# NUMERICAL AND EXPERIMENTAL ANALYSIS OF INTERNAL DEFECTS FORMATION DURING CROSS WEDGE ROLLING

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**Abstract.** *Cross-wedge rolling (CWR) is a metal forming process in which wedge shaped tools are assembled to rollers, and concave or convex plates, to manufacture axisymmetrical parts such as stepped shafts and pins to the automotive industry. Despite the advantages of this process associated with high productivity and reduction of raw materials, the formation of an internal defect, called Mannesmann, requires a careful inspection of the rolled parts. This defect has its origin in the center of the rolled parts and its causes are not yet fully identified. Based on the finite element method, numerical simulations of the CWR process in three dimensions were studied using simulation softwares, in order to analyze the influence of some geometric and process variables on the formation of this which is considered the main defect of the process. Tests were also performed in an experimental equipment available in the Mechanical Forming Laboratory covering the same variables cited for the simulation. The data from these tests were confronted with simulation results to determine the possible causes of the defect, to identify the process ideal conditions in order to avoid it, and also to evaluate the agreement of these results. Relative to the analyzed variables: relative reduction, forming angle and process speed, the data from the numeric simulation presented a good agreement with the data from the practical tests, using the maximum equivalent strain in the center of the rolled part as analysis criterium. The simulation software can provide useful information helping to take a decision about the tool's geometric characteristics and process conditions. According to the analysis criterium adopted, a bigger percentage of defective parts is associated to increasing values of relative reduction, decreasing values of forming angles and decreasing values of process speed. It was not noticed a good trend about the influence of the initial temperature on the formation of the internal defects.*

**Keywords**: *metal forming; finite element method; simulation*

## 1. INTRODUCTION

Manufacturing processes improvement has become more and more important to get products with better quality and reduced costs. With increasing costs of energy and raw material, processes that reduce or save these resources are constantly pursued. Cross Wedge Rolling (CWR) offers advantages in both of them. Besides, it is a friendly environment process that can improve work conditions and reduce disposable residues. Parts commonly produced by CWR process are stepped axes to automotive industries and their auto parts suppliers (DONG, Y., LOVELL, M. and TAGAVI, K., 1998) and (BUTTON, S. T. and GENTILE, F. C., 2001).

The first researches with the CWR process done by these authors were didactic and intriguing at the same time. In the didactic way, they provided us good information and increased the knowledge about this forming process that still remains restricted within a small group of industries. And intriguing, due the presence of internal defects whose challenge many researchers around the world (SILVA, M. L. N., 2004)

During these initial experiments, despite of working at conditions that the defects were not expected, it was possible to note that these defects were present in almost all parts produced, even when stability conditions of the process related with the forming angle ($\alpha$), the stretching angle ($\beta$) and the relative reduction ($\delta$ = workpiece diameter/rolled diameter) were applied.

It was also noted that these internal defects were eliminated if the parts recently rolled were hot formed by other forming process, like hot forging. The available thermal energy and lack of oxidation in these central cavities made possible the “welding” of the defects surfaces.

However, near net shape parts produced by CWR process and subsequently machined does not present conditions to eliminate the defects by post-processing.

Nowadays, efforts are made to eliminate internal and external defects that limit CWR production. A significant number of articles has been published based on analytical methods and experimental results. Despite some of these papers evaluate the influence of rolling temperature and its distribution into the rolled parts, there is no known work that relates this variable with the presence of the internal defects. The same can be stated about speed rolling (PATER, Z., 2003) and (LI, Q and LOVELL, M., 2005) and (PATER, Z., 2006).

To know the causes of these defects is essential to avoid them and only the complete understanding of the variables influence can allow the right choice of these variables in order to obtain parts without defects (SILVA, M. L. N., 2008).

LI with other authors (LI, Q., et al, 2002) accomplished a widely research concerning to the internal defects and their causes. These authors point out to the intense plastic deformation that leads to axial failures and the accumulation of excessive tensile stresses during the rotations of the workpiece. FU and DEAN (1993) resumed the mainly factors witch cause the central cavities:

- The cyclic nature of the stresses and strain in the workpiece central region.
- The accumulation of micro-cracks due to low cycle fatigue.
- Torsion due different rotation speeds associated to diameter variation of the produced part.
- High amount of non-metallic inclusions within the workpiece.

## 2. MATERIALS AND METHODS

### 2.1. Experimental methods

SAE 1045 steel was chosen to the workpieces because it is a commercial steel, widely used in the production of automotive components.

