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Araştırma Makalesi / Research Article

Estimate of The Flow Stress and Damage Model Parameter Coefficients from Tensile Test with The Help of a Code

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ABSTRACT: Metal forming, machining, crashing, etc. in simulations, not only the boundary conditions are given perfectly, but also another important input is the properties of the material used. Defining these properties correctly increases the confidence in using the results of the simulation in practice. One of the most well-known parametric models representing the stress-strain relationship at different temperatures and strain rates in simulation programs is the Johnson-Cook flow stress model and ductile damage model. However, the process of obtaining JC parameters for the material is quite long and tiring. Combined evaluation of multiple tests and simulation results, curve fitting, regression and optimization procedures necessitate an organized mathematical operation process. With the program written, it was tried to get both fast and accurate parameter results by using different mathematical solution methods. Parameter constants are obtained automatically by entering different test types, test device result format and simulation report format entries in a hierarchical order using the written program. The user can visually check the tests and results with on the same graphics and intervene in the detection of critical points of the tests when necessary. By using different curve fitting algorithms, finding the most suitable parameters is provided.

Keywords: Flow stress model, Ductile damage model, Curve fitting, Optimization, JC parameters.

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Kod Yardımı ile Çekme Testinden Akış Gerilmesi ve Hasar Modeli Parametre Katsayılarının Tahmini

ÖZET: Sadece sınır şartlarının kusursuz verilmesi değil, metal şekillendirme, imalat, çarpışma vb. simülasyonlarda en önemli diğer bir girdi de kullanılan malzemeye ait özellikleridir. Bu özelliklerinin doğru tanımlanması, simülasyonun sonuçlarının uygulamada kullanımına olan güveni artırır. Simulasyon programlarında farklı sıcaklıklarda ve şekil değiştirme hızlarında stress-strain ilişkisini temsil eden parametrik modellerin en çok tanınmışlarından biri Johnson-Cook gerilme akışı ve sünek hasar modelidir. Ancak malzemeye ait JC parametrelerinin elde edilmesi süreci oldukça uzun ve yorucudur. Çok sayıda testin ve simülasyon sonuçlarının beraber değerlendirilmesi, eğri uydurma, regresyon ve optimizasyon prosedürleri, organize bir matematiksel işlem uygulama sürecini zorunlu kılar. Yaptığımız program ile farklı yapıdaki testler, test cihazı sonuç ve simülasyon rapor format girdileri, hiyerarşiye uygun bir düzende girilerek, parametre katsayıları otomatik elde edilmektedir. Kullanıcı testlere ve sonuçlara ait ortak grafiklerle görsel olarak kontrol edebilmekte, gerekli durumlarda testlere ait kritik noktaların bulunmasına müdahale edebilmektedir. Farklı eğri uydurma algoritmaları kullanılarak en uygun parametrelerin bulunması sağlanmaktadır.

Anahtar Kelimeler: Akma gerilmesi modeli, Sünek hasar modeli, Eğri uydurma, Optimizasyon, JC parametreleri.

1. INTRODUCTION

Various tests are applied to metallic materials, material producers who have to share information about the material and, of course, in order to have information about whether the selected material is sufficient for the application. In fact, the tensile test, in which we reach the most basic information of materials from the stress-strain curves, is the most basic mechanical test, although we sometimes need much more different tests. In tensile tests, when the specimen fixed to two jaws is pulled at a constant speed, sometimes the displacement between the jaws and sometimes the relative movement of the two points on the specimen is determined optically and the extension are combined with the load-cell to which a jaw is attached to the load-extension curve. However, the curve for which we have found more important information is the stress-strain curve proposed by Thomas Young and drawn using the information taken from the load-extension graph (Figure 1). A single test or a single curve alone cannot be sufficient to respond to all the conditions the selected material will encounter in practice. Hundreds of curves may need to be drawn to give information about the changing material behavior at different strain rates and different ambient temperatures. Flow stress and damage models have been defined, since they can simply show the material behavior for each case instead of giving many curves. These models express the situation that the user will encounter in practice in a simple form.

Different models are used to define the behavior of the material to be used in simulation programs and the damage condition in the elastic-plastic region. For example, Cowper Symonds, Steinberg Guinan, Johnson-Cook etc. models are frequently used in finite element analysis programs (Immanuel and Panigrahi, 2018; Korkmaz et al., 2020; Shokry, 2019; Wang and Liu, 2015). One of the most well-known models is the Johnson-Cook model. There have been many studies aiming at obtaining especially Johnson-Cook parameters constants and using these parameters (Korkmaz et al., 2020; Akbari et al., 2016; Chen et al., 2019; Lalwani et al., 2009; Gupta et al., 2014; Shrot and Bäker, 2012; Banerjee et al., 2015). The accuracy of the simulation results of any manufacturing process also depends on the accuracy of these models used. It is also very important to give the material behavior in accordance with the program used. In the comparison studies of the Johnson-Cook model whose parameter constants we are trying to estimate, although it is not valid for every situation, Zerilli-Armstrong and Steinberg-Guinian etc. It was found to be more successful than models such as (Banerjee, 2005, 2012; Jing et al., 2017; Zhang et al., 2019). This model describes the change in deformation behavior of metallic material under different temperatures and different deformation rates using two equations and ten parameter constants.

