurface up Milling	1331,15	30,62	2,3
Subsurface down Milling	1421,55	55,15	3,87

According to Table 3 the subsurface has a lower deviation and it is justified by the elimination of the surface roughness influence. The down milling has a higher deviation and it is justified by the mechanics of the residual stress composed with the metallurgical influence of the workpiece material.

The surface roughness plays an important role at the residual stress measurement and there is a lack of information about how the chemical etching must be done and the period that can be considered as enough for eliminating the influence of the surface roughness.

The majority of the articles discussing residual stress on machining are concerned about material behavior only for its mechanical characteristics. The literature does not relate the physical metallurgy as an important aspect that must be considered when observing residual stress. This view point is totally neglected by many authors and it is a mistake because the metallurgy is not a secondary variable in the machining system. And also the values presented by many authors do not take into account the stress history of the workpiece material. Modelling residual stress must inform the amount of stress already applied onto the material before the machining operation in order to stablish not only the intensity but also the direction of the residual stress observed.

Based on the comparison of the down milling and up milling results, it is observed higher deviation for the down milling and for the whole set of combinations the tangential milling induces compressive residual stress which decreases the tensile behavior observed at the workpiece.

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