To evaluate some process variables related to tools geometry, the following values were adopted:

| | | |
|---|---|---|
| Forming angle | $\alpha$: | $20^o$ e $25^o$ |
| Stretching angle | $\beta$: | $7^o$ |
| Relative reduction | $\delta$: | 1.41; 1.44; 1.51; 1.57; 1.61 e 1.70. |

and then, seven combinations were tested:

1) $\alpha = 20^o$ , $\delta = 1.61$
2) $\alpha = 20^o$ , $\delta = 1.44$
3) $\alpha = 20^o$ , $\delta = 1.57$
4) $\alpha = 20^o$ , $\delta = 1.70$
5) $\alpha = 25^o$ , $\delta = 1.41$
6) $\alpha = 25^o$ , $\delta = 1.51$
7) $\alpha = 25^o$ , $\delta = 1.61$

Each forming angle was defined by a specific tool set, and to define each relative reduction plates with different thickness were assembled between the lower tool and the tool holder.

The initial temperature of the workpieces and the speed rolling were also considered. In the literature review, it was noted that the range of temperatures is always chosen from 1100 to 1200 °C. Thus, the chosen temperatures in the tests were 1050, 1100 e 1150 °C. Three rolling speeds were defined to the tests: 100, 150 e 200 mm/s. The higher value is the limit speed of the equipment available at the Metal Forming Laboratory where the tests were carried out .

### 2.2. Numerical analysis

Numerical simulations were performed with the MSC Superform 2005 commercial software. In order to minimize CPU time, only the tools' surfaces in touch with the workpieces were considered in the finite element model. It was assumed the tools as rigid bodies and the workpiece as rigid-plastic, with 6,000 solid elements with 8 nodes.

The material chosen to model the workpiece was the steel $C_{45}$ (equivalent to SAE 1045) available in the software materials library. First, the admitted speed to each tool was 200 mm/s (relative speed: 400 mm/s). Both tools were considered as mobile tools, one in the opposite direction to another. Afterward, simulations with the speeds 100, 150, 200 and 250 mm/s (only to the lower tool) were done. The upper tool was assumed as static to represents the real condition of the experimental tests. The initial temperatures of the workpieces were: 1000, 1100, 1200 and 1250 °C.

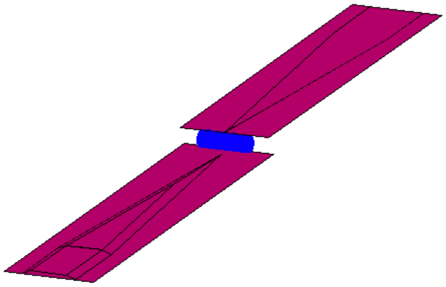

Figure 1. Representation of  tools surfaces at the beginning of the process

Other constants for heat transfer and friction used in the simulations were:

| | |
|---|---|
| – Convection coefficient | $h = 0{,}3\ W/m^2.K$ |
| – Radiation emissivity | $\varepsilon = 0$ |
| – Environment temperature | 40 $^oC$ |
| – Thermal conductivity | $h_c = 10\ W/m^2.K$ |
| – Constant friction factor | $m = 1$ |

Three workpiece diameters were used in the simulations: 27; 30 and 35 mm, and the relative reductions were 1.43; 1.54 and 1.65. The values $20^o$ and $25^o$ were considered to the forming angle ($\alpha$). The stretching angle ($\beta$) was assumed equal to $7^o$ .

## 3. SIMULATION RESULTS

Many different results can be presented by the finite element software, but the equivalent plastic strain was chosen to analyze the presence of internal defects as shown in Fig. 2 that presents a typical distribution of equivalent strain generated by the CWR process in a cross-section plane in the center of the rolled workpiece. The highest plastic strain is found at the workpiece core. Simulation results were collected during rolling process to analyze the maximum values of equivalent plastic strain on that region, and to relate them to the process variables studied in this work.

