NUMERICAL AND EXPERIMENTAL ANALYSIS OF CROSS WEDGE ROLLING OF STEEL HOLLOWED SHAFTS

Marcelo Iamarino Fernandes Russo, mifr_10@uol.com.br
Mário Luiz Nunes da Silva, nunesmar@fem.unicamp.br
Sérgio Tonini Button, sergio1@fem.unicamp.br
State University of Campinas – DEMa-FEM -UNICAMP, CP 6122, 13083-970 – Campinas - SP

Abstract. *Manufacturing of hollowed shafts by cross wedge rolling (CWR) when compared to other processes presents many advantages associated to reduced processing time and material scrap. The objective of this work was to study this process and define the best conditions to form shafts with the best mechanical properties with a minimum weight. CWR tests were carried out with AISI 1045 steel hollowed samples. The internal diameter varied from 5 to 9 mm, corresponding to weight reductions up to 41%. These samples were heated at three temperatures for15 minutes. The rolling speed was fixed at 12 m/min. The products rolled were still-air cooled, and then analyzed to evaluate the presence of surface defects. Samples of these products were cut off, polished and etched to analyze microstructures and hardness. Other specimens were machined from these products and tensile tests were carried to evaluate the yield stress and the ultimate stress. The influence of different processing conditions was also analyzed with a commercial software to evaluate the stress and strain distributions, and the final shape of the internal hole after rolling. The experimental results showed that rolling temperature was not significant on the products properties and microstructure. The numerical results showed that distortions in the hole after rolling can be reasonably predicted.*

Keywords*: metal forming, steel, mechanical properties, numerical simulation*

1. INTRODUCTION

Tubular components like hollowed shafts have been designed to substitute bulk components because of the overall reduction of mechanical systems weight. The proper choice of diameters ratio (outer versus bore diameter) define the best condition of weight reduction without a significant loss in mechanical strength.

Manufacturing of hollowed shafts and tubular parts is one of the most difficult metal forming processes. Cross Wedge Rolling (CWR) is one of the alternative methods to manufacture these components, because it presents many advantages related to reduced processing time and material scrap, although rolled products show some defects like wall thickness variation and bore ovalization. These defects are caused by the incorrect choice of process parameters like tools angles, and the length of the calibration zone (Bartnicki and Pater, 2005-a).

Bartnicki and Pater (2004) stated that the calibration zone has to be reduced to avoid bore ovalization . Simulation of the CWR process with the finite element method showed the modification of the bore geometry during the process and confirms the influence of the calibration zone on the bore geometry.

Two solutions to avoid this defect were presented by Neugebauer et al. (2002) with mandrels positioned in the shaft bore. In the first solution a stationary mandrel is free to move with the shaft during rolling, while in the second solution the axial movement of two mandrels is controlled to follow a pre-defined path.

However Bartnicki and Pater (2005-b) concluded that bore ovalization does not depend on the use of mandrels that influence mostly the homogeneity of the tube wall thickness, an important feature when high precision tubes are to be manufactured.

The main objective of this work is to define the best conditions for the manufacturing of steel hollowed shafts with the CWR process.

2. MATERIALS AND METHODS

2.1. Experimental Procedure

CWR tests to manufacture hollowed shafts were carried out in a laboratory equipment described by Gentile (2004).

Billets were separated from a SAE 1045 steel hot rolled bar to form workpieces 80 mm long and 25 mm in diameter which were drilled with four different bore diameters: 5, 7, 8 and 9 mm corresponding to weight reductions between 13 and 41%, and an increase in the maximum shear stress between 2 and 17%, calculated for torsion tests as defined by Garcia et al. (2000).

Then these workpieces were heated to 1000 or 1100 ^{o}C for 15 minutes before rolling. The rolling speed was fixed in 12 m/min, the maximum speed possible with the laboratory equipment. After rolling, workpieces were air cooled.

The CWR tools used in the tests were the same described by Gentile (2004) and present the characteristics shown in Table 1.

