ANALYSIS OF RESIDUAL STRESSES, SURFACE INTEGRITY AND CUTTING FORCES ON THE HARD END MILLING OF SAE 4340

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Abstract. *This work aim to evaluate the influences of cutting parameters (cutting speed, feed rate per tooth and cutting depth) on the surface integrity of end milled prismatic work pieces made of steel SAE 4340 quenched to 52 HRC, machined with conventional coated tools from carbide inserts. The surface integrity characteristics were analyzed through the surface roughness, white layer formation and residual stresses. The milling cutting forces were measured by a tri-directional dynamometer, coupled to the table of the milling tool. The data acquisition was carried out through the commercial system HBM Spider-Cadman. The statistical design of the experiments was planned and carried out by a central composite design and analyzed using the software Statistica. The residual stresses were measured by the technique of incremental blind hole and interpreted by the integral method using the software H-Drill. The results show that the cutting depth was the parameter that most influenced the milling cutting forces. Regarding the surface integrity, the surface roughness presented average roughness "Ra" only found in the finishing machining processes such as grinding or even honing / polishing. However, with small variations in thickness, it was noted the presence of white layer in all work pieces. The residual stresses, in the majority of work pieces, were shown to be positive on the work pieces surface, and a strongly compressive state in the sub surface. No correlationship was observed between the milling cutting forces and the surface integrity at a statistical significant level of confidence.*

Keywords*: Hard milling, machining, hardened steel, surface integrity, residual stresses.*

1. INTRODUCTION

The concepts and developed knowledge in the machining of hard steel are applied to get desired surfaces and production in the lesser possible time, eliminating future operations, mainly, the grinding. The choice of the tool and the adequate application of the cutting parameters can not only contribute with the attainment of the specified surfaces, but provide the execution of the operations with lesser costs (Koshy et al., 2002).

One of the aspects of this research, is the study of the machining parameters influence, in the surface integrity that has significant influences in the life of products (Poulachon et al., 2003-A).

However, beyond the surface integrity, the behavior of the cutting forces has great importance for the optimization, the monitoring and the control of the machining processes. In virtue of its relative easiness of measurement and its relevance in the machining, many researchers have used cutting forces measurements, for the evaluation and agreement of the process and analysis of the kinematics and dynamics of the machine tool. With this knowledge, the dynamic stability, precision of positioning tool-part, conditions of the tool, machined surface and errors in the part, are explained by the basis of the analysis of the operating cutting forces (Schoroeter et al., 2001).

This work has for general objective to characterize the influence of the cutting parameters in the surface integrity, roughness and in the level of the residual stresses of the machined surface, during the finishing milling process of hardened steel SAE 4340, to 52 HRC. The cutting forces had been analyzed during the machining through a strain gage dynamometer. Through this characterization it is intended to supply qualitative information, that can guide the best choice of the machining parameters, in view of the quality and productivity.

1.2 Hard milling

The hard milling is a machining process of materials with hardness greater than 45 HRC, being that normally works with hardened materials between 58 and 68 HRC. To machining material that already had passed for heat treatment, it is verified some different characteristics of the hard milling when comparing with the conventional process without heat treatment or not hardened. In according to Koepfer (2007), these critical factors are:

- Machine stability;
- machining tool;
- tool holder;
- cooling system (when necessary);
- cutting parameters.

In according with Lima et al., 2002, the main reason for the adoption of this type of machining, is the possibility to eliminate the stage of grinding in the finishing operation, being possible to get parts with good dimensional and surface quality without the use of this last process. In such a way, it can be reduced in a significant form the time and aggregate costs of manufacture, since the possibility to use a simpler machine-tool, and to execute many kind of operations with only one setup, without the necessity of more transports and smaller costs with cutting tools, beyond allowing greater productive process and bigger productivity.

The point of view of machining time, the removal of the material in the hard state needs a bigger time when we compare to the accomplishment of the machining before the heat treatment. This fact is related to the determination of more aggressive cutting parameters ahead of the machining of the material before the heat treatment. However, to carrying out the machining in the hardened state, the stage of grinding can be eliminated (Altan et al., 2001). This option, beyond minimizing the time of preparation of machine, also reduces the chain of the process and facilitates the attainment of reduced tolerances of position and form.

1.3 White layer

The term white layer is originated by the white color that the layer presents in optic microscopy. In literature, the white layer is related, of a generic form, to a hard layer formed in ferrous materials under varied cutting conditions. The found typical thickness in literature is about 10 μm varying as the condition of cutting (Bosheh et al., 2005).

The white layer can be originated from the chip formation and can only be seen through optic microscopy. It influences the fatigue strength of the part, as well as the behavior of the same when submitted to the attrition, affecting significantly the performance of the machined component. They exists at least three different origins of its formation (Bosheh et al., 2005):

- the mechanism of plastic flow, which produces a homogeneous structure or a refined structure;
- heating mechanism and quenching;
- mechanism of reaction of the surface with the environment such as: nitriding, carburizing and oxidation.

