

Calibration and verification of the Johnson-Cook model for an austenitic steel under dynamic tension

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ABSTRACT

The paper presents the results of research on the properties of an austenitic steel used in the shipbuilding industry. Static tensile tests were conducted using an MTS testing machine, while dynamic tensile tests were carried out with rotary hammer at strain rates ranging from 250 to 2100 s⁻¹. The obtained results were used to calibrate a Johnson-Cook model and the corresponding failure parameters suitable for finite element method (FEM) analysis. This model was then used to simulate the response of the specimen subjected to impact loading at various strain rates.

Keywords: austenitic steel, static tensile test, dynamic tensile test, rotary hammer, plastic characteristics, strain rate, material model in terms of FEM, CAE.

INTRODUCTION

In today's reality, conducting numerical simulations has become a standard in the process of creating modern structures. They allow us to customise the entire structure to predictable operating conditions, as well as optimise our product at the construction stage.

Numerical simulations owe their popularity primarily to the speed of obtaining relatively accurate results, which would be time-consuming to obtain by the analytical method and costly to obtain by the experimental method.

The notion of dynamic processes, due to its complex nature, is highly demanding. Therefore, extensive and reliable material studies are a key element. An appropriate description of material properties enables numerical simulations to be carried out as close as possible to reality, while minimising errors in the obtained results.

The Johnson–Cook (JC) model remains a standard for describing the response of metals under large strains, high strain rates, and elevated temperatures. However, its parametrisation and reliability are still the subject of intensive research. For structural steels, Yendluri et al.

(2023) presented a complete identification of the ten JC parameters (strength and damage) for E250 steel, covering an extensive experimental programme (quasi-static tests, Split Hopkinson Pressure Bar (SHPB), a range of stress triaxialities η_{TRLAX} and temperatures) and rigorous validation with independent tests, underscoring the need for a holistic approach to model calibration in impact and blast applications [1]. In parallel, comparisons and modifications of the JC formulation are being pursued. For tool steels, it has been shown that a modified JC (MJC) and Arrhenius-type models can outperform the classical JC across broad thermomechanical regimes, especially where strain- or thermal-softening strongly affects the flow stress [2]. In aluminium matrix composites, where degradation leads to softening, it has been proposed to augment JC with a damage-induced softening term, improving agreement with σ - ϵ curves at high strain rates [3]. For austenitic steels, Jiang et al. (2024) performed an inverse identification of JC parameters for 304 steel using genetic algorithms and 3D cutting simulations, showing that application-driven optimisation (process-loading conditions) can substantially reduce force-prediction

errors and better reflect service conditions than parameters obtained solely from quasi-static/SHPB tests [4]. Taken together, these studies confirm that JC identification should span the full strain-rate range relevant to the intended application, along with the corresponding temperatures. Moreover, model modifications or extensions of damage evolution are often necessary when softening is observed. Additionally, in the work of Guo and Nemat-Nasser on Nitronic-50 steel, based on uniaxial compression tests, a strong dependence of the flow (yield) stress on strain rate (up to $\sim 8 \times 10^3 \text{ s}^{-1}$) and temperature (77–1000 K) was demonstrated, including the presence of dynamic strain ageing (DSA) in the range 400–1000 K (most pronounced at low rates and diminishing at higher rates), as well as an increasing role of viscous resistance to dislocation motion at $\dot{\epsilon} = 10^3 \text{ s}^{-1}$. The authors also distinguished adiabatic and isothermal responses at high rates, confirmed by measuring and analyzing differences in the stress–strain curves[5]. Against this backdrop, the present work provides a set of JC parameters for an austenitic steel over the strain-rate range relevant to rapidly changing processes (impacts, wave interactions), together with combined numerical–experimental validation aimed at finite-element (FE) applications and may serve as a basis for follow-on studies involving comprehensive parameter identification across other stress states and temperatures.

Despite major advances in constitutive modelling of materials, physics-based models are still insufficiently advanced to capture the full complexity of the dynamic response of metals.