Table 1. CWR tooling dimensions

Initial billet diameter: 25 mm
Final product minor diameter: 14 mm
Diameter reduction δ = 1.79
Edge angle $\beta = 7^o$
Rolling angle α = 20^o
Total length L = 462 mm
Calibration zone length L3 = 95 mm

Table 2 shows the process conditions of the twenty three tests carried out in this work. Tests 7, 11 e 19 were defined to compare the results from tests with bulk (without bore) and hollowed workpieces.

Table 2 – Tests conditions

Test Number	Bore diameter (mm)	Heating Temperature (ºC)	Surface oxidation before test	Test Number	Bore diameter (mm)	Heating Temperature (ºC)	Surface oxidation before test
1	5	1100	No	**13**	8	1100	Yes
2	5	1100	No	**14**	9	1100	Yes
3	7	1100	No	**15**	9	1100	Yes
4	7	1100	No	**16**	9	1100	Yes
5	7	1100	No	**17**	8	1000	Yes
6	8	1100	No	**18**	9	1000	Yes
7	bulk billet	1100	Yes	**19**	bulk billet	1000	Yes
8	5	1100	Yes	**20**	5	1000	Yes
9	5	1100	Yes	**21**	7	1000	Yes
10	7	1100	Yes	**22**	8	900	Yes
11	bulk billet	1100	Yes	**23**	9	900	Yes
12	8	1100	Yes				

Rolled products were analyzed by visual inspection, and then samples were cut off as shown in Fig. 1 to analyze the microstructure and hardness of each section, as well to measure the minor bore diameter after rolling. Other samples were analyzed with tensile tests to evaluate their mechanical properties.

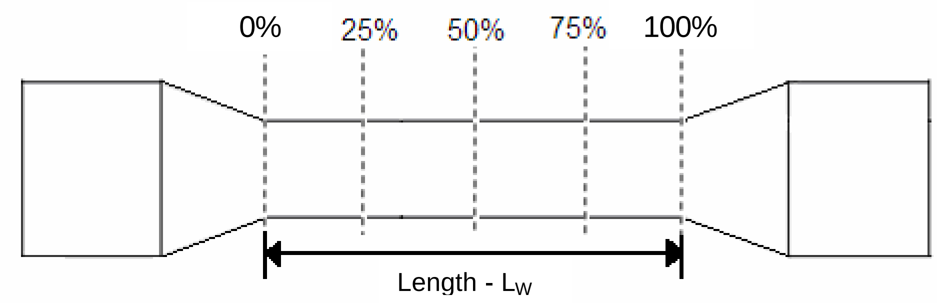


Figure 1 – Location of the cross sections separated to microstructure and hardness analysis

2.2. Numerical Analysis

The CWR process was also analyzed by the finite element method with the commercial software MSC.Superform 2005. All the process conditions shown in Table 1 and described in section 2.1 were simulated with a bore diameter of 9 mm. Six thousand quadratic elements were applied to the workpiece 3D model, with the relax and remesh procedures defined during the simulation.

Figure 2 shows the discretization elements of the tooling and workpiece models used in the simulation.