1.4 Residual stresses

The residual stress is defined, according to Matsumoto et al., 1986, as a tension that remains in the machined component after the request that it was submitted. The residual stress is introduced in the surface through the process of the material removal, and its presence can be useful or disastrous depending on the application of the part and the same one can be of traction or compression, high or low.

The residual stresses are introduced in the metal for mechanical, thermal, chemical or a combination of these processes, resulting in a permanent change in its form (Evans, 1971). As example the following processes can be cited:

- Mechanic: machining, mechanical conformation, assembly;
- Thermal: welding, casting, heat treatment;
- Chemistry: oxidation, corrosion, electroplating.

1.5 Cutting forces

The knowledge of the involved forces in the cutting processes are very interesting to analyze the machinability of the finished material, to define economic methods of the view of energetic point and to allow the correct choose of a rigid machine-tool to guarantee dimensional quality.

During the machining, it does not know the direction of the cutting forces, and this cannot be measured. For in such a way, becomes necessary to project components of machining forces in orthogonal plans, being thus become known directions (Diniz et al, 2001). These machining forces can be decomposed in active and passive components:

- Active cutting forces: Cutting force;
  Cutting force feed rate;
- Passive cutting force: Cutting force depth;

However, only the active forces, for being contained in the work plan, consume power. Although this fact, the value of the passive force has an important influence in the milling process, therefore the buckling of the tool holder depends directly on the value of this force. The force components, considering a cartesian plan, in the cutting tool in contact with the part are express in accordance Altintas, 2000.

2. EXPERIMENTAL PROCEDURE

The machining tests had been carried out through an experimental planning composed by a central point, in order to get a reliability of the results and to know the relation between the independent and the dependent variables. The mainly studied variables are:

Independent variables: cutting speed (v_c), feed rate (f_z), cutting depth (a_p)

Dependent variables (answers): Cutting forces, roughness, white layer, residual stresses

Twenty bodies test of steel AISI 4340, quenched and tempered had been machined, with average hardness of 52 HRC.

The machining assays had been carried out through two tools:

- Rough operation: diameter of 50 mm with four cutting edges with interchangeable inserts SPKN 12 03 ED R;
- Finishing operation: diameter of 63 mm with five cutting edges with interchangeable inserts, model R245-063Q22-12M, position angle of 45 degrees, rake angle of 16 degrees and carbide tools with covering GC 4020 HC (R245-12 T3M-PM).

For the finishing operation for each new body test the insert was changed, in order to discard the wear influence in the tests.

The experiments had been carried out by a conventional vertical milling, model FU-1 (ISO 40), presenting the following specifications techniques:

- Maximum speed: 6000 rpm;
- Maximum feed rate velocity: 1500 mm/min;
- Digital ruler in the three axles: X, Y and Z.

The white layer was identified through an optic microscope with magnifying of 500x, model Olympus BH2-UMA. The samples had been removed through one “cut off”, and etched with Nital 2%.

The analyses of residual stresses had been carried out through the incremental hole drilling (IHD) technique. This is a semi destructive method (the volume of removed material is not considered harmful to the performance of the component or can be repaired) based in the measure of the alleviated deformation, caused for the introduction of a small blind hole in the surface of the component.

The cutting forces had been measured by a dynamometer. Its construction were based on the work of Saglam et al., (2001) and are constituted basically of a table, instrumented with four load cells, distributed two the two, in two orthogonal directions. Each one of the load cells was instrumented with eight strain gauges, in order to measure deformations in the axial and transversal directions.

4. RESULTS

The results for all the tests are illustrated in Tab. 1.

Table 1 – Results for the cutting forces, roughness, white layer and residual stresses