The present study addresses this need by focusing on an austenitic steel used in ship structures and presenting a consistent calibration and verification workflow for FE applications. The novelty lies in the use of a unique rotary-hammer test rig to perform dynamic tension over a wide strain-rate range of 250–2100 s^{-1} , which bridges the measurement gap between classical quasi-static testing and very high rates, while better reflecting the service conditions of thin-walled hull components. From a marine applications viewpoint, the calibrated JC model is directly useful for analyses of structural resistance to impact and shock loading. A consistent perspective is presented in [6], where the Johnson–Cook model was also used to describe a non-magnetic steel and the dynamic characteristics were obtained from static and dynamic tests.

Austenitic steels owe their popularity to properties such as corrosion resistance, high strength at relatively low weight and, above all, amagnetism [7–9]. Due to these properties, they are widely used in the chemical, energy, medical, aerospace and food industries [7–10]. Austenitic steels are also increasingly used in the defence industry, especially in the construction of modern mine destroyers (Figure 1) and submarines. The reason for this is the demanding environmental conditions, such as high humidity, elevated temperatures and the impact loads caused by the detonation of explosive charges for which the strain rates reach over 10^4 s^{-1} [6, 8, 11–15].

In response to the increasing use of austenitic steels in the marine industry, especially in the context of military structures, static and dynamic material tests were carried out to determine the material characteristics in the Johnson-Cook model. A properly developed model allows for implementation in numerical simulations using the finite element method, providing an effective tool for assessing the resistance of structures, especially in the context of ship hulls. Computer simulations enable the conducting detailed analyses of resistance to impact loads, providing an alternative to risky physical experiments that would involve high costs and potential damage to the test object, thus generating significant economic losses.

MATERIAL AND SAMPLES FOR TESTS

Standardised specimens were prepared from austenitic steel material for quasi-static tensile tests on a MTS 810-02 tensile testing machine according to PN-EN ISO 6892-1:2020-5 [17] (Figure 2a). Austenitic steel is suitable for contact with seawater. It is characterised by its non-magnetic properties and resistance to intergranular corrosion [7–9, 11]. To perform the dynamic tensile test on a rotary hammer, threaded circular specimens were made with a working-part diameter of 5 mm and a length of 40 mm (Figure 2b).

Static tensile test

After preparing the specimens and collecting initial measurements, in accordance with the norm (Figure 3) the steel specimens – with a cross-sectional area of 8 mm² and an original gauge length of 40 mm – were subjected to static tensile test



Figure 1. German Frankenthal class mine destroyer made of austenitic steel [16]

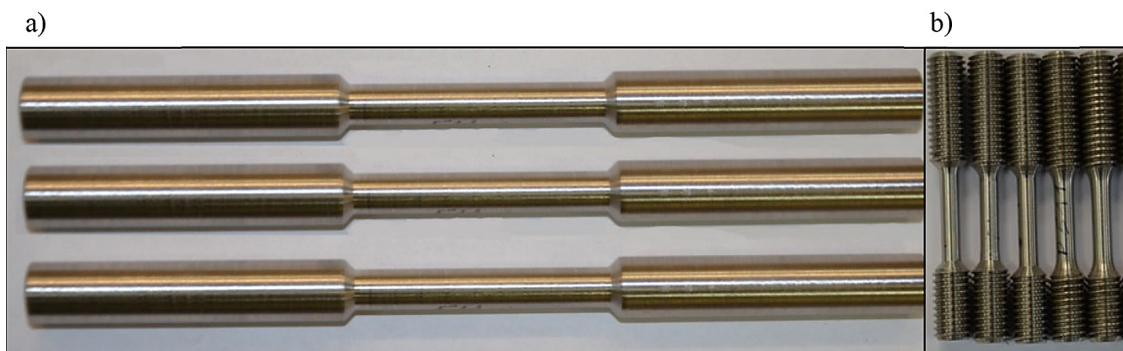


Figure 2. Specimens of tested steel for a) static and b) dynamic tests

and based on the results obtained, nominal stress-strain diagrams were created, taking into account the constant cross-sectional area of the specimen – S_0 throughout the whole process (Figure 4).