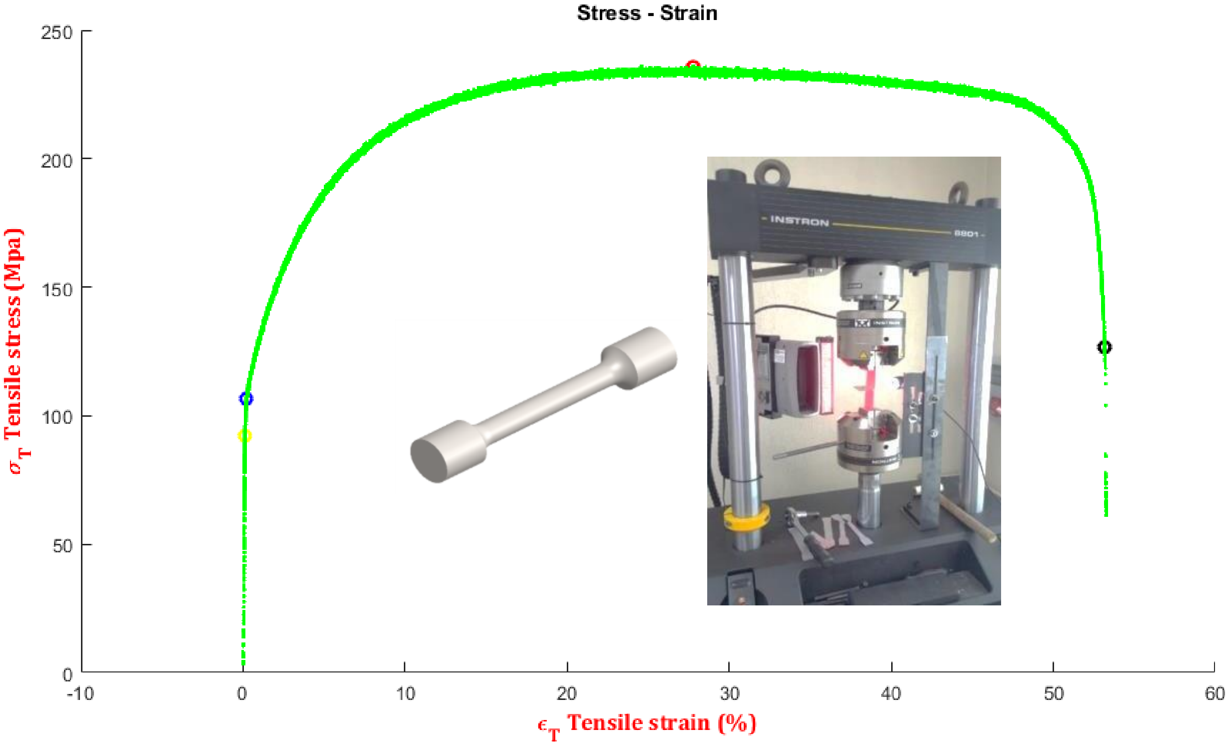


Figure 1. Tensile test curve and its experimental result

2. MATERIALS AND METHODS

2.1 Johnson-Cook Models

The relationships between stress and strain in metallic materials can be easily explained by Johnson-Cook model under conditions of deformation, strain rate and temperature. It is still widely used by many researchers to describe the flow stress behavior of many different materials (Raut, N. et al. 2021; Niu, L. et al, 2020). Although there are some redeveloped differences due to some limitations in different materials (Shokry, A. et al, 2021; Mareau, C., 2020), the traditional flow stress model is expressed as;

$$\sigma = (A + B\varepsilon^n)\left(1 + Cln(\dot{\varepsilon^*})\right)(1 - T^{*m}) \tag{1}$$

where σ is the equivalent stress and ϵ is the equivalent plastic strain (Johnson and Cook, 1983, 1985)

A is the yield stress of the material under reference conditions, B is the strain hardening constant, n is the strain hardening coefficient, C is the strengthening coefficient of strain rate, and m is the thermal softening coefficient. The terms in three different brackets given in equation (1) describe the strain hardening effect, the strengthening effect of the strain rate, and finally the temperature effect, from left to right respectively on the stress flow (2). In the flow stress model, $\dot{\varepsilon}^*$ and $T^*$are defined and calculated as,

$$ln(\dot{\varepsilon}^*) = ln\left(\frac{\dot{\varepsilon}}{\dot{\epsilon_{ref}}}\right)\begin{Bmatrix} 0 & for & \dot{\epsilon_{ref}} = \dot{\varepsilon} \\ + & for & \dot{\epsilon_{ref}} > \dot{\varepsilon} \\ - & for & \dot{\epsilon_{ref}} < \dot{\varepsilon} \end{Bmatrix} \quad (2)$$

$$T^* = \begin{Bmatrix} 0 & for & T < T_{ref} \\ \frac{T - T_{ref}}{T_m - T_{ref}} & for & T_{ref} \leq T \leq T_m \\ 1 & for & T < T_m \end{Bmatrix} \quad (3)$$

Here $\dot{\varepsilon}^*$ defines the strain rate, which is dimensionless, T^* is the homologous temperature. T is the deformation temperature, T_m is the melting temperature of the metal. $\dot{\epsilon_{ref}}$ and T_{ref} were used to define the strain rate and deformation temperature taken as reference in experiments, respectively (Banerjee, 2005).