	vc	fz	ap	Fresult	Rough	White layer	R stress surface		R stress $_{min}$	
test	(m/min)	(mm/rev)	(mm)	N	Ra	e (µm)	X (MPa)	Y (MPa)	X (MPa)	Y (MPa)
1	150	0,05	0,08	132,39	0,11	4,38	-45	-18	-330	-46
2	150	0,05	0,16	601,23	0,16	2,50	156	180	-461	-443
3	150	0,10	0,08	613,97	0,18	1,88	3	117	-35	3
4	150	0,10	0,16	420,03	0,23	0,63	-59	-63	-99	-128
5	210	0,05	0,08	331,68	0,11	1,25	117	210	-457	-415
6	210	0,05	0,16	874,25	0,09	1,25	122	13	-5	-32
7	210	0,10	0,08	462,90	0,16	1,25	63	165	-357	-316
8	210	0,10	0,16	608,43	0,21	1,88	96	60	-564	-371
9	130	0,08	0,12	538,27	0,14	1,25	-33	-20	-82	-111
10	230	0,08	0,12	769,06	0,16	1,25	60	11	-24	-43
11	180	0,03	0,12	493,43	0,09	1,25	234	67	-631	-387
12	180	0,12	0,12	283,45	0,13	1,25	-95	-111	-248	-202
13	180	0,08	0,05	257,59	0,21	1,25	139	116	-272	-298
14	180	0,08	0,19	694,22	0,15	1,88	48	132	-102	-65
15	180	0,08	0,12	417,42	0,28	1,25	5	-53	-128	-132
16	180	0,08	0,12	518,53	0,16	1,88	102	-56	-315	-423
17	180	0,08	0,12	533,30	0,08	1,25	-33	23	-191	-169
18	180	0,08	0,12	582,53	0,22	2,50	-76	-275	-188	-629
19	180	0,08	0,12	633,85	0,14	1,88	-170	-92	-183	-214
20	180	0,08	0,12	310,25	0,16	2,50	-95	39	-592	-419

4.1 Cutting forces

The data of the resultant cutting forces, measured in the tests, can be verified in Tab. 1.

It was observed that the resultant force was influenced for the cutting depth, for the cutting speed and for the interaction between the cutting depth and the feed rate, that they are the statistical more important variable, as Fig. 1.

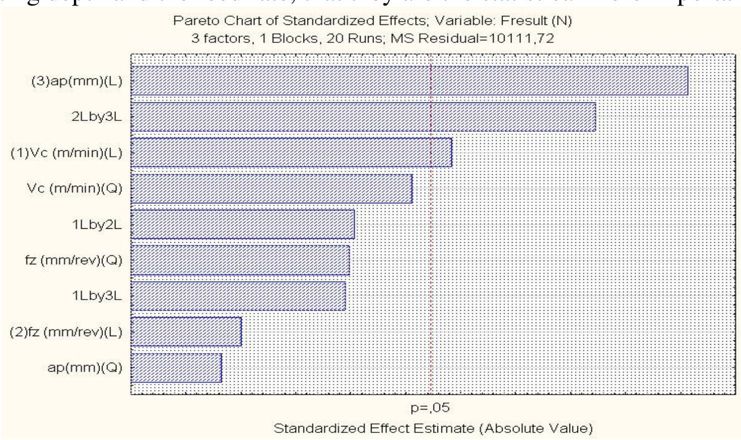
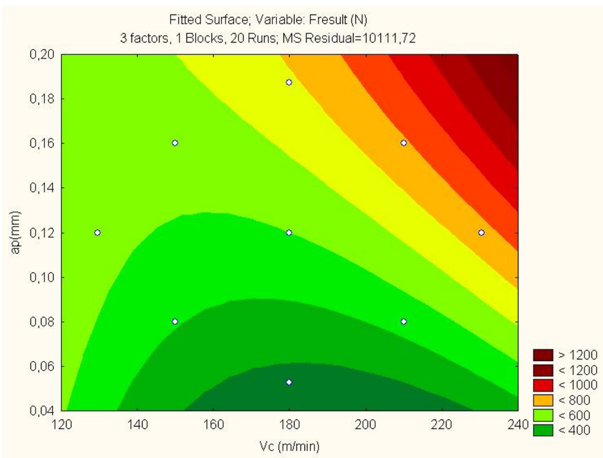


Figure 1 – Pareto chart for the resultant cutting force

The graphs of the Fig. 2 demonstrate the variation of resultant force as function of the independent variables.



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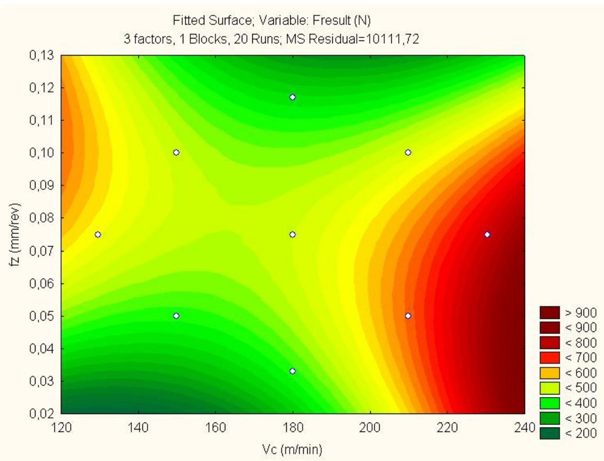

