24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-2129
A NEW COMPUTATIONAL METHOD FOR DETERMINING THE PARAMETERS OF JOHNSON-COOK MODEL

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Abstract. *It is known for long that the study of plastic deformation of metals is extremely important to have full knowledge of the forces acting on a given process. Currently, various mechanical processes occur at high strain rates, such as the ballistic area, impact test vehicles, boilers explosion, and the failure of the sheet metal forming processes. The understanding of the processes is related to the study of the mechanics of the process, which seeks to determine the reasons why failures occur. Particularly, in cases involving high strain rates, it is common to use the Johnson-Cook model, fine detailing the stress field in such cases that can also be included the effect temperature. In this model, we can see the influence of the elastic-plastic term, which characterizes the elastic and plastic fields of the material, the presence of the viscous term, which shows the influence of the strain rate in the process and the term of thermal softening, which introduces the influence of temperature. A problem encountered by those who use this model is the difficulty in getting the parameters. Currently there is no simple, concise and clear methodology for this calculation and those in need of the equation must resort to literature, which rarely have such methodologies and procedures, or develop your own method.*

Keywords: *Forming of Metals, Strain rate, Temperature in metal forming, Johnson-Cook model.*

1. INTRODUCTION

Several empirical and semi-empirical models are currently used for computational plasticity determining and according to Hoge & Mukherjee (1977), the Johnson-Cook model (1985) is the most commonly used despite purely empirical. However, there is currently no normalizing methodology for calculating precisely Johnson-Cook model, leading each user to develop its own method. The equation (1) employed in this work is developed through each individual terms of the general Johnson-Cook model's equation.

$$\sigma = (A + B\varepsilon^n)\left[1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_0}{T_f - T_0}\right)^m\right] \tag{1}$$

Variation of temperature can be calculated by equation (2), where β is the Taylor-Quinney coefficient, ρ specific mass and c_p specific heat of the material.

$$\Delta T = \frac{\beta}{\rho c_p}\int \sigma d\epsilon \tag{2}$$

The first term of equation (1) corresponds to the elastic-plastic part, the second term to the viscous term and the third to the thermal softening. Using the proposed method, to determine the pre-exponential factor (*B*) and the hardening exponent (*n*) it is necessary to analyse only term elastic-plastic. It is known that the constant *A* is the yield strength of the material. However, with two remaining unknowns, two equations are needed, calculated with two points on the strain-strain curve, to determine the parameters (*B*) and (*n*), as shown in equation (3).

$$\begin{cases} \sigma_1 = (A + B{\varepsilon_1}^n) \\ \sigma_2 = (A + B{\varepsilon_2}^n) \end{cases} \tag{3}$$

With due mathematical development, the hardening exponent (*n*) can be determined directly, according to equation (4).

$$n = \frac{\log\left(\frac{\sigma_2 - A}{\sigma_1 - A}\right)}{\log\left(\frac{\epsilon_2}{\epsilon_1}\right)} \quad (4)$$

With the result of equation (4), parameter (*B*) can be isolated in equation (3) to be determined directly with equation (5).

$$B = \frac{\sigma_1 - A}{{\epsilon_1}^{n}} \quad (5)$$

Adding the viscous term, and after the necessary manipulation, considering as reference strain rate $\dot{\epsilon}_0 = 1{,}0$, has the parameter (*C*), the strain-rate factor, determined in equation (6).

$$C = \frac{1}{\ln \dot{\varepsilon}}\left(\frac{\sigma}{A + B\,\varepsilon^{n}} - 1\right) \quad (6)$$

And finally, with the addition of the thermal softening term, it is possible to manipulate resulting equation, thus determining the parameter (*m*), the thermal softening exponent, as shown in equation (7).

$$m = \frac{\log\left|\frac{\sigma}{(A + B\varepsilon^{n})(1 + C\ln\dot{\varepsilon})} - 1\right|}{\log\left(\frac{T - T_0}{T_f - T_0}\right)} \quad (7)$$

2. EXPERIMENTAL PROCEDURE

For determining of the deformation curve through the Johnson-Cook parameters, it is not enough to apply them directly on equation (1), since an iterative method is required. Initially, an initial approximation must be carried out to determine the tension, subtracting from the equation (1) the thermal softening term, since no temperature information is available, and to determine it, the tension field is necessary. After the initial approximation, an initial temperature interval ΔT must be obtained, through equation (2). With this, the determination of temperature field of the material, considering the thermal softening term. The next step is recalculating the initial interval ΔT, reapplying it in equation (1), repeating iteratively, until an acceptable minimum error is obtained. At the end of the process, a curve can be plotted with the vector of stresses and their respective deformations, as shown by Scaduto & Menezes (2016).