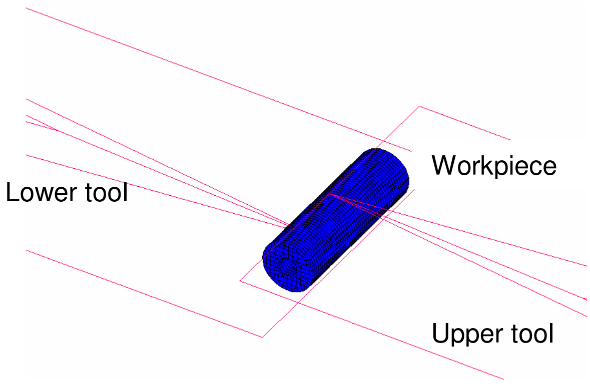
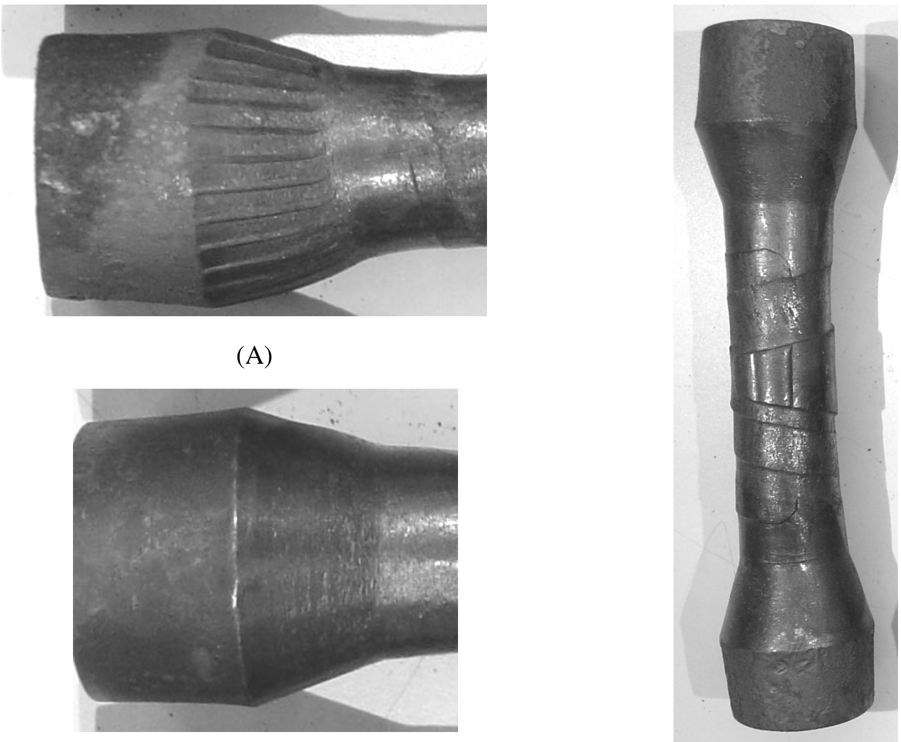


Figure 2. Finite element models of the workpiece and CWR tooling at the simulation beginning

3. RESULTS AND DISCUSSION

3.1. Experimental Results
3.1.1. Visual inspection

First CWR tests (1 to 6) were carried out at the temperature of 1100 ^{o}C and showed a strong sliding in the work and calibration zones making the process unstable and causing defects in the products like surface marks and bending, as shown in Fig. 3A and B. A simple solution was found when tests began to be carried out some seconds after the billet was taken off the furnace; an oxide layer was then formed on the billet surface, the process had run without problems and products did not present the defects found before (Figure 3C). Table 1 also shows a column to define the presence of surface oxidation.



(A)

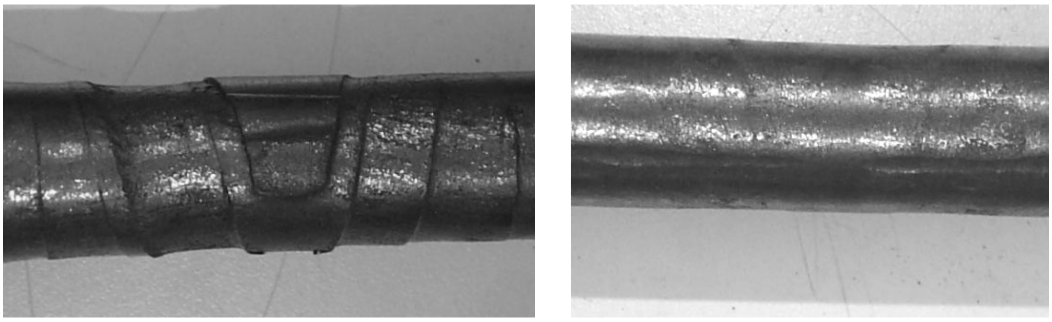
(B)

(C)

Figure 3 – Aspect of the tapered region of workpieces: (A) grooves defect (B) bending, and (C) without defects

The visual inspection of the rolled products showed that bulk and hollowed workpieces present almost the same surface aspect. Some of the products from billets with 8 and 9 mm in bore diameter were bent representing instability of the process when the workpiece bore diameter was increased.