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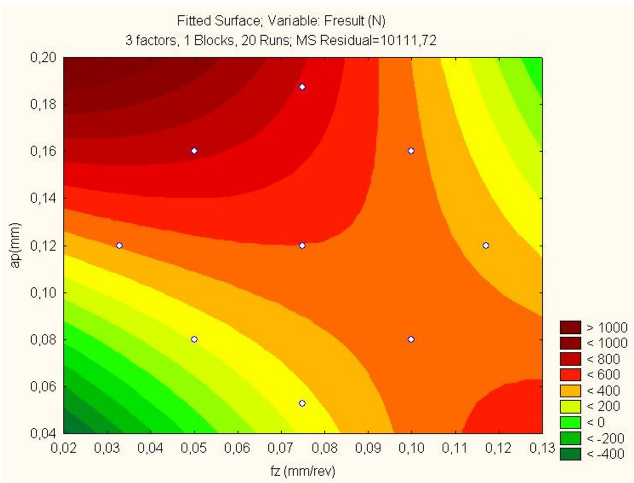


c)

Figure 2. Graphs: a) "v_c x a_p"; b) "v_c x f_z"; c) "f_z x a_p" for the resultant force

4.2 Roughness

The roughness of the test bodies had been measured in the perpendicular direction to the machining feed rate. In the Tab. 1, the average values of 3 measurements are showed.

Considering the reliability level of 95%, no one independent variable was representative for the roughness results in according with Fig. 3. On the other hand, the prominence of independent variable is observed for the "f_z". The behavior of this variable can be evaluated by Fig. 4.

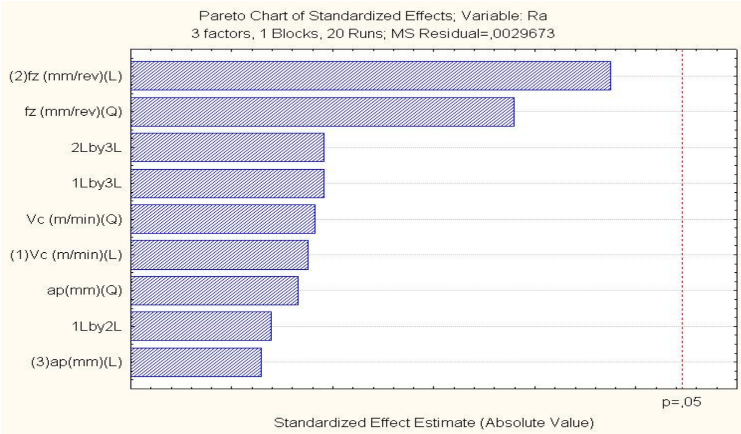


Figure 3 – Pareto chart for the roughness

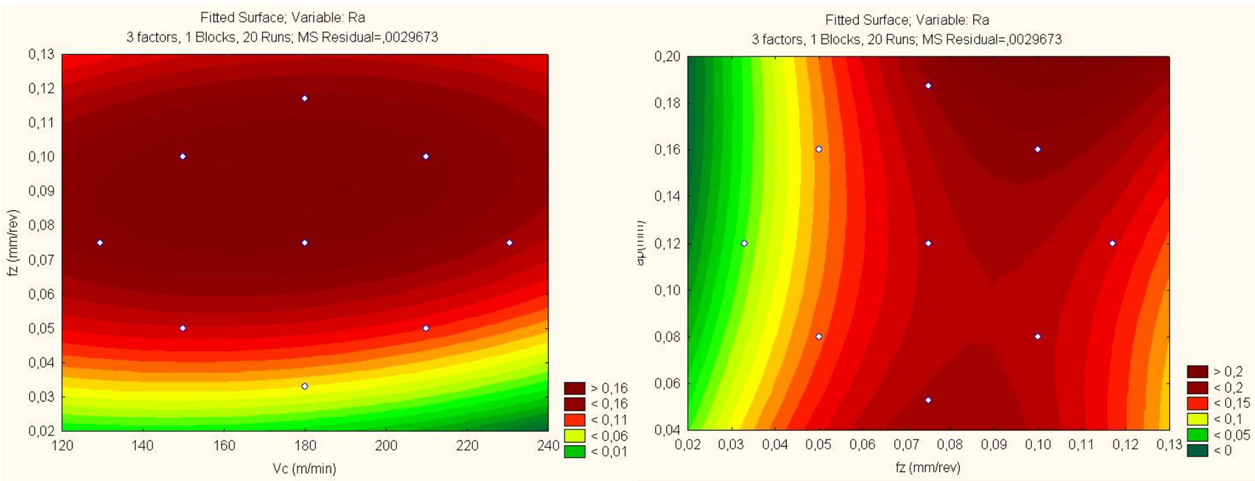


Figure 4. Graphs: "v_c x f_Z" e "f_Z x a_p" for roughness "Ra"

2.3 White layer

The measured thicknesses of the white layer had been organized in the Tab. 1 where a great uniformity in these layers can be observed, facilitating the measurements and analysis. The Figure 5 shows the micrograph of the sample of the body test 1 with magnifying of 500x, where a tempered martensitic structure can be observed soon below of the white layer, had the heat treatment.