2.2 Determination of JC Flow Stress Parameter Constants

If the strengthening effect of strain rate and thermal softening effect are neglected in equation (1) which defines the flow stress, n and B constans can be obtained approximately by using the stress and strain values under reference deformation conditions. For this, the linear relationship between $ln(\sigma - A)$ and $ln(\varepsilon)$ is found using the first order regression model as in Figure 2a.

When the thermal softening effect is eliminated, it will be easy to find the constant C from the slope of the curve between $\frac{\sigma}{(A+B\epsilon^n)} - 1$ and $ln(\dot{\varepsilon}^*)$ using the values obtained at different strain rate (Figure 2b). If this time the strengthening effect of the strain rate is eliminated from equation (1), we can calculate the m value from the slope of the relation curve between $ln\left(\frac{\sigma}{(A+B\epsilon^n)} - 1\right)$ and $ln(T^*)$, where the values obtained at different temperatures are used (Figure 2c).

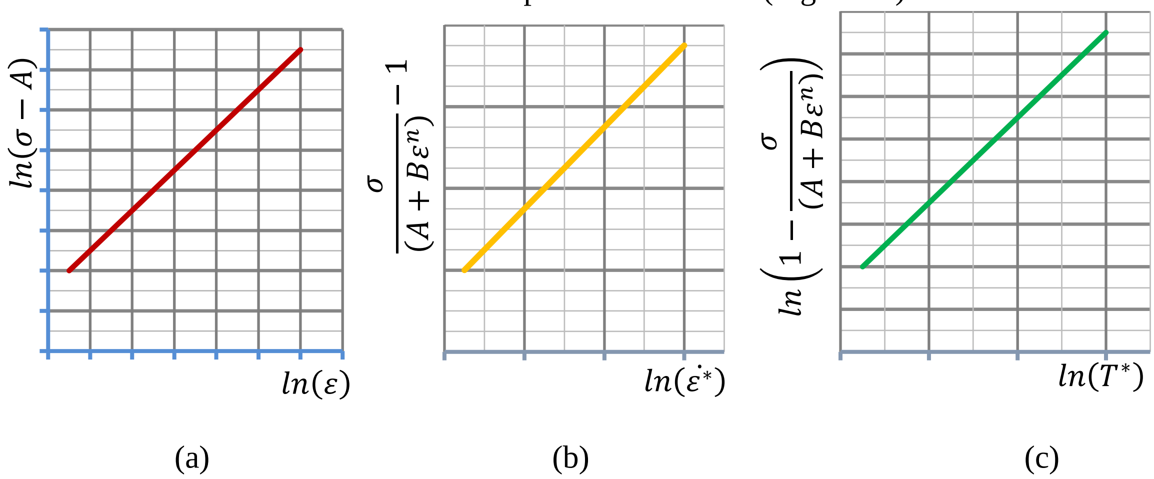


Figure 2. $ln(\sigma - A) \sim ln(\varepsilon)$ graph arranged to obtain Johnson-Cook parameters B and n (a), arranged to obtain the C parameter $\frac{\sigma}{(A+B\epsilon^n)} - 1 \sim ln(\dot{\varepsilon}^*)$ graph (b), $ln\left(\frac{\sigma}{(A+B\varepsilon^n)} - 1\right) \sim ln(T^*)$ graph (c) arranged to obtain the m parameter

2.3 Determination of JC Damage Model Material Constants

The damage model of Johnson-Cook where fracture strain is dependent on stress triaxiality, strain rate and temperature are determined as given below (Banerjee, 2005);

$$\varepsilon_f = \left(D_1 + D_2 e^{(D_3 \eta)}\right)\left(1 + D_4 ln(\dot{\varepsilon}^*)\right)(1 + D_5 T^*) \quad (4)$$

$$\eta = \left(\frac{\sigma_m}{\sigma_{eq}}\right) \quad (5)$$

Here $D_{1\text{-}5}$ defines the damage model parameters, σ_m average stress, σ_{eq} equivalent stress. Damage to an element is defined based on a cumulative damage law and given in a linear form (Kupchella et al., 2005) as shown below:

$$D = \sum \frac{\Delta\varepsilon}{\varepsilon_f} \quad (6)$$

Where $\Delta\varepsilon$ is the incremental strain and ε_f is the strain equivalent to fracture under current stress, strain rate and temperature conditions. Due to the formation of fracture, the strength of the material decreases during deformation and the relationship of sufficient stress to realize whether damage has occurred can be expressed as:

$$\sigma_D = (1 - D)\sigma_{eq} \quad (7)$$

In (7), σ_D is the damage stress and D is the damage parameter. Damage starts when the D value is greater than one. Stress triaxiality and the magnitude of the equivalent stress can be obtained from undamaged specimens in the region until neck formation, considering the plastic behavior (Bacha et al., 2007). In (4), which defines the magnitude of the strain that causes the damage, if the effect of strain rate and thermal softening effects are neglected, the linear relationship between ε_f and η is obtained by using the regression model, D_1, D_2, D_3 values are obtained approximately by using the stress and strain values at the reference deformation conditions (Figure 3a).

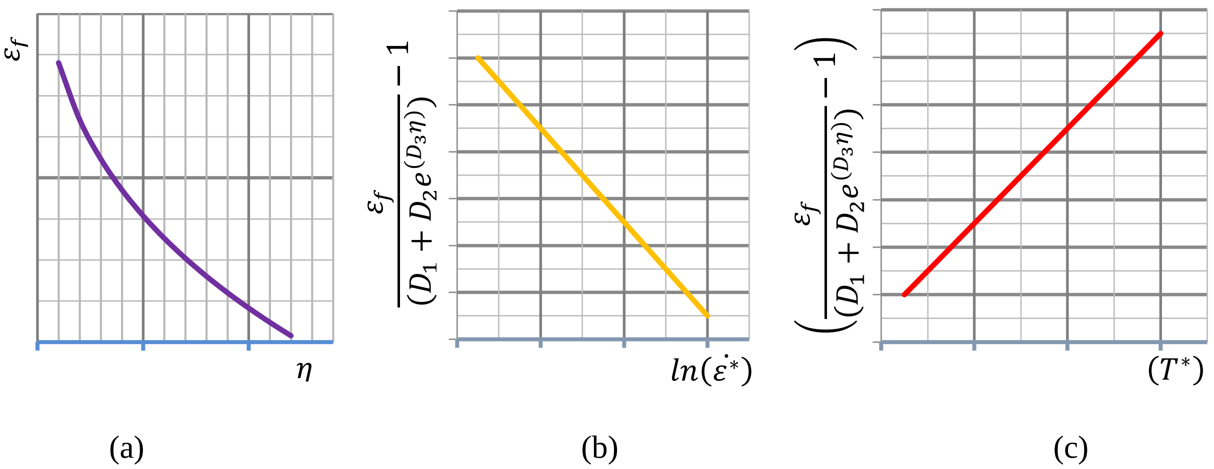


Figure 3. $\eta \sim \varepsilon_f$ graph drawn to obtain Johnson-Cook D_1, D_2, D_3 damage parameters (a), $\frac{\varepsilon_f}{(D_1+D_2 e^{(D_3\eta)})} \sim ln(\dot{\varepsilon}^*)$ graph arranged to obtain D_4 damage parameter (b), $\left(\frac{\varepsilon_f}{(D_1+D_2 e^{(D_3\eta)})} - 1\right) \sim (T^*)$ graph arranged to obtain D_5 damage parameter (c)

If the thermal softening effect is eliminated from (4), D_4 is determined by using the values we obtained for different test rate $\frac{\varepsilon_f}{(D_1+D_2e^{(D_3\eta)})}$ and $ln(\dot{\varepsilon}^*)$ can be found from the slope (Figure 3b). This time, if the effect of the strain rate is eliminated from (4), we can calculate the D_5 damage parameter with $\left(\frac{\varepsilon_f}{(D_1+D_2e^{(D_3\eta)})}-1\right)$ and (T^*) using the values we obtained at different temperatures. It will be quite easy to find from the slope of the relationship curve between (Figure 3c).

3. RESULTS AND DISCUSSION

3.1 Interface Used for Evaluation of Test Results

It takes a lot of time and effort to easily combine and evaluate a large number of tests to obtain model parameter constants. With the data coming from the test device, not all input parameters of some simulation programs can be accessed. Instead, the desired values should be obtained for the appropriate situation from the sample by simulating the tensile test as in Figure 2. As shown in Figure 4, using any program that can simulate the tensile test, applying an optimal mesh type and mesh number to the model designed in accordance with the standard, the obtained force, elongation, mises stress etc. values are matched with the tensile test data. When the tensile test and the data obtained from the simulation program are matched, the equivalent plastic strain and triaxiality values that cannot be taken from the test can be reached. It takes a long time to organize and evaluate both the displacement and force data from the tensile test device and other data from the simulation program without any confusion. An interface has been designed considering that it will be helpful and facilitate the work while trying to reach test results.