3. RESULTS AND DISCUSSION

In order to prove the effectiveness of the proposed method, the methodology was implemented with *MatLab® software*, performing analysis for different materials, with properties available in the literature, at high strain rates to evaluate in which points of the available stress-strain curve; the best values of the parameters of the Johnson-Cook model are obtained. The methodology is applied for two different materials, at three strain rates considered high (1000, 10000 and 100000 1/s).

3.1. 1045 STEEL

For the performance of the stress-strain curve, the model parameters of Johnson-Cook proposed by Altasim Technologies (2017) are shown in table (1).

Together with the parameters of the Johnson-Cook model, properties of the analyzed material are shown in table (2).

Table 1 – Theoretical parameters of the Johnson-Cook model for AISI 1045 steel (Altasim, 2017).

Parameter	Value
A	553,1 MPa
B	600,8 MPa

C	0,0134
m	1,0
n	0,234

Table 2 – Properties for the material AISI 1045 steel (ASM, 2017).

Parameter	Value
Young Modulus	200 x 10^8 MPa
Material Specific Weight	7830 kg/m³
Material Specific Heat	477 kJ/kg.K
Reference Temperature	293 K
Melting Temperature	1793 K

Thus, with experimental data available in the literature, it is possible to plot the stress-strain curve of AISI 1045 steel for each indicated strain rate, as shown in figure (1).

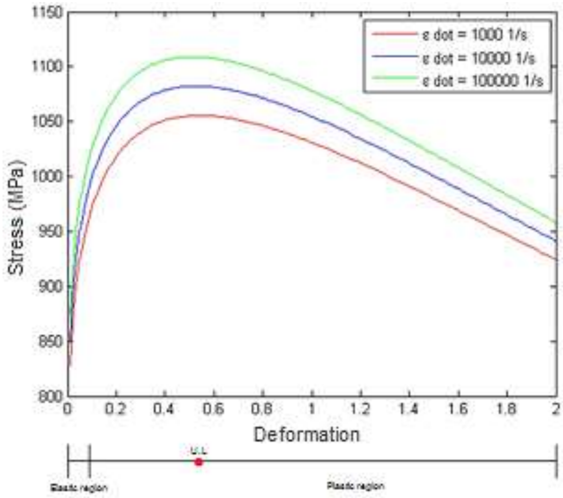

Figure 1. Stress-strain curve of AISI 1045 steel for three strain rates (Scaduto & Menezes, 2016).

It can be observed that when working with high strain rates, the elastic region of the curve is very small and the plastic deformation is very large. The higher the deformation rate, the greater the deformation for the same level of stress and consequently, its strength limit (LR) is also higher. These curves presented in figure (1) will be used as the basis for applying the model proposed to obtain the Johnson-Cook parameters for Steel AISI 1045. Equally, it can be demonstrated the material temperature gain for the three strain rates, as shown in figure (2). It is noticed that the temperature does not vary considerably with the strain rate changing. However, it can be noted a considerable increasing in temperature with deformation. This is due to the fact that the stress level variation by the strain rate is not high enough to determine large temperature variations. Even so, there is an increasing in temperature for a higher strain rate and for the same level of deformation.

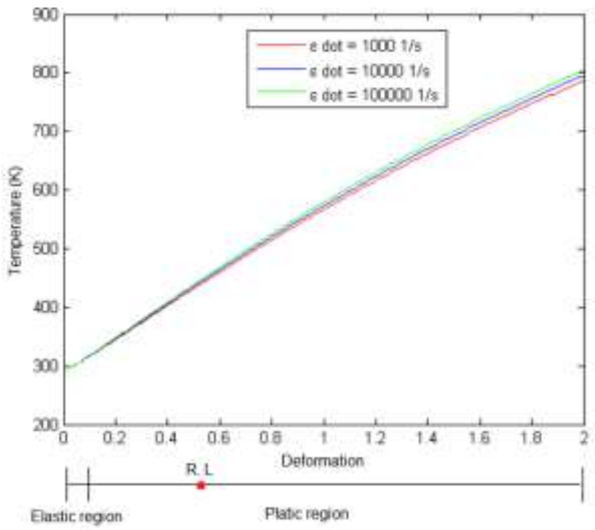

Figure 2. Temperature variation with the deformation of AISI 1045 Steel for three strain rates (Scaduto & Menezes, 2016).