Analyzing the photos of the test bodies, the presence of white layer can be noted in all of them. A justification for this is that the mechanism of plastic flow had produced a homogeneous and refined structure in the surface of the bodies and that, being the machined executed in the hardened material, the cutting temperature raised sufficient to provoke a re-temper of the surface. The steel SAE 4340, rich in carbon, also favors this mechanism (Bosheh et al., 2005).

Figure 5 – White layer in a specimen

It was observed that, the thickness of white layer was influenced by the interaction between the cutting speed and the feed rate, as Fig. 6.

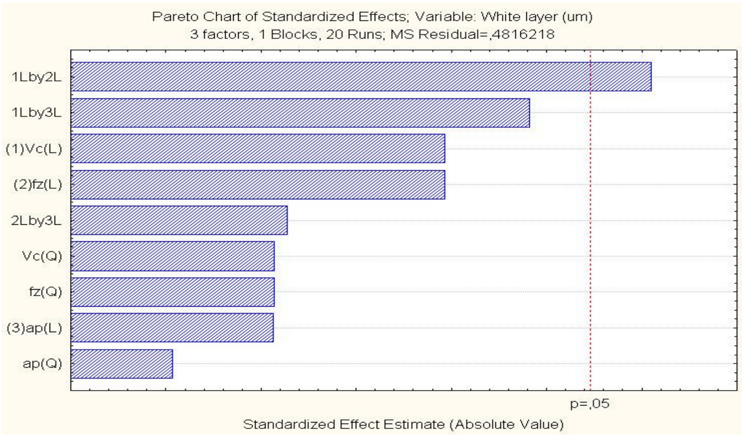
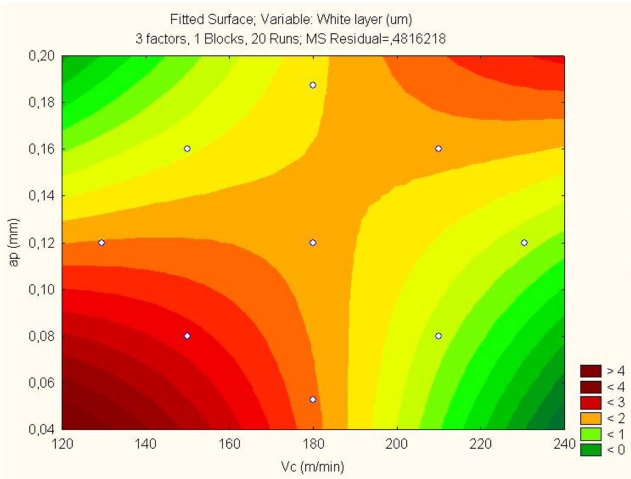
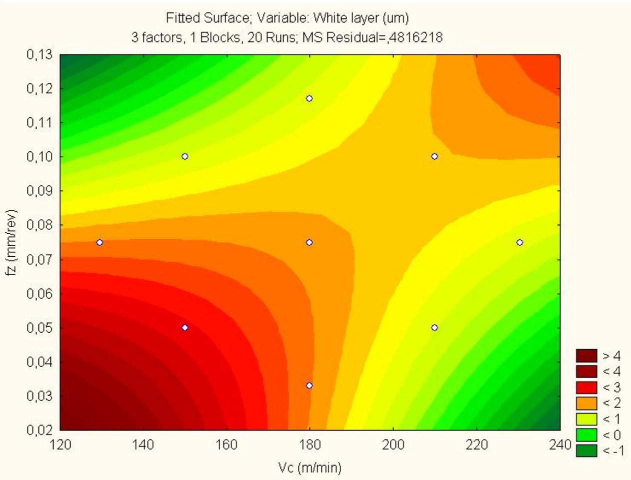


Figure 6. Pareto chart for the white layer thickness

The Fig. 7 demonstrates the variation of the of white layer thickness in function of the independent variable.



a)



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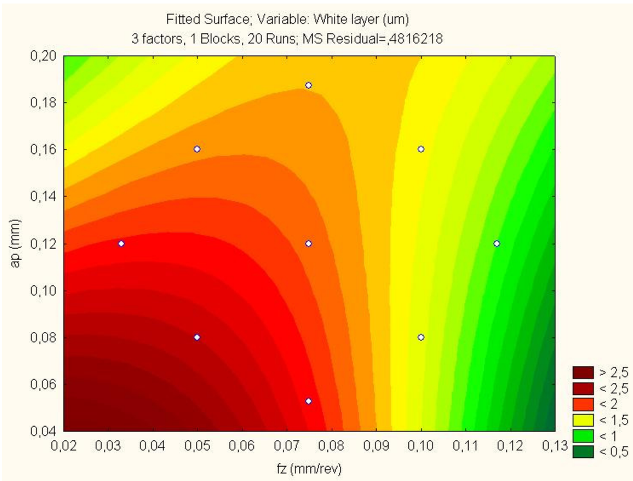


c)

Figure 7. Graphs: a) "Vc x a_p"; b) "Vc x f_z"; c) "f_z x a_p" for the white layer thickness

4.4 Residual stresses

The results for the residual stresses measurements are presented in terms of its respective profiles, from the surfaces of the parts. The Fig. 8 shows the typical behavior of the profile of the residual stresses measurements in the body of test 7. The Tab. 1 shows the values of the residual stresses in the surface and the peak of compression of the test bodies.

