VI CONGRESSO NACIONAL DE ENGENHARIA MECÂNICA
VI NATIONAL CONGRESS OF MECHANICAL ENGINEERING
18 a 21 de agosto de 2010 – Campina Grande – Paraíba - Brasil
August 18 – 21, 2010 – Campina Grande – Paraíba – Brazil

REDUCTION OF RESIDUAL STRESS IN MACHINED PARTS BY POSTERIOR COLD FORMING

Frederico Ozanan Neves[1] - fred@ufsj.edu.br
Durval Uchoas Braga[1] – durval@ufsj.edu.br
Marlon Mendes de Oliveira[1]
[1]Universidade Federal de São João del Rei – Praça Frei Orlando, 170 - CEP: 36.307-352 São João del-Rei – MG

Abstract: *Mechanical elements submitted to cyclical loads can fail by fatigue. If there is a residual stress of compressive nature in the critical region, the crack initiation and propagation can be reduced or eliminated. In this study a workpiece with a gear profile produced by a machining process was submitted to a forging operation. The punch had the empty profile of the gear tooth. Indentation test was carry out in three position along the profile – near the superior portion of the tooth profile, near the radius of the tooth root and near the base of the tooth. Indentation test was done at a region far from the profile before the workpiece to be deformed and was used as a standard sample. Numerical simulation was done to be compared to experimental results. The results statistically treated shows that the forging operation induced compressive residual stress in the tooth root, in the radius and base region. The forging operation did not change the stress nature near the head tooth. Numerical simulation results confirm the experimental tests. It can be concluded that a posterior cold forming improves the mechanical strength of the element.*
Keywords: *Residual Stress, Numerical Analysis, cold forming, indentation test*

1. INTRODUCTION

Residual stress are those that remains in the body when external loads are removed. Such stress can be result of heat treatments, mechanical loads, machining or other manufacturing processes. On machined parts residual stress are present in the worked surface and can be of tensile or compressive nature. Residual tensile stress should be avoided in parts submitted to mechanical cyclical loads because, by its nature, facilitate the crack nucleation and its propagation, lead them to fail by mechanical fatigue (Bianch et all, 2000). Otherwise, compressive residual stresses are beneficial to increase mechanical strength of the parts submitted to cyclical loads.

Residual stresses are inherent to machining process. By this, one approach is to reduce them using optimal operation parameters. To find such parameters is not easy, since the machining operation is under the influence of many variables: geometry tools, cutting speeds and feed rate, materials nature, lubrication and cooling, etc. The physical simulation is almost impossible in this case, requiring a large number of tests with high costs.

The presence of residual stress in elements machined is known and has been considered a long time. Liu and Barashi (1976) studied the presence of residual stresses in the surface machined and investigate the effect of the flank wear in the level of residual stress. The same effect has been investigated by Lin and Lee (1995). Both studies concluded that the bigger the flank wear greater was the level of residual stress in machined part. Jang et all (1996) studied the influence of feed rate and tool geometry on residual stress AISI 304 machined part. They concluded that residual stresses were of tensile nature. The residual stresses increased with increasing cutting speed and feed rate and decrease with increasing of cutting depth. More recently, Capello (2005) investigated the relationship between residual stresses and machining parameters, concluding that residual stresses may be tensile or compressive ones, depending on cutting conditions. They concluded that the residual stresses distribution remain the same, independently of machined material, suggesting that there is a common mechanism for their formation. In addition, they showed that the feed rate and tool tip radius influences more the residual stress magnitude than other parameters, especially cutting depth.

Fu and Wu (1995) presented a model to predicting stress induced in machined aluminum parts. According to the authors, residual stresses are tensile. In recent work, Salio et all (2006) presented a study on residual stress remaining in machined rings to gas turbines. They show how to select the cutting depth in order to minimize residual stress.

Cold forming also induce residual stresses in the worked parts. Cold forming parts presents important aspects in manufacturing, such as good quality surface, closed dimensional tolerances and, in addition, increases mechanical strength because of the microstructure and cold work hardening (Monezi, 2005). As in the case of residual stresses induced by machining processes, it can be tensile or compressive nature. Here too, it is convenient to minimize tensile residual stress in parts submitted to cyclical loads.