From now on, one can start the validation of the method proposed. So, taking the hardening exponent *n* from the Johnson-Cook model, a comparison is made between the values obtained by the proposed method through equation (4). It should be remembered that parameter *A* is the material yield limit, so no method will be proposed to obtain it. It will be used as an entry into the problem. Figure (3) shows the error variation of the parameter *n* for Steel AISI 1045, comparing the values obtained from the literature with those obtained using the method, for each level of deformation, using three high strain rates.

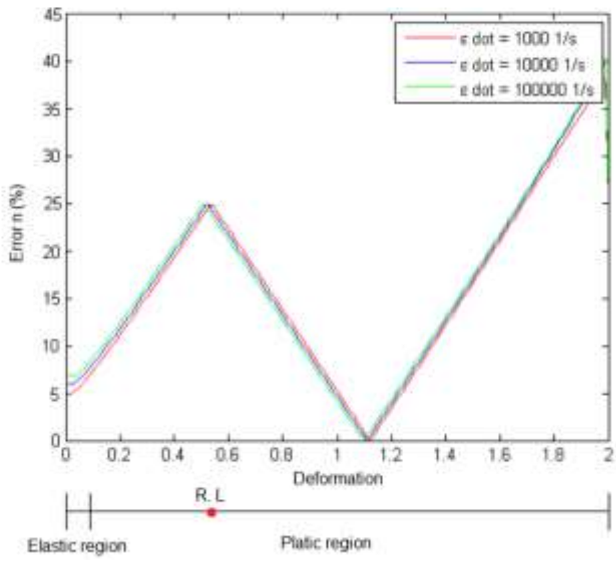

Figure 3. Error variation of the parameter *n* for AISI 1045 Steel comparing the value obtained by the method proposed with that found in the literature for each level of deformation for three strain rates (Scaduto & Menezes, 2016).

Looking at figure (3), it is noted that the error tends to zero for a level of deformation of about 1.12. To obtain a range of acceptable values, it is considered that for AISI 1045 Steel, better results are obtained for the parameter *n* in the strain range between 1 and 1.2, which corresponds to an error of approximately 5%. A general range valid for all materials will be discussed later after present the results obtained for two materials. As described before, when presenting the method, the second parameter to be calculated is the pre-exponential factor *B*. Figure (4) shows the error variation of parameter *B* for AISI 1045 Steel, comparing again the values obtained from the literature with those obtained by equation 5, for each level of deformation, using three different high strain rates.

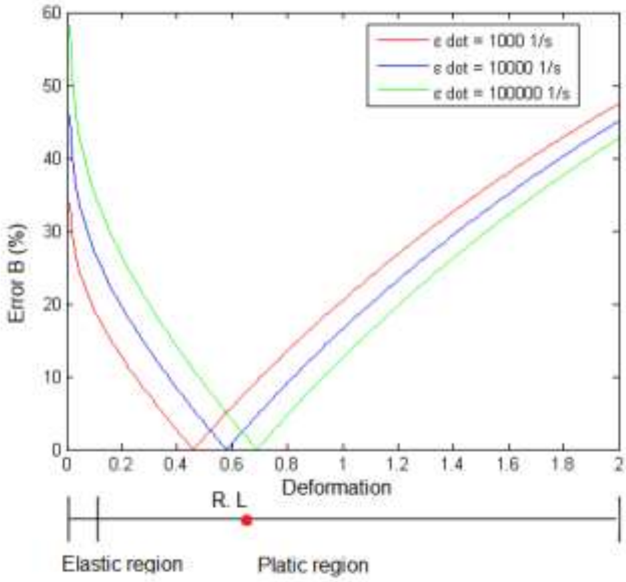

Figure 4. Error variation of parameter *B* for AISI 1045 Steel by comparing the value obtained by the method proposed with that found in the literature for each level of deformation for three different high strain rates (Scaduto & Menezes, 2016).