As it can be noticed in the graph of the test body 7 (Fig. 8) the residual stresses in the surface are positive (traction stress) and as the deep from the surface increases, it tends to invert, becoming negative (compression stress), until reaching its peak of ~0,1 mm of depth. To follow it grows returning for a traction tension, behavior observed in the bodies of test 2 - 3 - 5 - 6 - 7 - 8 - 10 - 11 - 13 - 14 - 15 - 16. The other bodies of test had shown the same behavior, even with compression residual stresses in the surface.

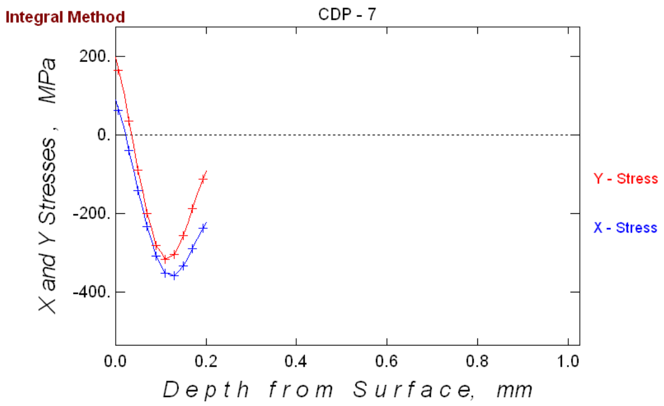


Figure 8. The typical behavior of the profile of the residual stresses measures in the body of test 7

As the curves of residual stresses in the direction of the feed rate (x), and in the perpendicular direction of feed rate (y), had presented similar behaviors, the statistics analysis was carried out for the residual stresses in “X” direction, that is, in the direction of the feed rate, as much for the traction residual stresses in the surface, as for the subsurface compression residual stresses (maximum residual stresses of compression).

The result of the surface residual stresses, in according to Fig. 9, showed that, the variable most representative was the feed rate.

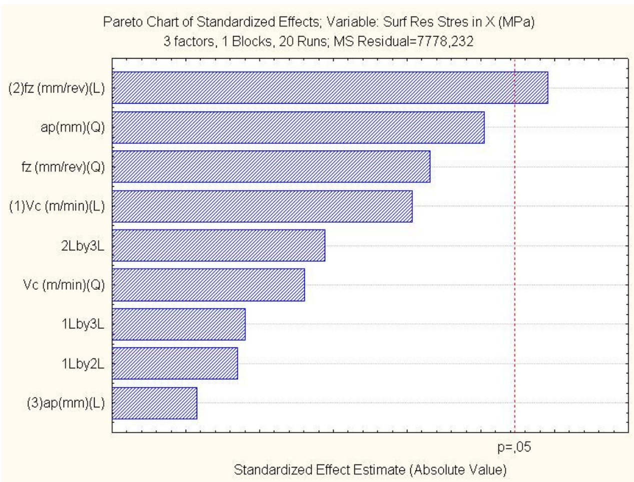


Figure 9. Pareto chart for the residual stresses on the surface

The graphs of Fig. 10 demonstrate to the variation of residual stresses in the surface in function of the independent variables.