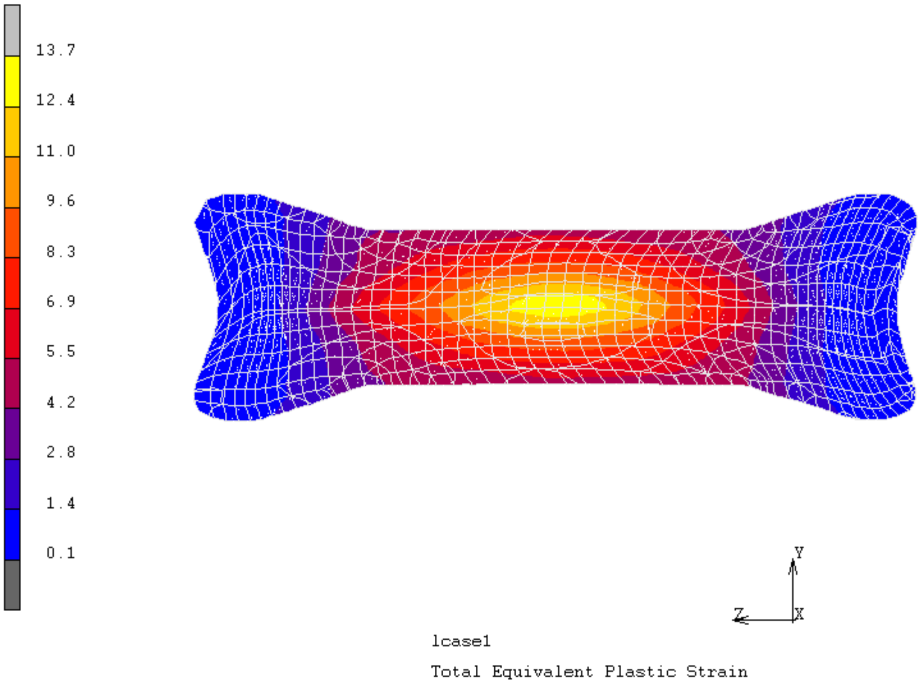

Figure 2. Distribution of equivalent plastic strains on the longitudinal cross-section plane of the rolled product

### 3.1. The influence of the relative reduction (δ)

Figure 3 shows that in the initial stages of the CWR process, plastic strain increases at a higher rate than in the final stages. Higher values of relative reduction were associated to larger strains.

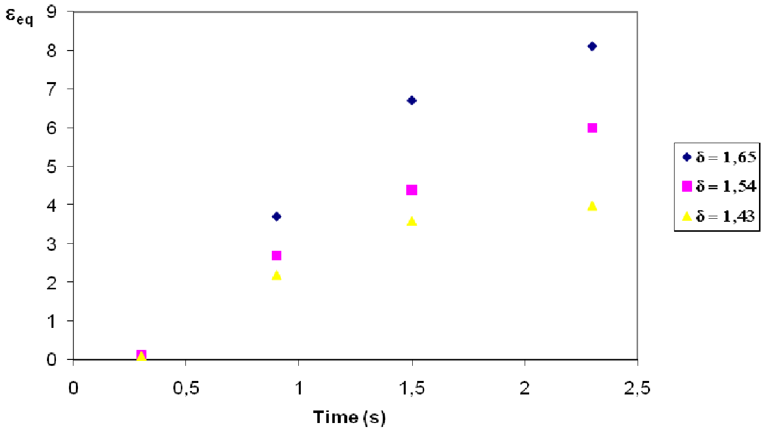

Figure 3. Maximum equivalent strain ($\varepsilon_{eq}$) as a function of process time and relative reduction ($\delta$)

### 3.2. The influence of the forming angle ($\alpha$)

Figure 4 shows that the maximum equivalent strain increases as the forming angle decreases. As a consequence of increasing that angle, the contact area between tool and workpiece increases causing the radial material flow to the detriment of the axial flow at the superficial regions of the workpiece.

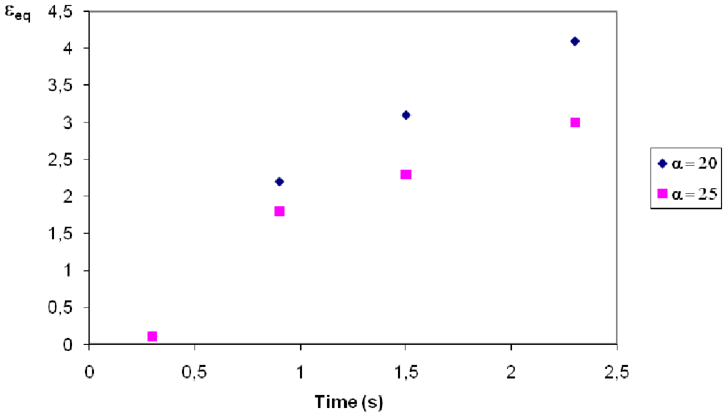

Figure 4. Maximum equivalent strain ($\varepsilon_{eq}$) as a function of process time and forming angle ($\alpha$)

### 3.3. The influence of rolling temperature

Figure 5 shows that temperature increase does not necessarily result in increases of the strain in the workpiece core. A significant increase of the maximum strain is observed when the rolling temperature is 1100 or 1200 °C, but for the other temperatures, 1000 e 1250 °C, maximum strain were very similar.