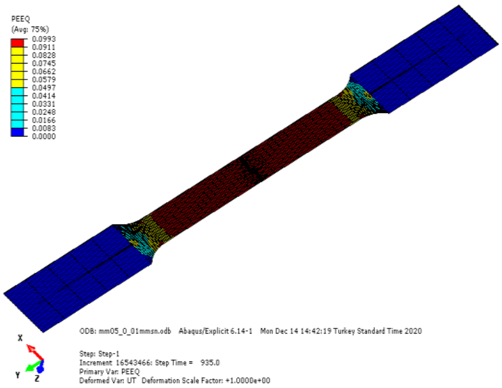
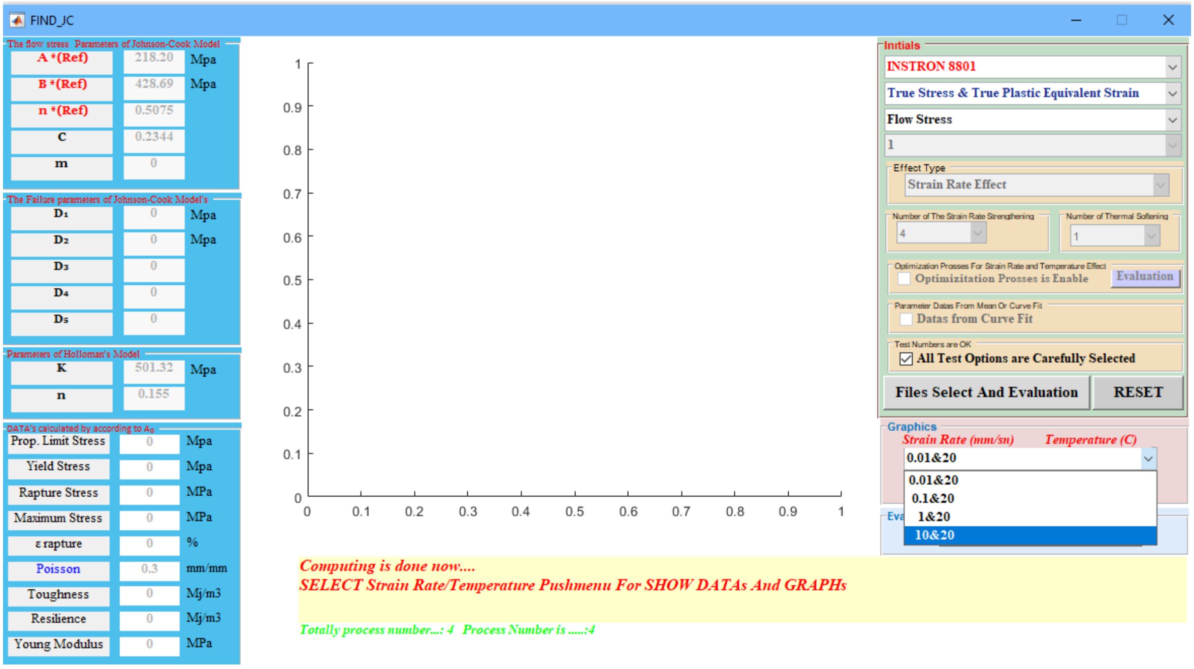


Figure 4. Simulation of a tensile test

In order for the test to process data in different formats from many different devices, the device must be selected initially. File types and contents of different formats are processed, basic test sample inputs, force and extension information are read and processed. As a result, the required values are given in the main interface (Figure 5). Ten coefficients of Johnson-Cook stress flow and damage parameters, Hollomon's hardening coefficient values, some critical fundamental values related to strain and stress, toughness, resilience and Young modulus are given in the interface. The K coefficient in Hollomon Equations is called the strength coefficient and the n coefficient is called the strain hardening exponent. The strain hardening coefficient refers to the ability of a material to harden. The low value of this coefficient, which generally varies between 0-0.5, indicates that the material will break before it hardens too much, and its high value indicates the ductile structure of the material. The formability of metals and their alloys is related to their hardening behavior (Praveen et al., 2004).

Since the hardening exponential determines the hardening capacity during plastic deformation, for example, the chip forming ability of the material in machining can be calculated (Yang and Putatunda,



2004).

Figure 5. Main interface view

As can be seen in Figure 6a, after selecting the test device for the data format, the condition for which type parameters should be calculated should be determined. Here, although the general request is for true strain- true stress, parameter constants can also be calculated for true plastic equivalent strain - Von Mises stress used in some simulation programs (Figure 6b). After selecting one of the two options, it is necessary to select different calculation procedures, namely the parameter type for Johnson-Cook stress flow parameter constants or damage parameter constants (Figure 6c). Since the data ranges taken in the tests can be varied, processing too much data may increase accuracy but also cause unnecessary waste of time. Since many iterations are required to estimate some parameter constants, the response time can be quite long. The evaluation of the result for few data points also causes incorrect values. Therefore, data range values should be chosen carefully (Figure 6d). The data describing the temperature and strain rate effects of Johnson-Cook stress flow and damage parameter constants both have different structures and the calculation procedures are different from each other. After determining which effect the calculation will be made (Figure 6e), the number of different temperatures or strain rates are selected to evaluate (Figure 6f, g). In the main interface, during the evaluation of more than one test, it is also determined whether the data will be done through the average or curve fitting procedure.