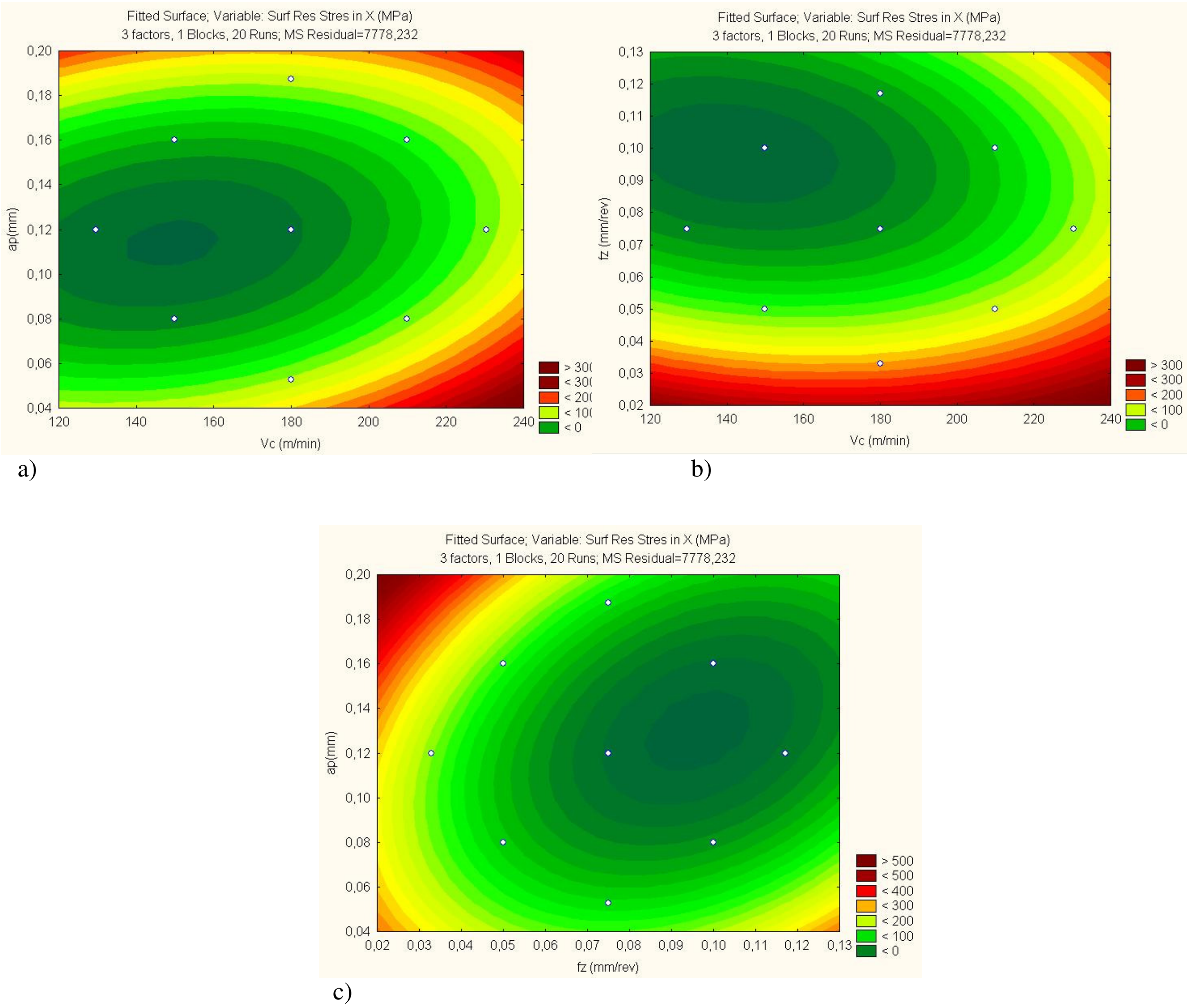


Figure 10. Graphs: a) "Vc x a_p"; b) "Vc x f_z"; c) "f_z x a_p" to surface residual stresses

In according to Fig. 11, it is observed that the maximum residual stress of compression (peak) was significantly influenced by the linear interaction of the feed rate and cutting speed.