The presence of residual stress in cold forming parts is well known. Neves et all (2005) presented a study to induce internal residual stress of steel tubes in wire drawing with fixed plug. Residual stress in internal measures by x-ray diffraction were compared with those obtained by numerical simulation. Residual compressive stress were forced into internal tube wall so it is possible to use it as a part submitted to cyclical stress. Similarly, the residual stress was used as a method to increase fatigue resistance in a study made by Matos et all (2004).

The method most used to measure residual stress is the x-ray diffraction. The method is quite described by Prevéy (1986). However, it is difficult to be employed in flat pieces, as well as require sophisticated equipments and specialized techniques. Recently a new technique is being employed. It evaluates the residual stress through an indentation test. It is hoped that a cold worked material submitted to a indentation test, presents a different result from that the same material not worked. If the nature of residual stresses are tensile, the test shall presents a surface hardness than a material not worked. Otherwise, if it is a compressive ones, the penetration is more difficult and the result of the test will be of higher values (Bocciarelli and Mayer, 2006). Then, a map of the level and distribution of residual stress can easily be obtained without the need for sophisticated and low cost.

This works investigate the possibility to introduce compressive residual stress in a tooth profile machined in a workpiece of a commercial aluminum by means of a posterior cold forging operation. The geometry of the machined workpiece studied is similar to a gear tooth. This geometry was choice because this kind of mechanical element is submitted to cyclical loads and fail by fatigue process. The region most critical is the tooth root. After the workpiece be machined, a tool with the same geometry of the tooth was forced over that surface, in a forging operation. Residual stress was them evaluated over entire region deformed. If compressive residual stress is present it can be supposed that an increasing in mechanical strength will prevent a fail by fatigue.

2. METHODOLOGY

2.1 Equipament

a) a tensile testing machine, EMIC 100kN;
b) a mechanical press- 40 t;
c) Indentation test machine - Vickers - Mitotoyo MVK – G1.

2.2 Workpieces

Workpieces were blocks of commercial Aluminum alloy. A empty profile of a gear tooth was machined in it. The profile was obtained using a normal module 2 (m = 2). 2. Fig. 1 presents a workpiece image and its dimensions.

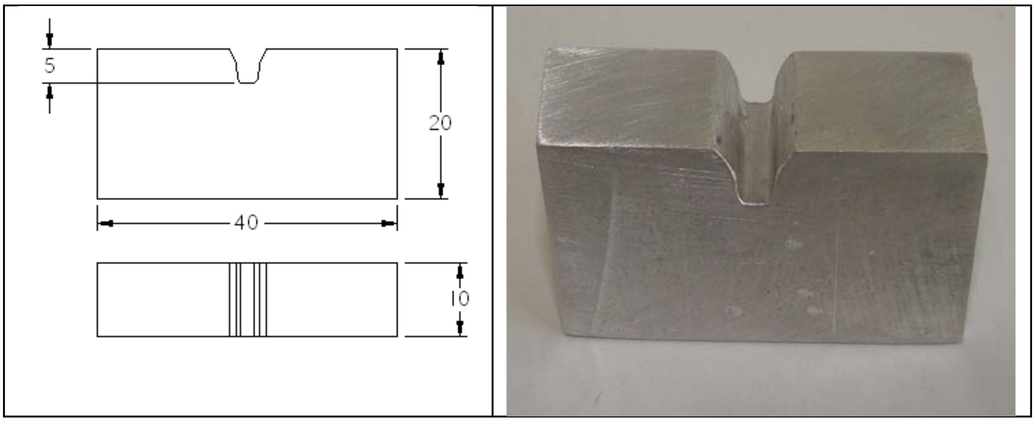

Figure 1 – Workpiece used in the experiment

2.3 Experimental Procedures

Four workpieces were machined from a single block in dimensions 10x50 mm. Then they were submitted to cold a cold forging operation. The punch, shows in Fig. 2, was made of AISI 1045 steel quenched and tempered to 27 HC.