Examining figure (4), it can be seen that the error tends to zero when the deformation is close to the strength limit (LR), or in the deformation range of 0.4 to 0.8, leading to an error of approximately 4%. A general range valid for all materials will be discussed later after presenting the results obtained for two materials. As described before when presenting the method, the third parameter to be calculated is the strain-rate factor *C*. Figure (5) shows the parameter *C* for AISI 1045 Steel, comparing as well the values obtained from the literature with those obtained by equation 6, for each level of deformation, using three different high strain rates.

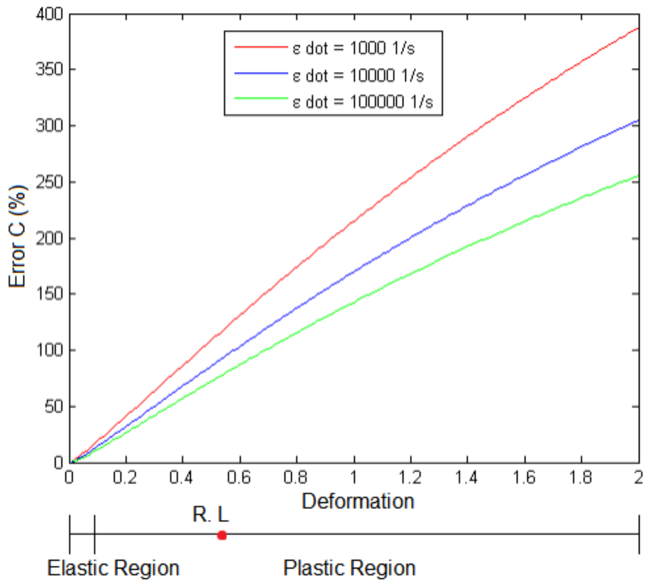

Figure 5. Error variation of the parameter *C* for AISI 1045 Steel comparing the value obtained by the method proposed with that found in the literature for each level of deformation for three different high strain rates (Scaduto & Menezes, 2016).

Looking at figure (5), it is verified that the error tends to zero when the deformation tends to zero, or yet in the elastic region defining an error of approximately 10%. Nevertheless, it can be observed that the smaller the deformation is, the smaller the error. A general range valid for all materials will be discussed later after present the results obtained for two materials. As described before, when presenting the method, the fourth and last parameter to be determined is the exponent that portrays the thermal softening effect *m*. Figure (6) shows the error variation of parameter *m* for AISI

1045 Steel, comparing the values obtained from the literature with those obtained by the method, for each level of deformation, using three different high strain rates.

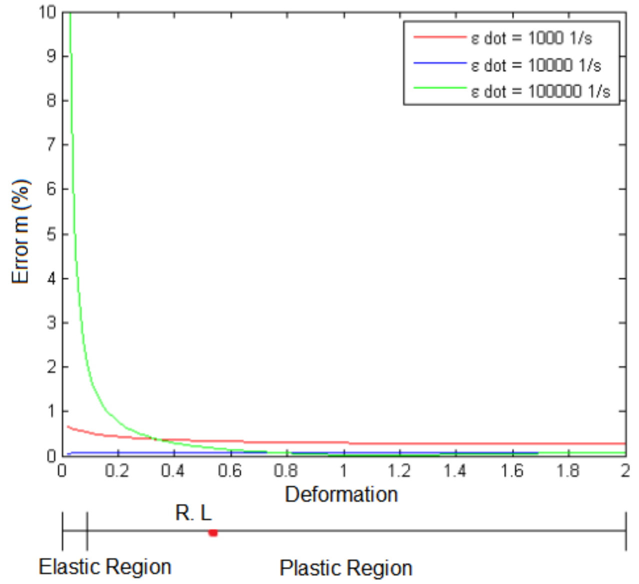

Figure 6. Variation of the error of the parameter *m* for AISI 1045 Steel comparing the value obtained by the method proposed with that found in the literature for each level of deformation for three different high strain rates (Scaduto & Menezes, 2016).

Observing Figure 6, it is noted that the error tends to zero when the curve enters in the plastic region, obtaining better results for higher levels of deformation, the leading to errors less than 1%. A general range valid for all materials will be discussed later after presenting the results obtained for the two materials. The errors obtained in the determination of this parameter are smaller than the checked for others, because in this case, the full Johnson-Cook model is used. In contrast, for the other parameters that is used an approximated formulation.