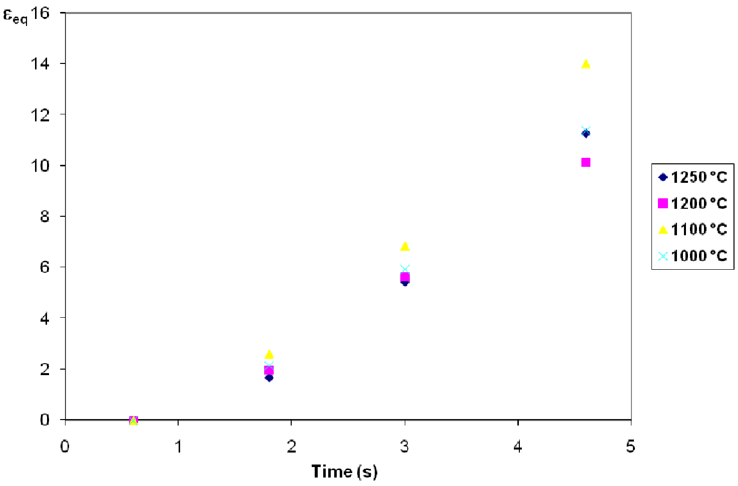

Figure 5. Maximum equivalent strain ($\varepsilon_{eq}$) as a function of process time and rolling temperature

### 3.4. The influence of rolling speed

As shown in Fig. 6, maximum strains with speeds 100; 150; 200 and 250 mm/s (if only the lower tool is driven) were between 11.5 and 14.0, however with rolling speed of 400 mm/s (when both tools are driven) this value was smaller and near to 4.0. Early tests indicated that there is a clear influence of the friction coefficient between tools and workpiece in the main stresses and even in the plastic strain on the core of the rolled workpiece. Increase in the friction coefficient means higher stresses and strains on the core of the workpiece. That conclusion agrees with the results obtained in this work, because higher speeds lead to smaller friction coefficients.

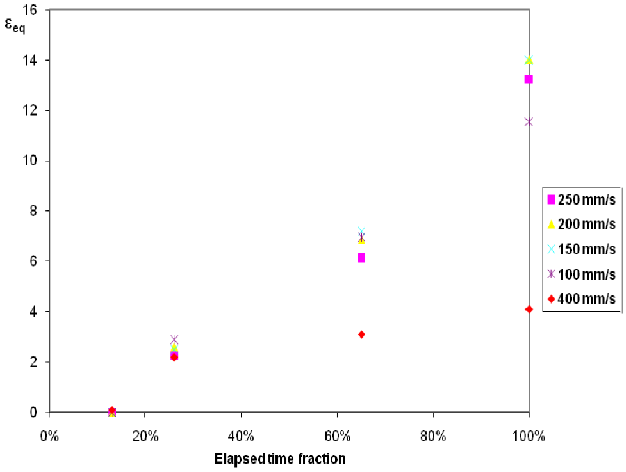

Figure 6. Maximum equivalent strain ($\varepsilon_{eq}$) as a function of process time and rolling speed

## 4. EXPERIMENTAL RESULTS

To compare the defects formed in the CWR tests, they were classified according to their sizes. Defects classified as “large” were those seen to the naked eye and defects classified as “small” were those seen only with 100x magnification. Figs. 7 (a) and (b) show examples of these two sizes of defects.