Figure 2 - Forging operation

Indentation Vickers test was made mapping the lateral surface of the tooth profile to determine the magnitude and distribution of residual stress after cold forming. The test were made in three position (P1, P2, P3) as shown in Fig. 3, in the two symmetrical sides of the tooth profile and in the both lateral faces of the workpiece. P2 is a point in the base of the tooth, P3 is a point in the region of the tooth root and P1 is a point at the region near the head of the tooth. P0 is measures take at a point very far from P1, P2 and P3 before cold forming.

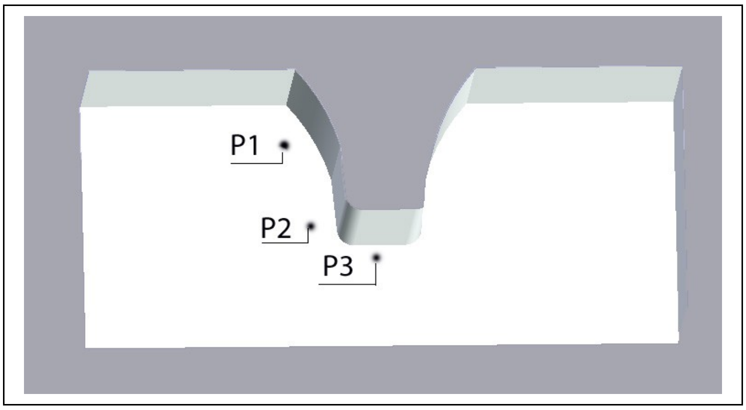

Figure 3 – Positions of indentation tests

2.4 Numerical Simulation

The numerical simulations were made using MARC software, a PATRAN platform. It was used 1500 iso-parametric elements of four nodes. The punch was simulated as rigid body. The material mechanical behavior was simulated as part-pieced linear according to the Holloman Equation $\sigma = 560\varepsilon^{0,6}$ MPa, obtained from tensile test. Poisson´s ratio was 0,33 and elastic modulus was 69 GPa. In the simulation, a descendent movement of 0,05 mm was imposed to punch since the instant it touch the material of the workpiece. At the end of the movement, the punch was retrieved.

2.5 Design of the Experiment

Results are statically treated using an Analysis of Variance – one way layout. The significance level α= 0,05 was used. From each position it was randomly chosen eight measures that are listed in Table 1.

3. Results and Discussion

Table 1. Vickers Hardness

Position	measures							
P3	171	170	171	170	168	168	171	171
P2	167	170	168	165	167	167	171	169
P1	158	162	161	159	157	158	158	156
P0	160	159	160	159	156	163	157	160

Figure (4) shows the media of the results to each position. It can be seen that the hardness at position P3 is higher than the hardness at position P0. It indicates that there is a compressive residual stress in that region which difficult a indentation. The same occurs to position P2. However, in position P1 the harness is lesser than in position P0, indicating that there is tensile residual stress in the region.

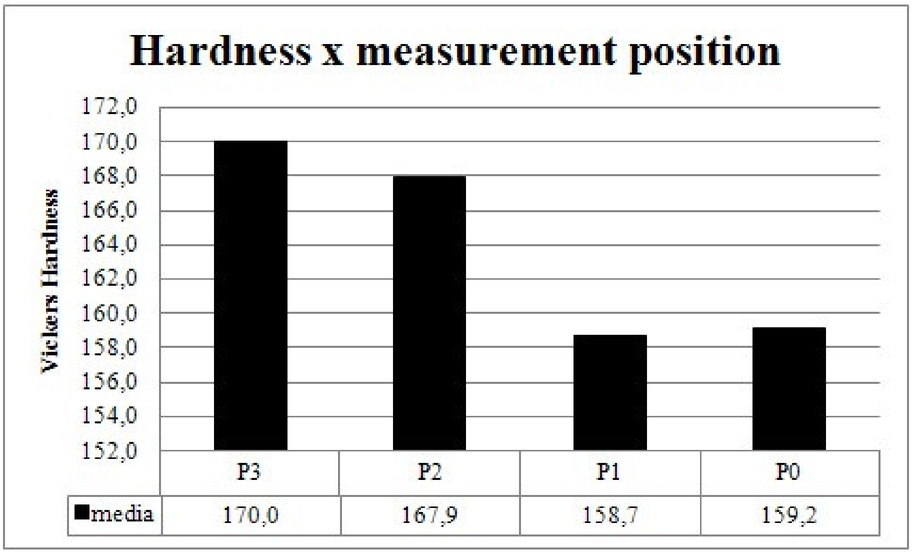

Figure 4 – Hardness measured at the positions P0 to P3.