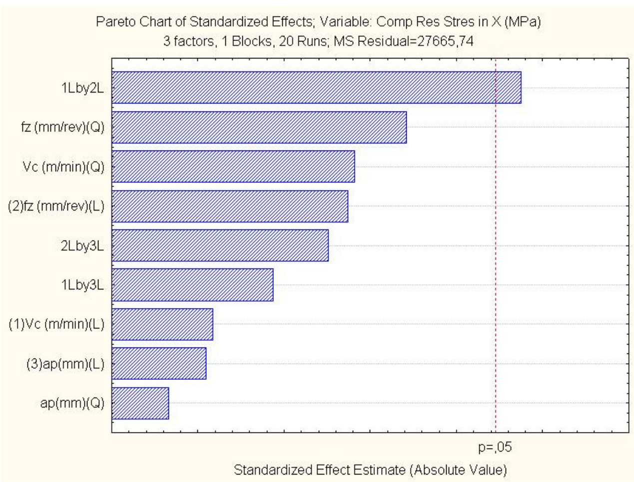
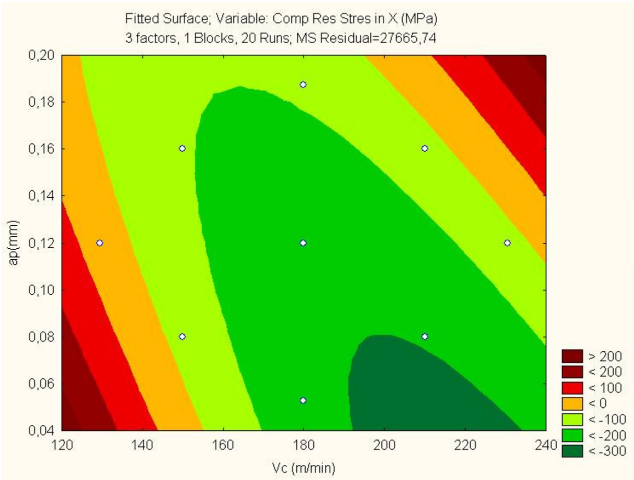
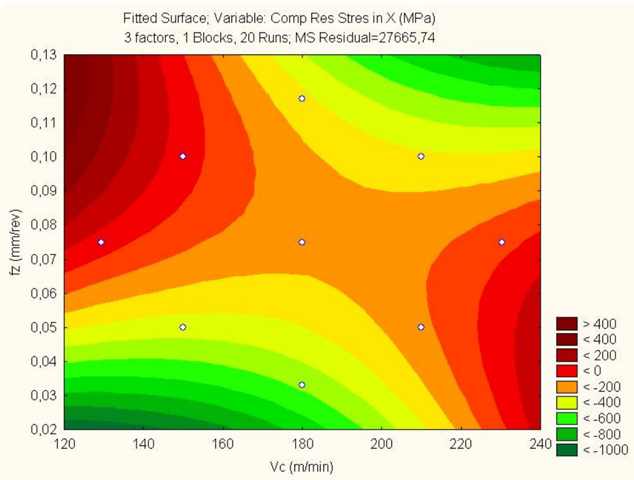


Figure 11. Pareto chart for the maximum residual stress of compression

The graphs of Fig. 12 demonstrate the variation of the maximum residual stresses of compression in function of the independent variables.



a)



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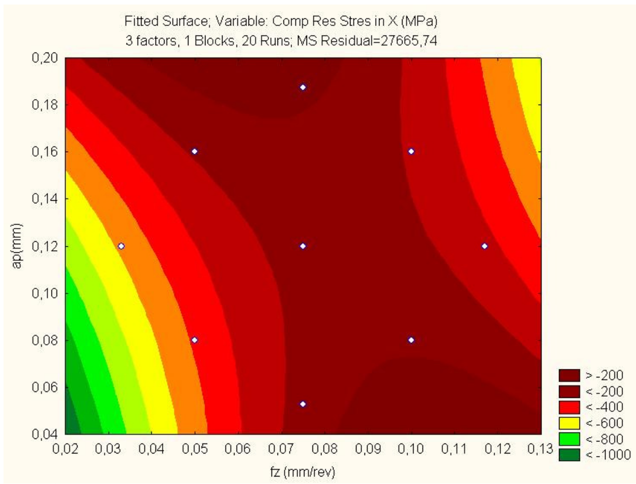

c)

Figure 12. Graphs: a) "Vc x a_p"; b) "Vc x f_z"; c) "f_z x a_p" for maximum residual stresses of compression

5. CONCLUSIONS

5.1 Cutting forces

- The resultant cutting force was significantly influenced by the passive cutting force depth;
- The cutting depth was the cutting parameter of bigger effect on the cutting forces;
- The cutting depth influenced the results of the cutting forces when it acted simultaneously with the cutting depth;
- The cutting speed influenced the cutting forces with lesser intensity that the other parameters;
- The cutting forces had grown with the increase of the cutting speed.

5.2 Roughness

- The measured values of the roughness had varied between 0,08 and 0,27µm;
- The gotten results, in terms of surface finishing, had been similar to the results of finishing operations, as grinding for example;
- The feed rate was the only parameter that had significant influence in the roughness;
- How much bigger it was the feed rate, worse was the surface in terms of the topography or roughness;

5.3 White layer

- All the test bodies had presented white layer in the surface;
- The cutting depth had small influence in the white layer thickness;
- The feed rate influenced the white layer thickness significantly when it acted simultaneously with the cutting speed.

5.4 Residual stresses

- The residual stresses had tended to be of traction in the surface of the bodies and of compression in the subsurface;
- In the subsurface, in depths about 0,1 mm, all the test bodies had presented peaks of residual stresses of compression, and after that the values returned to the traction stresses;
- Considering the measurement of the residual stresses in the direction of the feed rate, the traction maximum value in the surface was of 234 MPa and the maximum value of compression in the subsurface was -631 MPa.
- Surface residual stresses;
    - The feed rate was the parameter that most influenced the surface residual stresses;
    - The cutting speed and the cutting depth had little influence in the surface residual stresses.
- Maximum residual stresses of compression;
    - The cutting depth had little influence in the maximum residual stresses of compression.
    - The feed rate had expressive influences in the maximum residual stresses of compression when it acted simultaneously with the cutting speed.

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