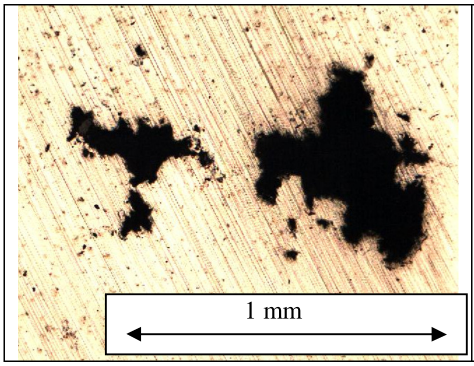

Figure 7 (a). Large defect

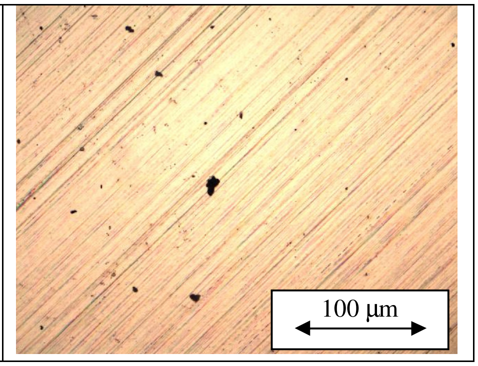

Figure 7(b). Small defect

### 4.1. The influence of the relative reduction (δ)

Figure 8 shows the results related to δ grouped by forming angles α to eliminate a possible influence of this angle in the analysis. The first four values refer to α = 20° with increasing relative reduction values. The last three values refer to α = 25° again with increasing relative reduction values.

In each of these two groups, a trend can be noted: higher values of relative reduction leads to higher percentage of defects. This conclusion can be directly associated to the simulation results for the maximum plastic strain as shown in Fig. 3.

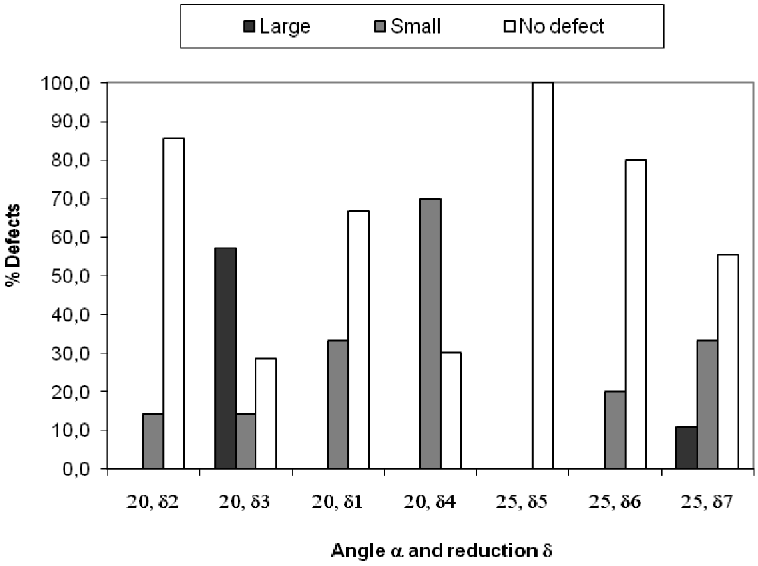

Figure 8. Central defects as a function of the forming angle (α) and relative reduction (δ)

### 4.2. The influence of forming angle α

When tools with forming angle α = 25° were used in the tests, there was a reduction of the percentage of both large and small defects (in consequence, there was a reduction on the percentage of total presence of defects) if compared to the tests with forming angle α = 20° (Fig. 9). Those results agree with the literature and confirm the results obtained in the numerical simulation for the maximum strain as a function of the forming angle (Fig. 4).

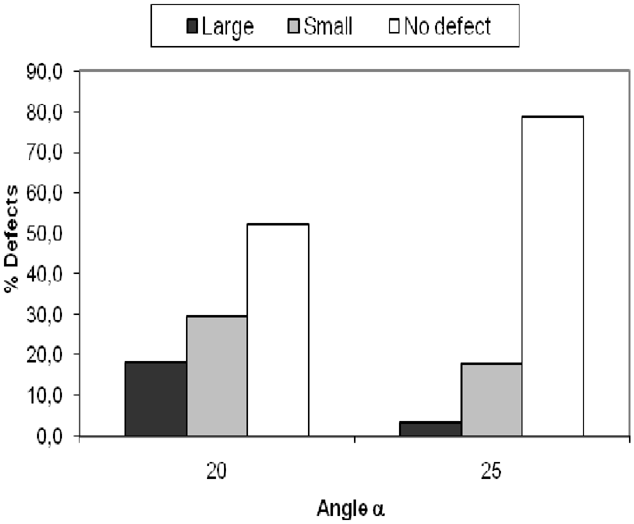

Figure 9. The influence of forming angle (α) on the formation of central defects

### 4.3. The influence of rolling speed

The temperature of 1100°C was fixed to analyze the rolling speed influence. As shown in Fig. 10, it was not noted a clear trend for the total occurrence of defects as a function of the rolling speed, but there was a distinct decrease of the large defects as speed increased. This conclusion is also confirmed by the simulation results (Fig. 6) that showed similar maximum strains for the speeds of 100, 150 and 200 mm/s.