Analysis of Variance is resumed in the Tab (2). From that the null hypothesis is rejected. Null hypothesis is H_0: $\sigma^2 = 0$, that is, means are equal. So, the treatment means differ, that is, the position of measurement affects the hardness and cold forming affects the residual stress. A contrast tests shows that there is a significance difference between positions, except between P0 and P1. Then, the hardness in this position P1 is the same that the material before cold forming. As the position P2 and P3 corresponds to the tooth root, it can be concluded that cold forming introduces a compressive residual stress in that regions.

Table 2 – Analysis of Variance

		DF	MS	F	F tab
SST	920,21	31	29,68		
SSA	826,18	3	275,39	82,00	2,95
SSerr	94,04	28	3,36		

DF = degrees of freedom
MS = Mean Square
F = calculated statistic of Fisher distribution
Ftab = F distribution
SST = Total sum of square
SSA = sum of square due to treatment
SSerr = sum of square due to error

Table 3 – Contrast between positions

Contrast	SSC/SSerr	F	Ftab
P0-P1	0,88	0,26	7,64
P0-P2	306,71	91,3	
P0-P3	472,41	140,7	
P1-P2	340,45	101,4	
P1-P3	514,07	153,1	
P2-P3	17,82	5,31	

Figure (5) show the result of the numerical simulation. In the figure, there is a region in the tooth root where the residual stress is more compressive (blue region), corresponding to position 2. In the base of the profile, corresponding to position P3, residual stress is still compressive. In the region corresponding to position P1, near the head of the tooth, there is a tensile residual stress.