Using the method described, the Johnson-Cook parameters for three strain rates analyzed, for Steel AISI 1045, considering the greatest possible errors. The data are arranged in the table (3)

Table 3 – Parameters of the Johnson-Cook calculated for AISI 1045 steel, considering highest errors (Scaduto & Menezes, 2016).

Parameter	1000 1/s	10000 1/s	100000 1/s
n	0,241	0,222	0,2513
B	616,64	619,53	625,22
C	0,012	0,0124	0,0217
m	1,0029	0,999	0,9996

3.1. 4340 STEEL

For the performance of the strain-strain curve, the model parameters of Johnson-Cook proposed by Altasim Technologies (1977), as shown in table (4).

Together with the parameters of the Johnson-Cook model, properties of the material analyzed, as shown in table (5).

Table 4 – Theoretical parameters of the Johnson-Cook model for AISI 4340 steel (Altasim, 2017).

Parameter	Value
A	792 MPa
B	510 MPa
C	0,014

m	1,03
n	0,26

Table 5 – Properties for the material AISI 4340 steel (ASM, 2017).

Parameter	Value
Young Module	200 x 10^8 MPa
Material Specific Weight	7850 kg/m³
Specific Heat	477 kJ/kg.K
Reference Temperature	293 K
Melting temperature	1697 K

With the theoretical information of literature, it is possible to plot the stress-strain curve of AISI 4340 steel for each indicated strain rate, as shown in figure (7).

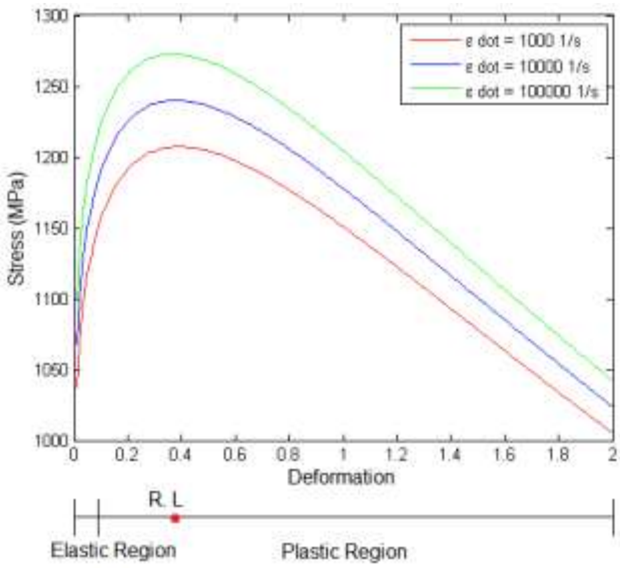

Figure 7. Stress-strain curves of AISI 4340 steel for three different high strain rates (Scaduto & Menezes, 2016).

Equally, it can be demonstrated the gain of temperature of the material for three strain rates, as shown in figure (8). Figure (3) shows the variation of the error of parameter n for Steel AISI 4340, comparing the values obtained from the literature with those obtained using the method, for each level of deformation, using three different high strain rates.

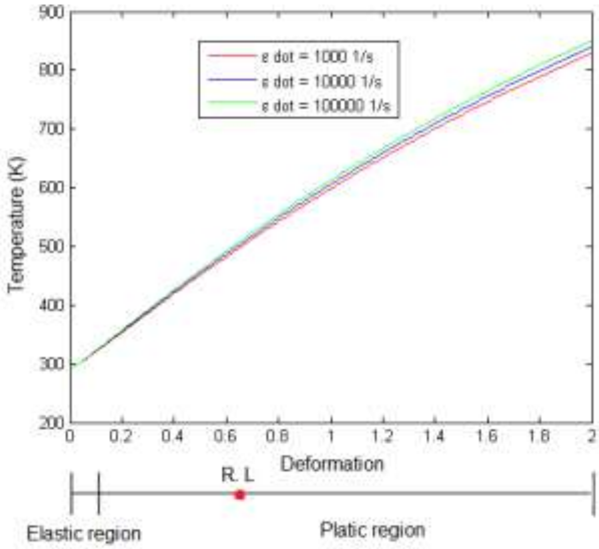

Figure 8. Temperature variation with the deformation of AISI 4340 Steel for three different high strain rates (Scaduto & Menezes, 2016).