All the hollowed products presented central marks which were more pronounced for the larger bore diameters (Fig. 4A), and were not observed for the bulk billets as seen in Fig. 4-B, maybe because of their greater stiffness.



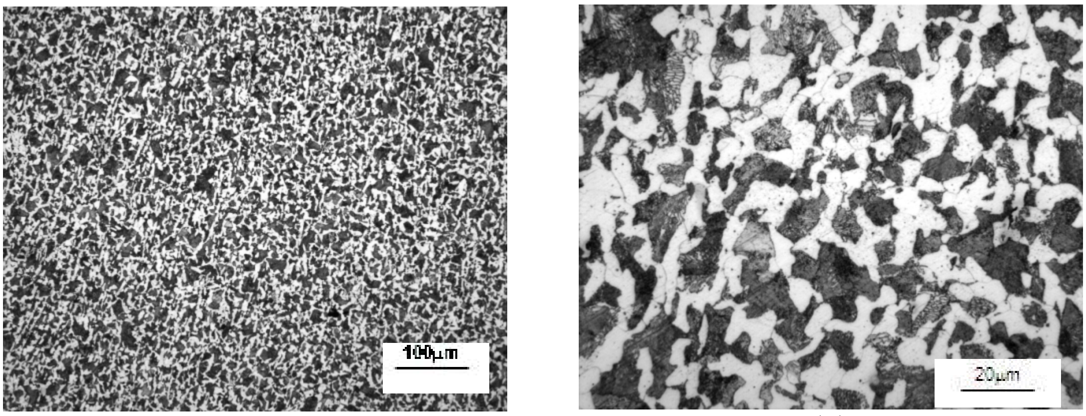
(A) (B)

Figure 4 – Aspect of the central region of the rolled products: (A) central marks (B) without defects

3.1.2. Microstructural analysis

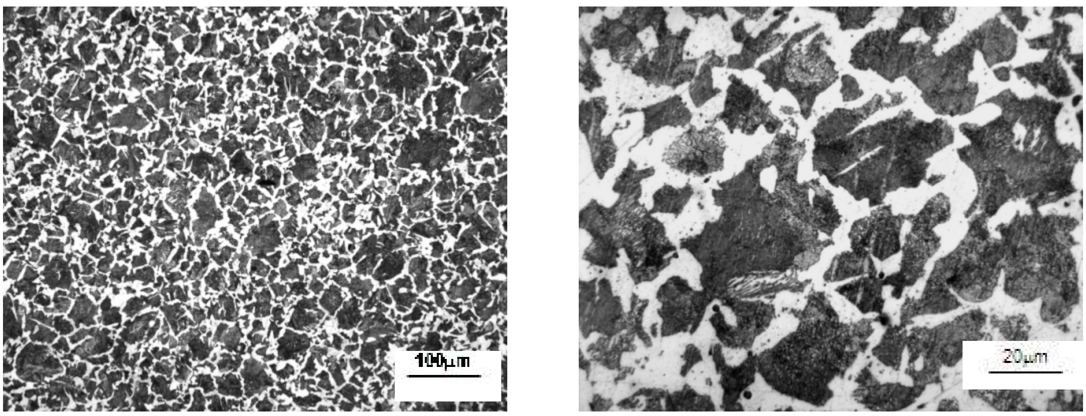
Six rolled products were selected for the microstructural analysis and cut off to analyze the section defined as 50% in Fig. 1. The samples were grounded, polished and etched with Nital 2% to observe the grain structure and the phases present in the material, with a optical microscope and magnifications of 200X and 1000X.

Figures 5A and B show the microstructures of the central region of the sample from the test 13. The as-received material was also prepared with the same procedure to compare its microstructure (Fig. 6) to those of the rolled products.



