EVALUATION OF THE DEFORMATION IN DRAWING OF AISI 304 STAINLESS STEEL BARS THROUGH THE VISIOPLASTICITY TECHNIQUE

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Abstract. *In this paper, the deformation in the single-pass drawing of AISI 304 stainless steel bars has been evaluated through the visioplasticity technique. Several processing conditions were considered in the analysis, comprising different die semi-angles and area reductions. This experimental method allowed the determination of the strain distribution in the cross section of the metal during and after drawing, also leading to the calculation of the final average deformation in the forming operation. The results showed the influence of the die semi-angle and the area reduction, as well as allowed the development of a linear expression between the redundant deformation factor and the geometric parameter* Δ *and the comparison of this equation with those obtained through theoretical approaches.*

Keywords*: drawing, deformation, visioplasticity, redundant deformation factor*

1. INTRODUCTION

Drawing is a cold forming operation in which the metal is pulled through a single or a series of dies, reducing its diameter and, consequently, increasing its length. A schematic illustration of the material flow during the process is exhibited in Fig. 1 (Rowe, 1977). At the beginning, the element near the surface moves towards the die in a direction parallel to the axis (Johnson and Rowe, 1968). As this element goes through the die, it is compelled to move with a radial velocity component. Finally, after leaving the deformation zone, the element near the surface of the metal moves again in the axial direction. This shearing process, whose magnitude decreases from the surface to the centerline of the bar (in this case, the elements move in a direction parallel to the drawing axis during all forming operation), leads to the occurrence of heterogeneous deformation in the cross section of the drawn material. This phenomenon, which depends on several factors, such as the die semi-angle and the reduction of area per pass, is important not only in the study of the forming process but also in the analysis of the subsequent work hardening behavior of the drawn metal.

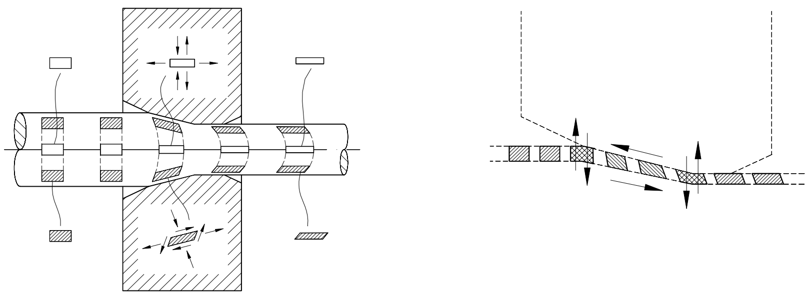


Figure 1. Schematic illustration of the metal flow during drawing operation (Rowe, 1977).

Several procedures for evaluating the deformation in the drawing operation have been developed. The visioplasticity technique, method developed by Thomsen (Thomsen *et al*., 1965; Shabaik and Kobayashi, 1966), is based on the experimental establishment of a velocity vector field and on the subsequent calculation of the strain rate and strain fields, making use of equilibrium and plasticity equations. The results are obtained through the distortion of grid lines previously marked on the sample. The method allows a detailed study of the mechanics of plastic deformation (Thomsen *et al*., 1965; Shabaik and Thomsen, 1968) and is reported as the procedure that provides the most realistic solution to the analysis of the material behavior in various forming operations (Rowe, 1977).

The visioplasticity technique, however, has predominantly been applied to problems associated with extrusion (e.g. Shabaik and Thomsen, 1968; Wang, 1998). The complex experimental work and the requirement of smoothing procedures for treating the data represent the disadvantages of the method (Shabaik and Kobayashi 1966; Wang, 1998), seldom employed in recent investigations concerning metal forming operations (Wang, 2000). In the case of drawing, as far as the present authors know, the analyses have been performed only for few materials and process parameters, with no reference to the calculation of the average effective strains ε_m as well as the redundant deformation factor ϕ (relationship between the average and the external deformation in the process). Our previous work has involved this type of evaluation for ferritic AISI 420 stainless steel bars (Corrêa *et al.*, 2006). The present investigation comprises a similar analysis, in this case, conducted for the austenitic AISI 304 stainless steel, a material whose structural and, therefore, work hardening characteristics differ from those observed in the ferritic metal. In addition to the visioplasticity investigation, the results related to the Caddell and Atkins's approach (Caddell and Atkins, 1968) for the study of the deformation in drawing are also displayed.