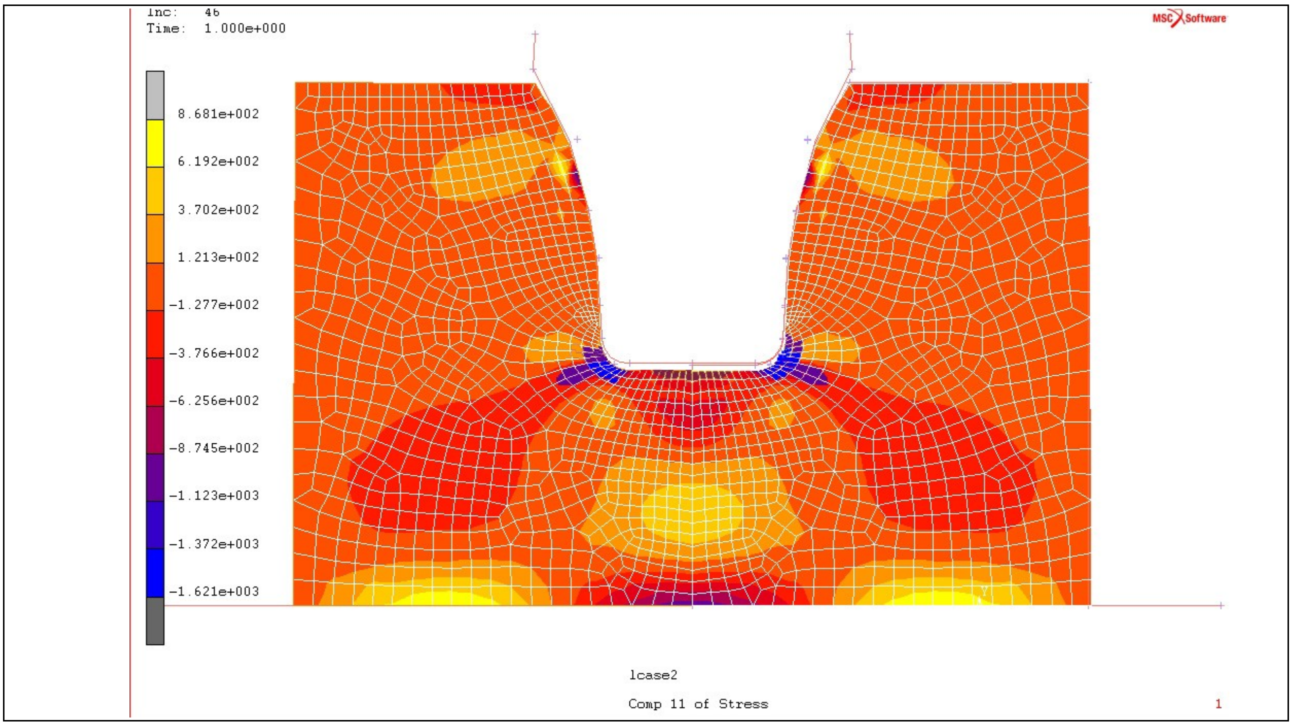

Figure 5 – Result of numerical simulation of the cold forging operation

4. CONCLUSIONS

- A cold forging operation executed in a tooth gear profile by a punch with the same profile induces residual stress over all regions on deformed.
- There is two regions with different nature of residual stress. One, near the tooth head where tensile residual stress is present and another, corresponding to tooth root, where there is a compressive residual stress.
- A numerical simulation confirms the existence of this regions with different residual stress
- Since compressive residual stress in the tooth roots result in an increasing of mechanical strength to parts submitted to cyclical loads, a posterior cold forming is a technique that can provide this improvement.

5. ACKNOWLEDGMENTS

Authors want to thanks FAPEMIG by financial support to the work.

6. REFERENCES

Bianch, E. C. et all. Análise do Comportamento da Microestrutura de Materiais Endurecidos Retificados com Rebolos de CBN. Materials Research, v. 3 n. 4, p. 147-154, 2000.

Bocciarelli, M.; Maier, G. Indentation and imprint mapping method for indentification of residual stress, Computational Materials Science (2006), doi:10.1016/j.commatsci. 2006.07.001

Fang, N. Slip-line modeling of machining with a rounded-edge tool—Part I: new model and theory. J. of Mechanics and Physics of Solids. v. 51, p. 715 – 742, 2003.

Fu, K. H. E Wu, C. F. A residual-stress model for the milling of aluminum alloy (2014-T6). J. Mat. Proc. Tech. V.51, p. 87 – 95, 1995

Jang, D. Y. et all. Surface residual stresses in machined austenitic stainless steel. Wear, V. 154, p. 178 – 173, 1996.

Lin, Z., Lee, B. An investigation of the residual stress of a machined workpiece considering tool flank wear. J. Mat. Proc. Tech., v. 151, p. 1 – 24, 1995.

Liu, C. R, Barashi., M M. Variables governing patterns of mechanical residual stress in a machined surface. ASME, J. of Eng. For Industry, v. 104, p. 257-264, 1982.

Mattos, P. F. P. et all. Residual stress e.ect on fatigue striation spacing in a cold-worked rivet hole. Theoretical and Applied Fracture Mechanics. v. 42, p.139–148, 2004

Monezi, C. Temas de Produção e Controle ll, seminários 1º semestre de 2005. São Paulo: Mackenzie. Disponível em http://meusite.mackenzie.com.br/carlosmonezi/ seminarios/ 1o_semestre/1_2005/forjamento.pdf. Acesso em: 31 de maio 2006.

Neves, F. O. ; Button, S. T. . Residual Stress on Stainless Steel A304 tube drawn with fixed plug. In: 18th International Congress of Mechanical Engineering, 2005, Ouro Preto. Anais do 18th International Congress of Mechanical Engineering. Rio de Janeiro : Ass. Brasileira de Engenharia Mecânica, 2005. v. CDROM.

Outeiro, J. C, Umbrello, D., Saoubi, R. M. Experimental and numerical modelling of the residual stresses induced in orthogonal cutting of AISI 316L steel. Int. J. Of Machining Tools & Manufacture. v. 46, p-1786-1794, 2006

Prevéy, P. S. X-ray diffraction residual stress techniques. In: Metals Handbook, ASM V. 10, P. 380 – 392, 1986.

Salio, M. et all. Prediction of residual stress distribution after turning in turbine disks. International Journal of Mechanical Sciences, v. 48, p. 976–984, 2006.

Ulutan, D. et al., Analytical modelling of residual stresses in machining, J. Mater. Process. Tech. (2006), doi:10.1016/j.jmatprotec.2006.09.032