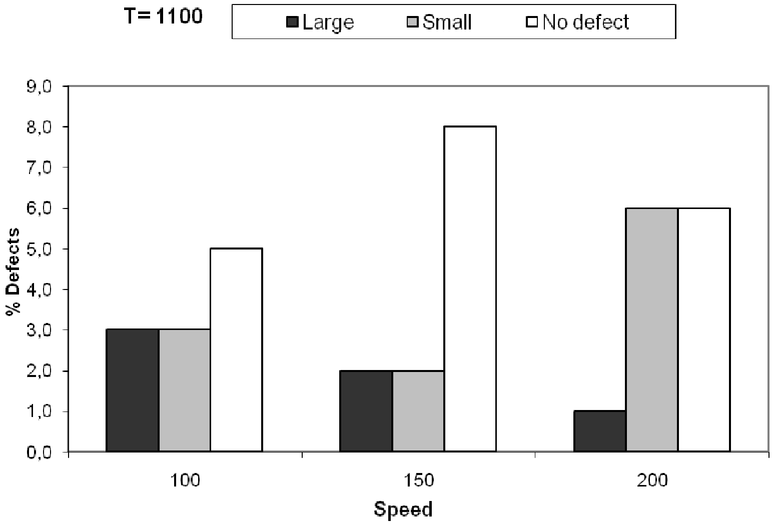

Figure 10. The influence of rolling speed on the formation of central defects

### 4.4. The influence of rolling temperature

The rolling speed of 200 mm/s was fixed to analyze the influence of the rolling temperature. Experimental results (Fig. 11) did not indicate a clear trend of the defects occurrence as a function of the temperature variation. However, the lower percentage of parts with defects occurred with the higher temperature of 1150 °C. Simulation results (Fig. 5) also show that maximum equivalent strain is not necessarily a function of the rolling temperature, except when the highest temperature was evaluated.

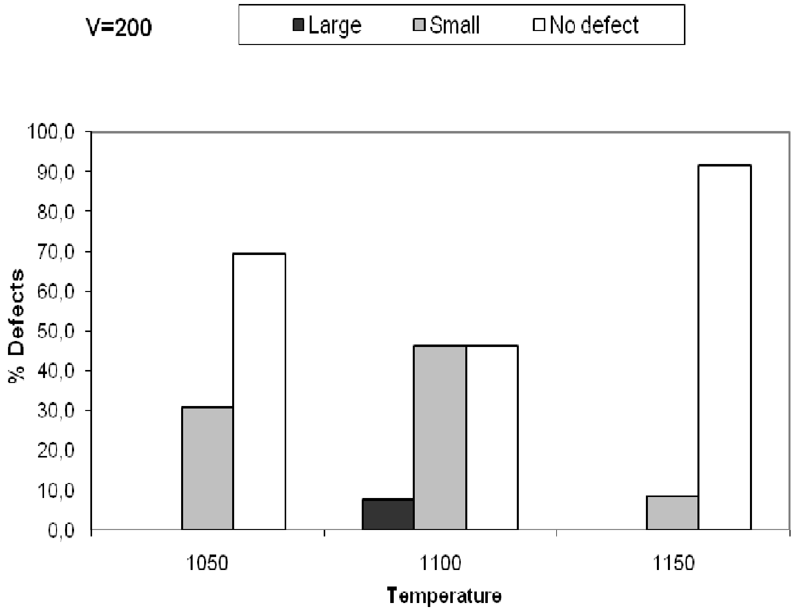

Figure 11. The influence of rolling speed on the formation of central defects

## 5. CONCLUSIONS

Based on the analysis of some variables of the CWR process (relative reduction (δ), forming angle (α), rolling temperature and rolling speed), it was observed that simulation results were consistent to experimental results, when the equivalent maximum strain in the core of the rolling workpiece is adopted as the analysis criterion to define when the internal defect is likely to be formed.

Considering these four process variables, the simulation software can provide useful information to help decision making when defining tools geometry and process conditions to optimize a CWR project.

From the numerical and experimental results it can be concluded that the formation of defects, even small ones, can be achieved if higher rolling speeds and forming angles are used.

The variable *rolling temperature* presented no correlation observed among the occurrence of defects and the different values of temperature adopted for this variable, neither in the numerical simulation nor in the experimental tests.

## 6. ACKNOWLEDGEMENTS

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