2. MATERIAL AND METHODS

The experiments were performed in AISI 304 stainless steel bars, whose chemical composition (weight percent) is presented in Tab. 1. In order to remove the effects of previous forming operations, the material was annealed at 1050ºC for 4200s and furnace cooled to room temperature, displaying a final average Vickers hardness of 125 ± 6 HV.

Table 1. Chemical composition of the AISI 304 stainless steel used in the experiments (wt. %).

element	C	Mn	Si	Cr	Ni	S
%	0.067	1.870	0.323	18.940	9.760	0.024

Two types of specimens were prepared for the experiments. The first one, related to the tensile test of the annealed metal, displayed a diameter of 10mm and a gauge length of 60mm (Fig. 2). The second type of specimen, used in the visioplasticity technique, was machined according to Fig. 3. In this case, sectioned stepped cylindrical bars were employed in the study, in order to allow the calculation of the straining distribution along the cross section of the drawn metal considering both area reductions r (8% and 20%) evaluated in analysis. The dimensions of the samples were estimated taking into account the already mentioned values of r and the die semi-angles α. Further details of the forming operation conditions are presented below. Finally, after machining, a coordinate grid of 1mm x 1mm was electro-chemically marked in the internal flattened surfaces of the samples.

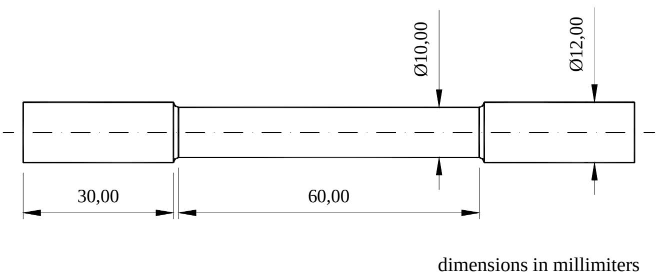


Figure 2. Specimen used in the tensile test of the AISI 304 stainless steel.

Tension was carried out in an Instron model 5582 machine at a crosshead speed of 6.67 x 10^{-2}mm/s, leading to an initial strain rate of 1.10 x $10^{-3}s^{-1}$. The experiments were completed in the annealed metal employing an Instron model 2630-100 electronic extensometer up to the beginning of necking. After this point, successive measurements of load, neck diameter and neck radius were performed, allowing the establishment of the complete effective stress-effective strain curve of the non-deformed metal.

Concerning the experimental method of the visioplasticity technique, single pass drawing was also conducted in an Instron model 5582 machine, specially adapted for the process. Six operation conditions were evaluated in the experiments, involving three die semi-angle α and two reductions of area r. Detailed information concerning this parameters as well as the external deformation ε related to them are displayed in Tab. 2. The crosshead speed of 1.67 x 10^{-1}mm/s was used in the tests, leading to strain rates from 3.34 x $10^{-3}s^{-1}$ to 2.35 x $10^{-2}s^{-1}$ (this value depended on α and r). Before the process, all samples were lubricated with a molybdenum disulfide paste.

Regarding the calculation method of the visioplasticity technique, the establishment of velocity vector fields and, therefore, strain rate and strain fields was performed through the classic procedure developed by Thomsen (Thomsen *et al.*, 1965; Shabaik and Kobayashi, 1966; Shabaik and Thomsen, 1968). The first step of the process, the determination of the flow function field, just after the measurement of the distorted grid lines, however, was carried out according to the method presented by Shabaik (Shabaik, 1972), based on the minimum squares mathematical technique. This procedure was employed in order to decrease the errors related to the experimental measurements, as a kind of smoothing procedure.