(a) (b) (c) (d)

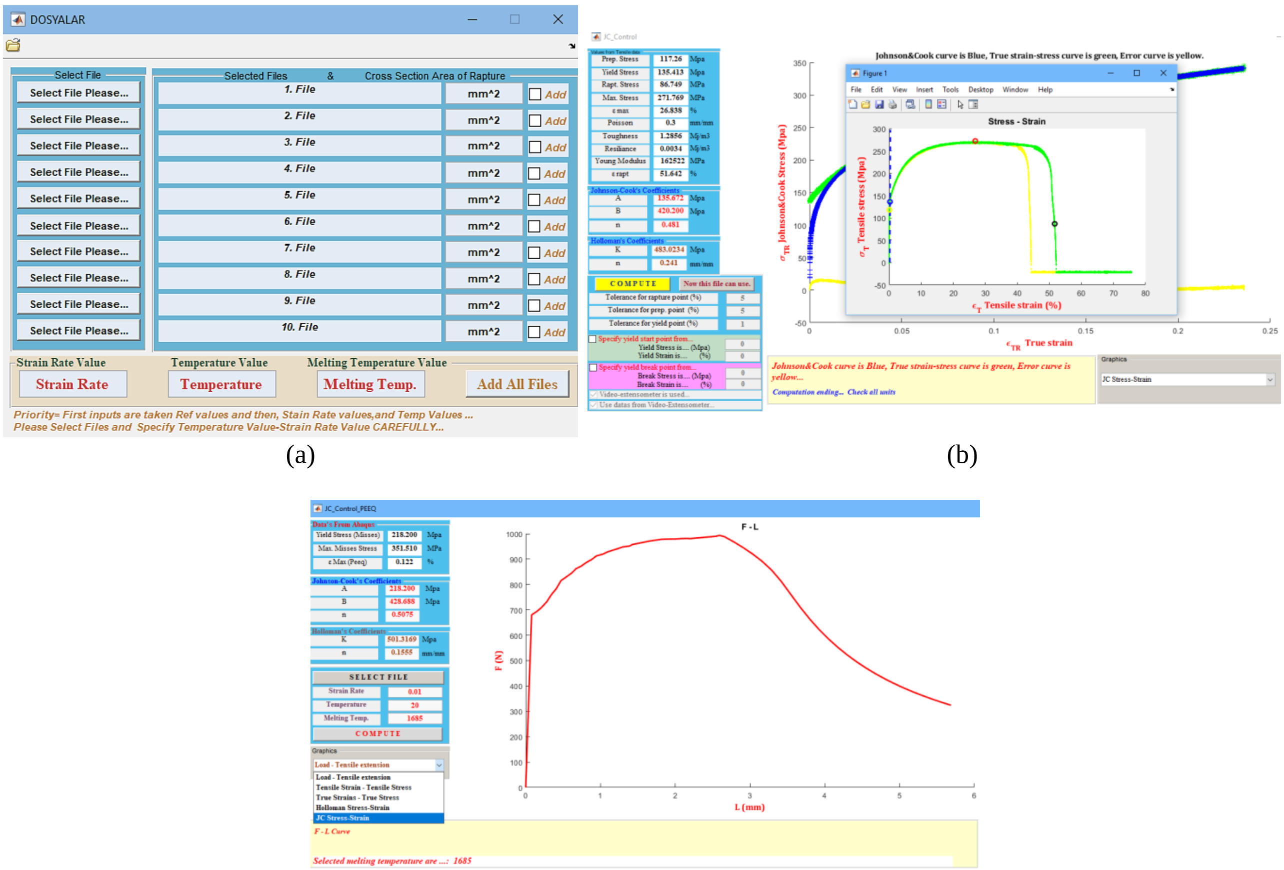
(e) (f) (g)

Figure 6. Selection interfaces for parameter types

Figure 7a shows the interface screen for taking into account by processing one or more test data. The data that are evaluated one by one can be selected out of the account if desired. As seen in Figure 7b, the flow stress parameters of the selected test are determined on the coefficient evaluation screen. Here, the file we receive from the test device is selected with the "Browser" and the data received are processed and the coefficients of the model are found. Since the tests are carried out with a large number of samples, separate evaluations can be made for each of them and the desired test can be included in the evaluation. The nonlinear least squares formulation is used when fitting the curve. The process gives an estimate of the model coefficients as a result of the curve fitting process. The least squares method used to obtain the coefficient estimates applies an iterative procedure that minimizes the total square of the residuals. Curve fitting requires a parametric model selection that relates the response data to the prediction data with one or more coefficients. In accordance with the form, we want the model, "a Two-Term Power Series Model" for Johnson-Cook parameters and "a Single-Term Power Series Model" for Holloman parameters were used.