(A) (B)

Figure 5. Microstructure of the central cross section of sample #13: (A) 200X , (B) 1000 X – Nital 2%



(A) (B)

Figure 6. Microstructure of the cross section – as-received material: (A) 200X , (B) 1000 X – Nital 2%

It was observed that the microstructure of all rolled samples is very similar and well represented by the pictures shown in Fig. 5, with small equiaxed grains and the phases ferrite and pearlite in the proportion expected for the SAE 1045 steel. Compared to the microstructure of the as-received material (Fig. 6), it was noticed that rolled products show grains more refined caused by the hot working present in the CWR process.

3.1.3. Tensile tests

Tensile tests with rolled samples (tests 6, 7, 8, 12, 19, 20, 22) were carried in a universal testing machine model Mohr & Federhaff with capacity of 400 kN. Table 3 shows the results obtained in these tests. Diameters were measured at the position 50% shown in Fig. 1.

The results obtained with the hollowed samples were very similar to those obtained with samples rolled from the bulk billets. Compared to the condition as hot rolled: yield stress 310 MPa, ultimate stress 565 MPa and elongation 16% (Materials Property Data, 2007), CWR products always presented better mechanical properties, directly corresponding to the refined grain structure observed in the microstructural analysis.

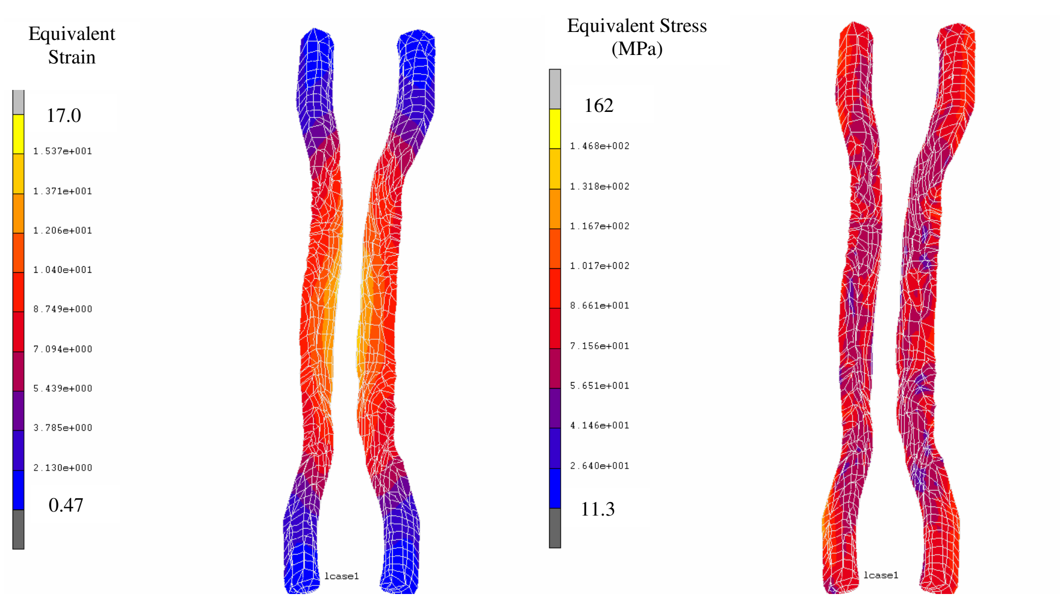
Table 3 – Results of the tensile tests

Sample number	Outer diameter after CWR (mm)	Bore diameter after CWR (mm)	Yield Stress (MPa)	Ultimate Stress (MPa)	Elongation (%)
6	15.7	2.5	374	575	18.2
7	16.7	bulk	463	625	18.8
8	17.4	4	415	627	18.5
12	17.4	5	382	612	18.3
19	16.7	bulk	393	599	18.9
20	17.5	4	383	610	17.1
22	17.6	5	372	614	18.3

3.2 Numerical analysis

In the first numerical tests the diameter reduction $\delta = 1.79$ was simulated and all tests failed because the workpiece always slid at the beginning of the process. This problem is similar to that found in the first experimental tests #1 to 6. Because it is not possible in the numerical analysis to generate the surface oxidation, the ratio δ was reduced to 1.54 when the process had run without any problem.