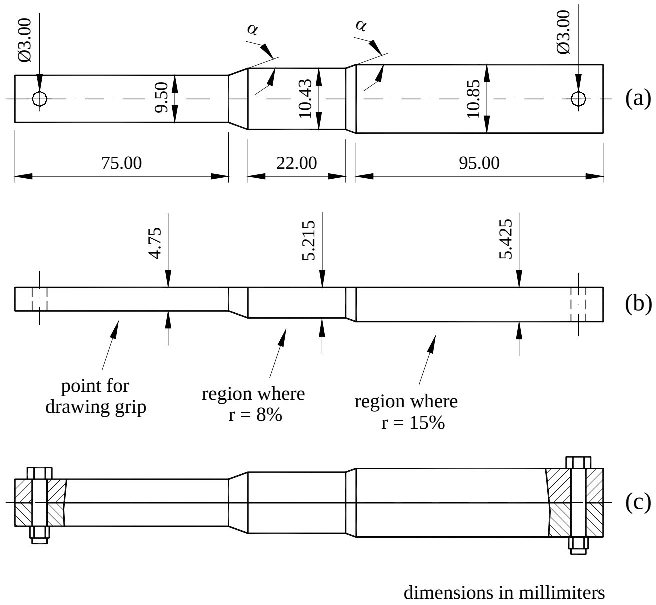


Figure 3. Specimen used in the visioplasticity experiments: (a) and (b) one part of the sample – different views, (c) "complete" specimen - two parts screwed together.

Table 2. Drawing parameters.

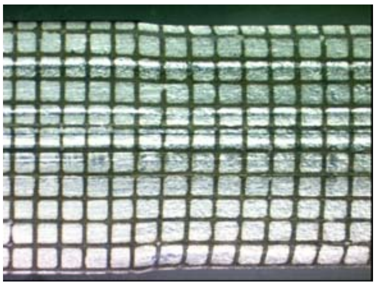
drawing condition	1	2	3	4	5	6
die semi-angle α	20º	20º	8º	8º	3º	3º
area reduction r	8%	15%	8%	15%	8%	15%
external deformation ε	0.083	0.163	0.083	0.163	0.083	0.163

3. RESULTS AND DISCUSSION

Figures 4 and 5 show the grid lines distortion images and the complete effective strain distributions in the cross section of the AISI 304 stainless steel bars during and after drawing obtained through the visioplasticity technique. The graphs were prepared considering deformation zones of 5mm and 9mm for the metal drawn with r = 8% and 15%, respectively. These values corresponded to the maximum deformation zone length observed in the process, related, for both reductions of area, to the die semi-angle = 3°. The final effective strain distributions along the radius of the bars are displayed in Fig. 6. In this case, third-order polynomial fit curves were used to represent the local values of effective strain in the metal.

In general, the results confirm the influence of the die geometry features, i.e., r and α, on the deformation distribution in the cross section of the drawn material. Concerning the images displayed in Fig. 4, the occurrence of increasing changes or distortion of the grid lines as the area reduction and the die semi-angle increase is clearly verified. This phenomenon is also observed in the curves exhibited in Fig. 5 and 6. Considering the results related to experiments performed with α = 20°, heterogeneous deformation profiles are observed in the entire deformation zone and at the end of the operation. At the beginning, the deformation starts in the central region of the bar, before the establishment of the tool/work-piece contact. As the operation is completed, this situation is inverted. The surface of the metal reaches the maximum value of strain, whereas the results in the central area of the bar become relatively similar to the external deformation ε. An analogous behavior is exhibited in the experiments carried out with α = 8°, whose results, however, are less pronounced than those obtained in the tests conducted with α = 20°. Finally, for α = 3°, the strain distributions along the cross section of the bars are almost uniform during and after the process.