Figure (9) shows error variations of parameter n for Steel AISI 4340, comparing the values obtained from the literature with those obtained using the method, for each level of deformation, using three different high strain rates.

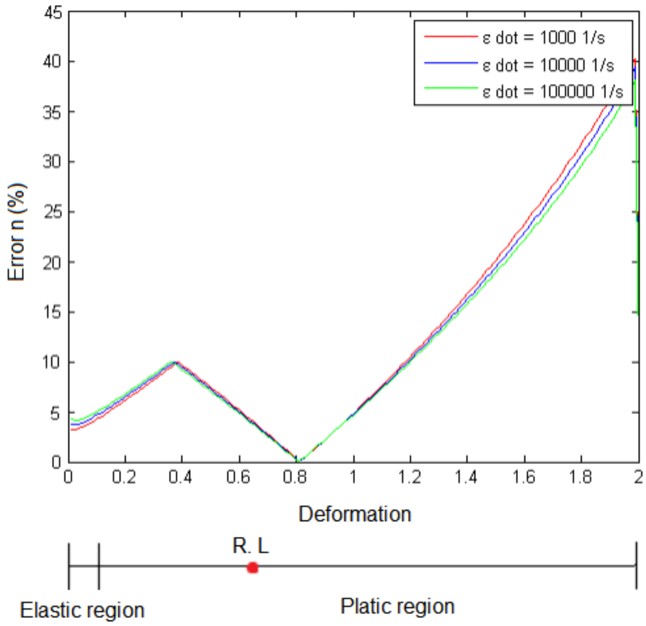

Figure 9. Error variations of the parameter *n* for AISI 4340 Steel comparing the value obtained by the method proposed in the literature for each level of deformation at three different high strain rates (Scaduto & Menezes, 2016).

As described in the method presentation, the second parameter to be calculated is the pre-exponential factor *B*. Figure (10) shows error variations of the parameter B for AISI 4340 Steel, comparing again the values obtained from the literature with those obtained by the method, for each level of deformation, using three different high strain rates.

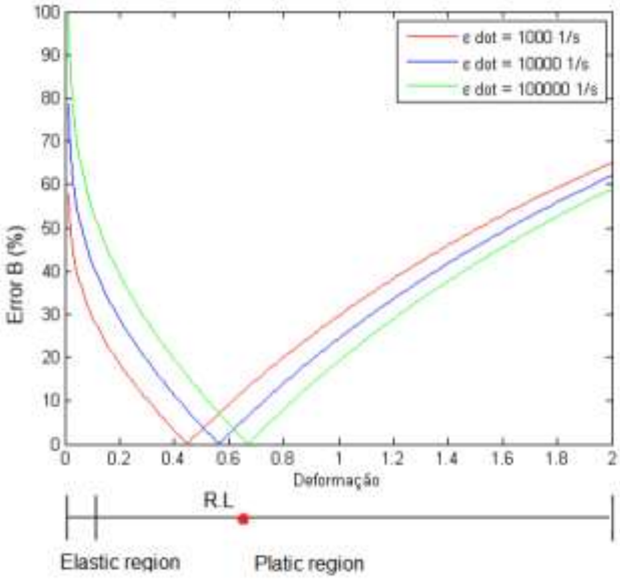

Figure 10. Error variations of the parameter *B* for AISI 1045 Steel by comparing the value obtained by the method proposed in the literature for each level of deformation at three different high strain rates (Scaduto & Menezes, 2016).

Figure (11) shows the parameter C for the AISI 4340 Steel, comparing the values obtained from the literature with those obtained by the method, for each level of deformation, using three different high strain rates.