Robust least-squares fitting method, least absolute residue structure, curve fitting by minimizing the total square of residues, select parameter coefficients determined according to the largest R-squared value resulting in the case of choosing "Trust-Region" or "Levenberg-Marquardt" algorithm. The R-squared is a statistical measure of how close the data is to the fit regression line. It is also known as the coefficient of determination or the multiple coefficients of determination for multiple regression. In general, it can be said that the higher the R-square, the better the selected model fits your data.

In Figure 7b, both the flow stress values and the values of some critical points, obtained from the calculated data, are given. Both finding critical points in strain-stress curves of materials with many different structures and very variable data vibrations / oscillations make it difficult to calculations of critical points. A few peaks of vibration greatly affect the finding the location of these critical points. Using a few close data values and limited by tolerance criteria, the slope of the curve is calculated. All critical points on the stress-strain curve are controlled by the program from the end to the beginning and from the beginning to the end. These locations can also be determined by the user, in case of doubt about the location of the critical points found. If different devices can be used to find strain from extension values such as grips that hold the sample, then extensometers such as video extensometers can also be selected from the program screen. If the flow stress parameter constants are to be estimated according to Misses stresses and equivalent plastic strain, it is naturally easier to process the regular data coming from the simulation and to locate the critical points (Figure 7c).



(a) (b)

(c)

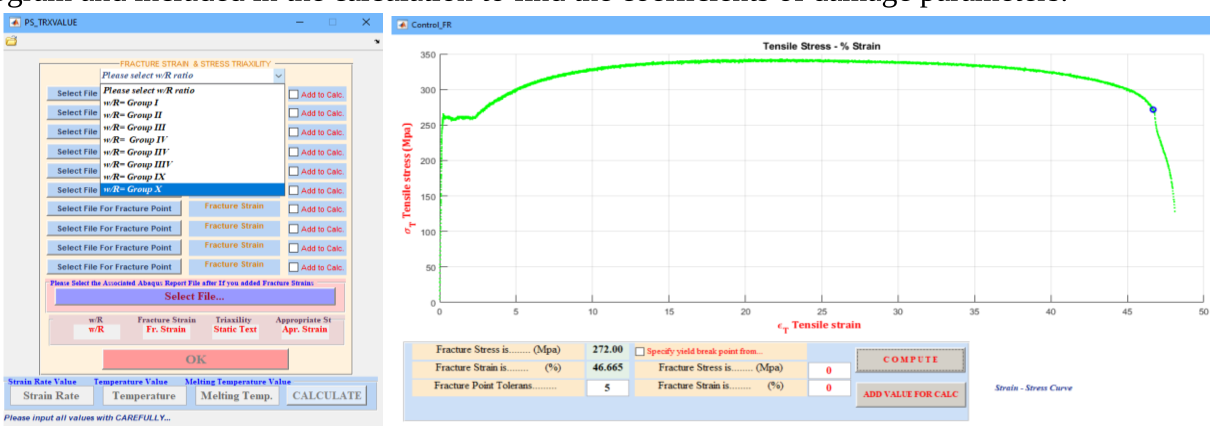
Figure 7. Interface of evaluation and input determination for flow stress parameters

The data belonging to the tests performed for each temperature and strain rate selected for the parameters are processed by the linear regression procedure and the values of C strengthening coefficient of the strain rate (Figure 8a) and m thermal softening coefficient (Figure 8b) are found. All parameters of the tests used to find the constants and the values of the critical points can be monitored by selecting the relevant graphic. In Figure 5. if you want to make optimization as seen in the main interface, the program uses the find minimum of constrained nonlinear multivariable function, for the default interior-point algorithm, from lower bound to upper bound. New strengthening coefficient of the strain rate and m thermal softening coefficient values it replaces the old values on interface screen.

(a) (b)

Figure 8. Interface for strengthening coefficient of the strain rate(C) and thermal softening coefficient(m)