Results similar to those displayed in Figs. 4-6 have been previously reported (at least, qualitatively) in several investigations, performed with distinct materials, carried out with the same deformation evaluation approach (Sadok and Packo, 1989; Sadok *et al.*, 1994), or considering different procedures, such as the microhardness profile (Backofen, 1972; Cetlin, 1984) and the finite element methods (Sadok and Packo, 1989; Dixit and Dixit, 1995; Gifford *et al.*, 2000). In addition to the establishment of the deformation distribution in the cross section of drawn metals, some of these studies have involved the calculation of the average effective strain ε_m and the redundant deformation factor ϕ in the forming operation, as well as the analysis of the relationship between these parameters and the die geometry features. The investigations concerning the visioplasticity technique, except the already mentioned AISI 420 stainless steel bars analysis (Corrêa *et al.*, 2006), however, have never involved this type of evaluation. It seems that visioplasticity has been restricted, as far as the present authors know, to the determination of the strain profiles.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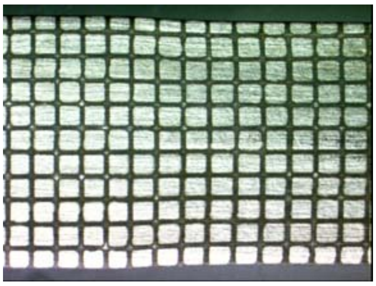
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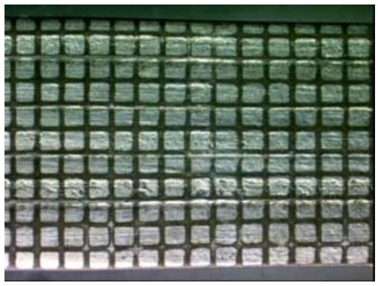
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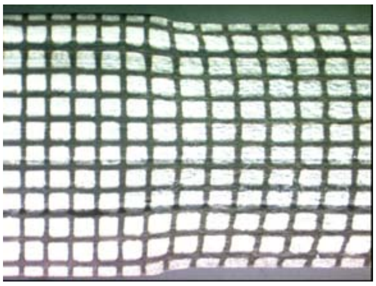
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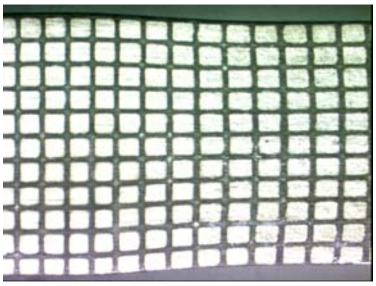
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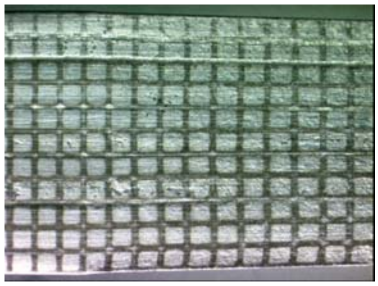
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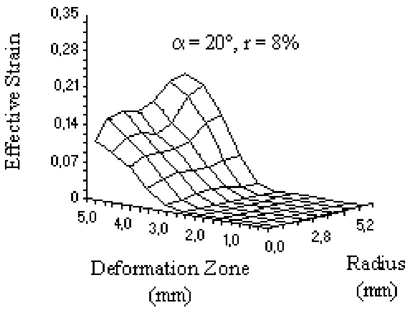
Figure 4. Grid line distortion images of the AISI 304 stainless steel drawn samples – visioplasticity technique: (a) α = 20º/r = 8%, (b) α = 8º/r = 8%, (c) α = 3º/r = 8%, (d) α = 20º/r = 15%, (e) α = 8º/r = 15%, (f) α = 3º/r = 15%.



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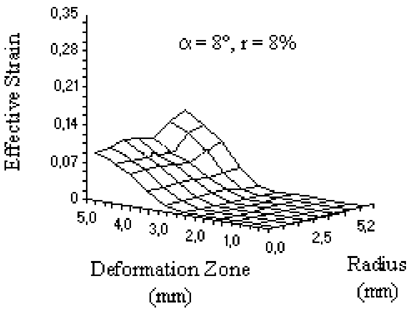

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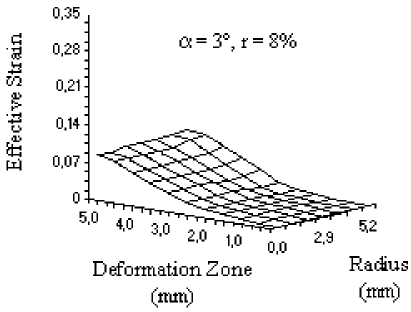

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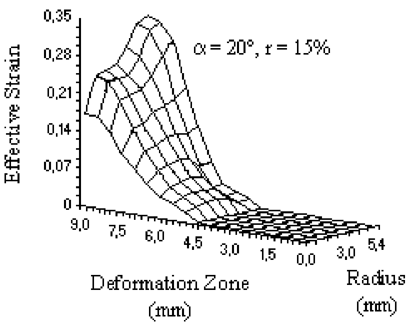

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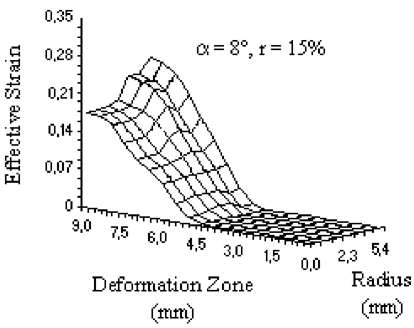

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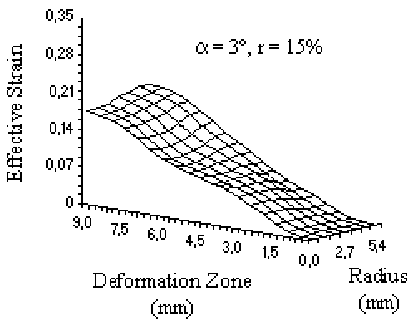

(f)

Figure 5. Effective strain distribution along the cross section of the AISI 304 stainless steel bars during and after drawing – visioplasticity technique: (a) α = 20º/r = 8%, (b) α = 8º/r = 8%, (c) α = 3º/r = 8%, (d) α = 20º/r = 15%, (e) α = 8º/r = 15%, (f) α = 3º/r = 15%.