Figure 7 shows the numerical results for the equivalent plastic strain (A) and for the equivalent von Mises stress (B) obtained with the FEM simulation for the longitudinal section of the rolled product.



(A) (B)

Figure 7. FEM results for the total equivalent plastic strain (A) and von Mises equivalent of stress [MPa] (B) calculated at the longitudinal section of the rolled product.

It can be observed in Fig. 7A that the most deformed region is found near the billet surface, followed by the inner surface. The regions of the billet ends do not present any deformation since the tools are positioned to keep the initial diameter of the billet during the process.

The aspect of the bore with different diameters along is length is confirmed by the result tests showed in Table 3, and this aspect is one of the problems caused by the process, as observed in the introduction.

Figure 7B shows that CWR causes an irregular stress distribution in the product that represents the complex stress state that mixes compression, torsion and tensile stresses caused by the rotational movement associated to the elongation of the workpiece.

In both figures it can be observed a slight bending of the workpiece that was also confirmed in the experimental results (Fig. 3B).

4. CONCLUSIONS

Results obtained with the CWR tests showed that this process is capable for the manufacturing of hollowed shafts with good overall quality. It was also found that the rolling speed must be the maximum available for the equipment and that the process success is achieved when the billet is air cooled for few seconds before being rolled to form an oxide layer on the billet surface.

To avoid workpiece distortion during rolling the ratio outer diameter/inner diameter must be kept above 2.0, since process instability was observed for inner diameters greater than 8 mm (diameter ratio near 1.75).

Results of the tensile tests showed that the mechanical properties of the hollowed shafts are very similar to those of bulk shafts, and are better than the properties in the condition as hot-rolled.

Numerical results showed that distortions of the bore after rolling can be reasonably predicted, as well as the probability of sliding in process with high diameter ratio (δ).

It was also observed that the great difficult in CWR of hollowed shafts is to control the bore size and shape to keep it circular. The central marks observed in these shafts are not relevant since they are commonly removed when machining these shafts to their final dimensions and geometry.

5. ACKNOWLEDGEMENTS

Authors are thankful to FAPESP – Fundação de Amparo à Pesquisa do Estado de São Paulo (Proc. 04/0744-6 & 05/00085-0) for its finantial support to this work.

6. REFERENCES

BARTNICKI, J. PATER, Z. The aspects of stability in cross-wedge rolling processes of hollowed shafts. Journal of Materials Processing Technology, v. 155-156, p.1867-1873, 2004.

BARTNICKI, J. PATER, Z. Removing of Ovalization Phenomenon in CWR Process of Hollowed Shafts, Anais do Advanced Materials and Manufacturing Processes Conference, Phys. Techn. Inst. Nat. Academy of Sciences of Belarus, p. 264-267, 2005-a.

BARTNICKI, J. PATER, Z. Problematic of Internal Mandrel Application in CWR of Hollowed Shafts, Anais do Advanced Materials and Manufacturing Processes Conference, Phys. Techn. Inst. Nat. Academy of Sciences of Belarus, p. 268-271 2005-b.

GARCIA, A., SPIM, J., DOS SANTOS, C. Ensaios dos materiais. Rio de Janeiro: LTC, 2000. p. 92-94.

GENTILE, F. Estudo do Processo de Laminação Transversal com Cunha (Cross Wedge Rolling) para Fabricação de Eixos Escalonados. 2004. 190f. Tese (Doutorado em Materiais e Processos de Fabricação) – Faculdade de Engenharia Mecânica, Universidade Estadual de Campinas, Campinas.

MATERIAL PROPERTY DATA, 05 May 2007 <http://www.matweb.com>

NEUGEBAUER, R. et al. Optimization of processing routes for cross rolling and spin extrusion. Journal of Materials Processing Technology, v.125-126, p. 856-862, 2002.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.