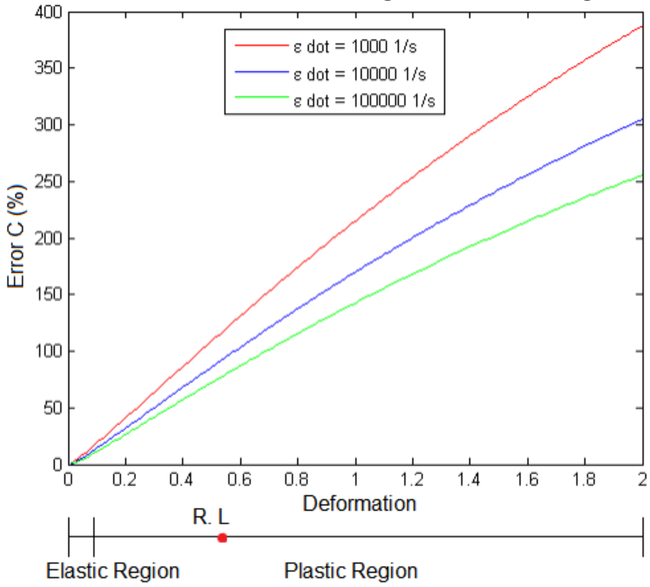

Figure 11. Error variations of the parameter *C* for AISI 4340 Steel comparing the value obtained by the method with those proposed in the literature for each level of deformation at three different high strain rates (Scaduto & Menezes, 2016).

Figure (12) shows error variations of the parameter *m* for AISI Steel 4340, comparing the values obtained from the literature with those obtained by the method, for each level of deformation, using three different high strain rates.

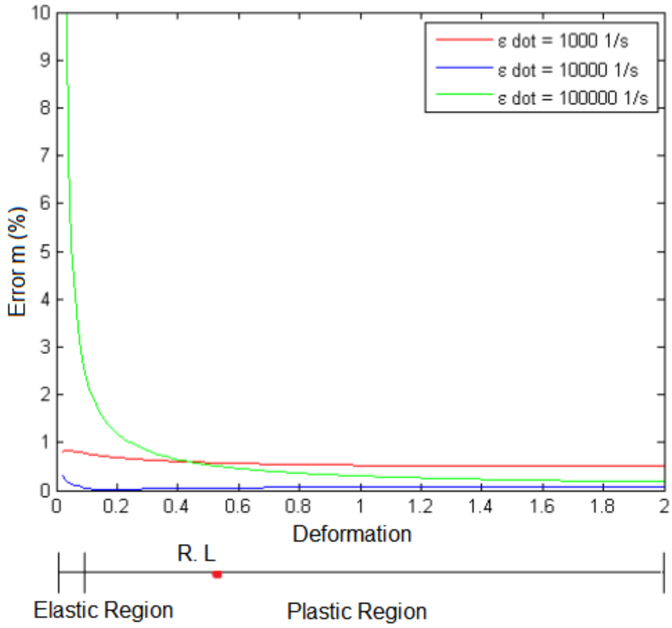

Figure 12. Error variations of the parameter *m* for AISI 4340 Steel comparing the value obtained by the method with those proposed in the literature for each level of deformation at three different high strain rates (Scaduto & Menezes, 2016).

Using the method described, the Johnson-Cook parameters for the three different strain rates analyzed, for Steel AISI 4340, considering the greatest possible errors. The data are arranged in the table (6).

Table 6 – Parameters of the Johnson-Cook calculated for AISI 4340 steel, considering highest errors (Scaduto & Menezes, 2016).

Parameter	1000 1/s	10000 1/s	100000 1/s
n	0,219	0,221	0,2431
B	501,19	500,59	500,36
C	0,013	0,0129	1,0132
m	1,0397	1,023	1,0405

4. CONCLUSIONS

The *n* parameter was the one that obtained the biggest errors, since it was taken from equation containing only one term of the model used. It was necessary to open up too much the interval of obtaining the parameter *n*, causing greater errors, since the points with smaller errors did not converge for the analyzed materials. The determination of *B* parameter has implied in a maximum error of 4% and a convergence case for both material applications. The determination of parameter *C*, which was the penultimate parameter defined implied a maximum error of 10%, which can be attributed to the position of the stress-strain pair used in the curve considered. This pair should be closer to the origin of the curve, which would lead to errors less than 1%. The last parameter calculated was the coefficient *m*, which implied errors less than 1% on the entire plastic part of the curve. This low error is due to the fact that the complete equation was used to obtain it, since the other parameters were already defined. In general, therefore, the methodology proposed was satisfactory for all tested materials with errors less than 15%, as well simple and clear in their nature.

5. ACKNOWLEDGEMENTS

UNESP, the Engineering Faculty and Mechanical Engineering Department for material and financial support.

6. REFERENCES

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