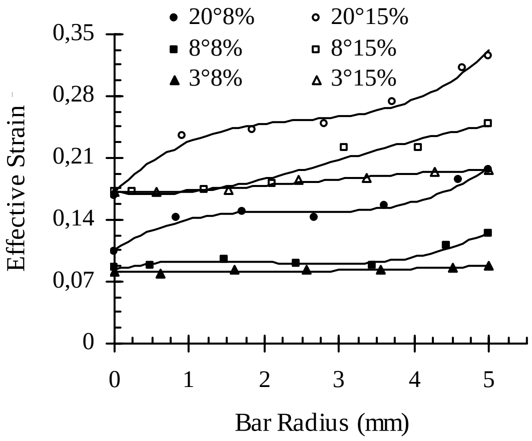

Figure 6. Final effective strain distribution along the cross section of the AISI 304 stainless steel drawn bars.

Therefore, Tab. 3 presents the average effective strains ε_{mv} and the redundant deformation factors ϕ_v of the AISI 304 stainless steel drawn bars, whose values have been calculated employing the final effective strain distributions obtained through the visioplasticity technique, already exhibited in Fig. 6, and the procedure formerly displayed in a microhardness profile method analysis (Cetlin, 1984). The geometric parameter Δ for each drawing condition is also presented in Tab. 3, involving the effects of both die features, the semi-angle α and the reduction of area r, as shown in Eq. (1).

$$\Delta = \frac{d_i + d_f}{d_i - d_f} \, sen \, \alpha \tag{1}$$

Where d_i and d_f are the initial and the final diameters of the bar, for each drawing pass.

Table 3. Values of parameter Δ for each drawing condition evaluated in the investigation and of average effective strain ε_{mv} and redundant deformation factor ϕ_v of the AISI 304 stainless steel drawn bars obtained through the visioplasticity technique.

drawing condition	α = 20° r = 8%	α = 20° r = 15%	α = 8° r = 8%	α = 8° r = 15%	α = 3° r = 8%	α = 3° r = 15%
parameter Δ	16.75	8.60	6.7	3.44	2.51	1.29
average effective strain ε_{mv}	0.158	0.270	0.097	0.214	0.084	0.186
redundant deformation factor ϕ_v	1.389	1.664	1.159	1.318	1.007	1.147

Figure 7 exhibits the experimental redundant deformation factors ϕ_v and a linear equation describing the relationship between these values and the parameter Δ. The ϕ_{CA} - Δ expression established for the AISI 304 stainless steel drawn bars according to the procedure proposed by Caddell and Atkins (Caddell and Atkins, 1968) is also displayed (Fig. 7b). In this case, the equation was obtained using the strength coefficient and the strain-hardening exponent, both Hollomon's equation terms calculated with the tensile flow curve of the annealed metal, and the empirical formulation based on experimental stress-strain curves superposition technique results. This classical deformation evaluation method, contrasting with the others previously mentioned, allows only the estimation of the average deformation in the drawing process (and consequently the calculation of ϕ) with no analysis of the strain profiles of the metal. The technique is based on the assumption that the drawing stress is given by the area under the tensile flow curve of the undrawn material up to a certain value of strain corresponding to the average deformation imparted by the forming operation (Caddell and Atkins; 1968, Cetlin, 1987). In other words, the tensile yield stress of the drawn bar would be equal to the ordinate of the stress-strain curve of the annealed metal at the average effective strain in the process.