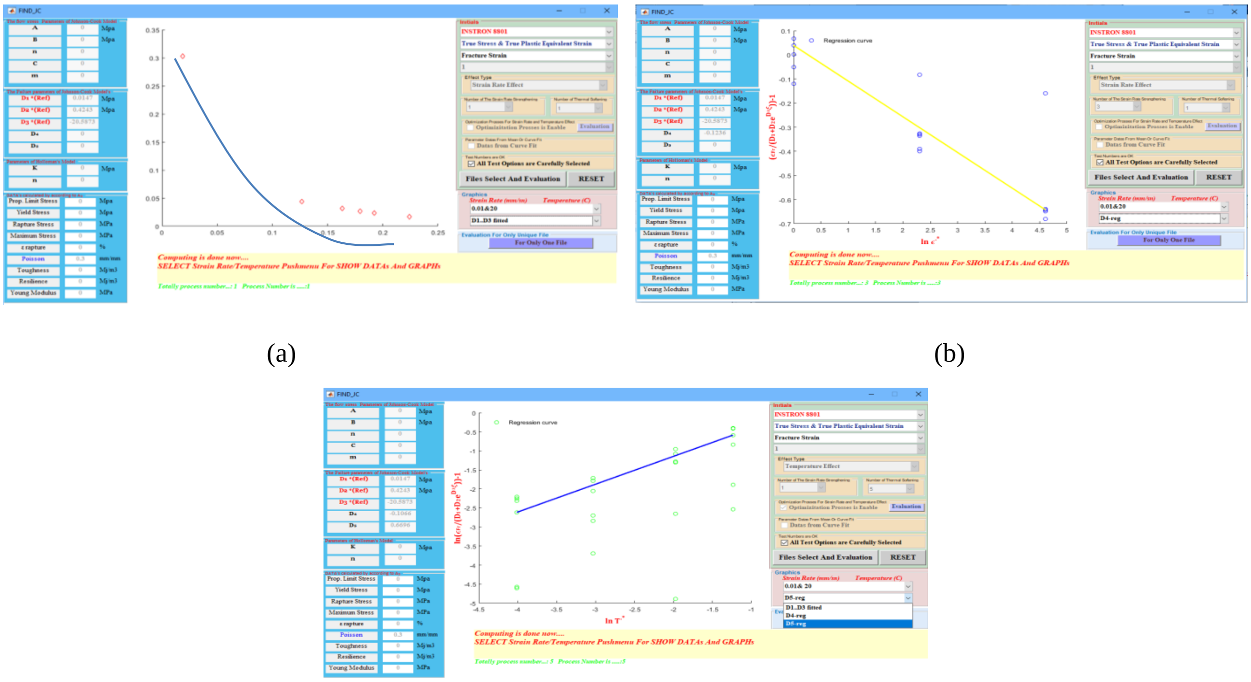
Johnson-Cook defined the damage parameters depending on the stress triaxiality, strain rate and temperature to obtain the fracture strain. Five parameter constants help us solve the fracture strain with a simply defined formula. The test results are evaluated by applying tensile test at different strain rate and under different temperatures on specially prepared test samples for these parameters. A large number of test data taken for different group tests are entered into the program as in Figure 9a. Any number of tests belonging to the specified group can be included or removed from the calculation. When the test file is selected, it is found automatically by following the slope of the fracture strain graph in the interface (Figure 9b). Finding a specific point from thousands of data belonging to the test can sometimes be erroneous due to peak vibrations occurring in the device. The user can determine the fracture strain point within the narrow area limited by intervening in the graphical inclination control tolerance when desired. Parameters are obtained by evaluating the fracture strain and stress triaxiality values at this moment, automatically or determined by the user. For the stress triaxiality that cannot be obtained from the tensile test, the simulation is referred. As seen in Figure 9-a, after the test results are entered into the program and the fracture strain is determined. The stress triaxiality matching the fracture strain is found from the report file coming from the simulation program and included in the calculation to find the coefficients of damage parameters.



(a) (b)

Figure 9. Main interface for damage parameters and fracture strain point finding interface in tests

Damage parameter constants $D_{1\text{-}3}$ are found by curve fitting procedures using the test results and simulation report results that coincide with these results (Figure 10a). Here, as applied to find flow stress parameters, it determines the parameter coefficients for the maximum controlled R-square value using different algorithm options. The R-squared is the measure of how close the curve is to the regression line formed by the parameters found. The largest R-squared value shows the option for the selected model that best fits the experimental data. Regression procedures are applied to find the strain rate parameter constant, D_4 and temperature parameter constant D_5 (Figure 10b, c). The constants are the slope of the curve that is drawn in case of temperature or strain rate change. If desired, after finding $D_{4.5}$, optimization can be applied as in the option of determining the stress strengthening coefficient and thermal softening coefficient in the flow stress parameters (Figure 5).



(a) (b)

(c)

Figure 10. Interfaces for damage parameters ($D_{1.5}$)

4. CONCLUSION

One of the most well-known parametric models representing the stress-strain relationship and fracture strain of metallic materials used in simulation programs is Johnson-Cook's model. They defined this relationship in a simple form for large deformation conditions, high strain rate and elevated temperature. However, obtaining the JC parameter coefficients of a material is a very time-consuming process. It is a complex task, respectively, to prepare test samples with different geometries in the workshop, to apply many tests in the laboratory, to organize test data and simulation reports in different formats, to process them together in a mathematical program. This program has been designed to make the study easier in this process and to enter data in an order to estimate JC stress flow and JC ductile damage model parameters, and when required, curve fitting, optimization and regression procedures are applied using algorithms to obtain the most optimal results. The program has been tested with the different types of test results we have designed, and it has been observed that it has effective data entries and satisfactory results. As with every program, it will need to be updated in accordance with the feedbacks of the users and with different details.

5. ACKNOWLEDGEMENTS

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6. CONFLICT OF INTEREST

Author approve that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper.

7. AUTHOR CONTRIBUTION

Ahmet ÇETKİN has the full responsibility of the paper about determining the concept of the research, data collection, data analysis and interpretation of the results, preparation of the manuscript and critical analysis of the intellectual content with the final approval.

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