Considering the visioplasticity results, despite the dispersion of the data, an increasing relationship between ϕ_v and Δ is clearly observed in Fig. 7. A similar behavior is verified in Caddell and Atkins's approach, whose results, however, were found to be higher (in general, for $\Delta > 2.5$) and more sensitive to variations of the geometric parameter (Δ) than those calculated through the experimental technique. In this case, the differences between ϕ_v and ϕ_{CA} are certainly associated with the use of distinct straining evaluation methods and with specific aspects of Caddell and Atkins's model. The superposition technique reflects the hardening characteristics of the material and its final mechanical properties, whereas the visioplasticity results would not be influenced by the subsequent mechanical behavior of the metal. Finally, in order to allow the comparison between the results attained in the 304 stainless steel and the 420 stainless steel analysis, Fig. 8 exhibits the experimental data and the ϕ_v - Δ expression obtained for the ferritic metal (Corrêa *et al*., 2006). The AISI 420 stainless steel (the redundant deformation factor) is clearly more sensitive to variations of the parameter Δ than the material evaluated in this investigation.

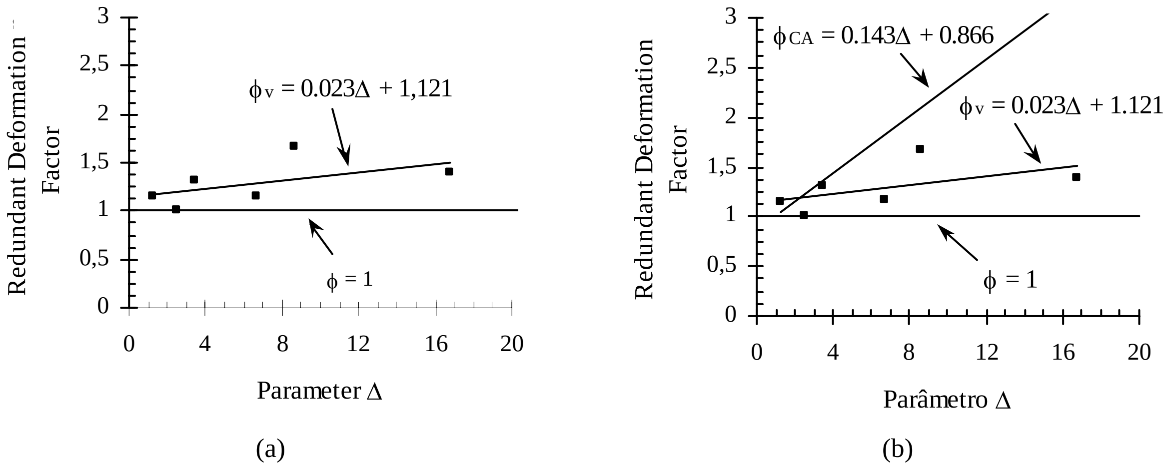

Figure 7. Relationship between the redundant deformation factor ϕ and the geometric parameter Δ obtained through: (a) visioplasticity technique and (b) visioplasticity technique and Caddell and Atkins's approach (Caddell and Atkins, 1968) for austenitic 304 stainless steel bars.

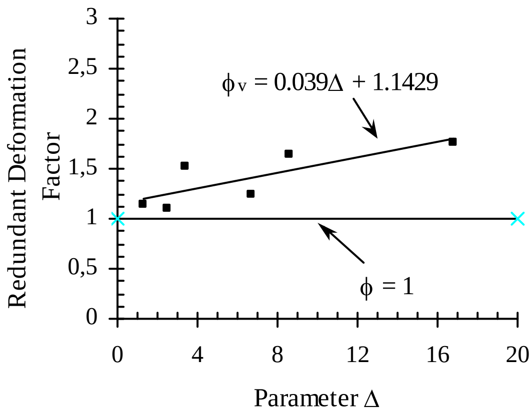

Figure 8. Relationship between the redundant deformation factor ϕ and the geometric parameter Δ obtained through the visioplasticity technique for ferritic AISI 420 stainless steel bars (Corrêa *et al*., 2006).

4. CONCLUSIONS

- The results showed the influence of the geometric die features on the deformation distribution in the cross section of the AISI 304 stainless steel drawn bars. The strain profiles were found to be more heterogeneous as the die semi-angle increases.
- A linear and increasing relationship between the redundant deformation factor obtained through the visioplasticity technique and the parameter Δ for the AISI 304 stainless steel bars was established.
- The redundant deformation factor values obtained through the formulation proposed by Caddell and Atkins based on the stress-strain curves superposition technique were higher and more sensitive to variations of the parameter Δ than those calculated through visioplasticity.

5. ACKNOWLEDGEMENTS

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