Based on the results obtained, a Young's modulus of $E = 191.87$ GPa was determined in the elastic range. In addition, the nominal values of the conventional yield strength R_e of 980 MPa and the tensile strength R_m of 1080 MPa can be estimated.

Test of dynamic mechanical properties on a rotary hammer

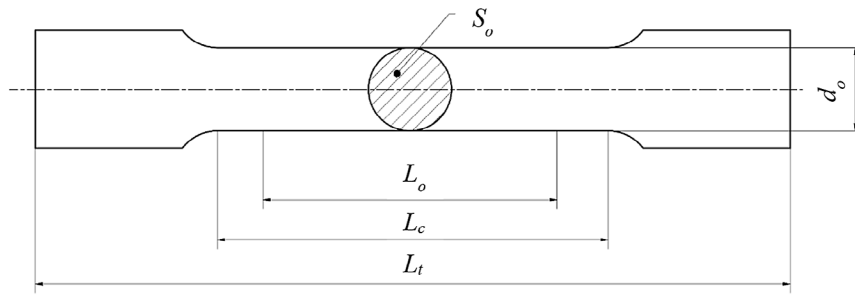
The plastic behaviour of the material under short-duration deformation was investigated using a unique rotary hammer station located at the Laboratory of Fundamentals of Technology at the Polish Naval Academy. The device (Figure 5)

enables the acceleration of the flywheel to a peripheral linear velocity ranging from 10 to 50 m/s. The strain rate is determined as the ratio of the specimen's fracture velocity to its gauge length [12, 15, 18].

$$\dot{\epsilon} = \frac{d\epsilon}{dt} = \frac{d}{dt} \left(\frac{v \cdot t}{l} \right) = \frac{v}{l} \quad (1)$$

Summarizing the above, for a specimen with a gauge length of 20 mm, the corresponding strain rates achieved range from $250 \div 2100 \text{ s}^{-1}$.

The instrumentation integrated with the rotary hammer stand captures the fracture force of the specimen at strain rates ranging from 250 to 2100 s^{-1} . These measurements are subsequently used to calculate the true stress values associated with the ultimate tensile strength – $R_{m, \text{true}}$ (Table 1).



S_o – original diameter of the parallel length of circular test specimen;
 L_c – parallel length;
 L_o – original gauge length;
 L_t – total length of test specimen;
 d_o – original cross-sectional area of the parallel length.

Figure 3. Initial measurements for circular specimens

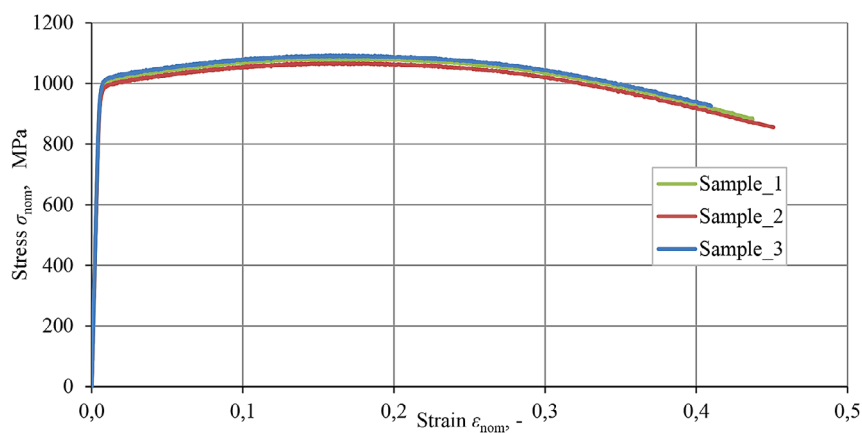


Figure 4. The results of tensile test – nominal charts of tested steel

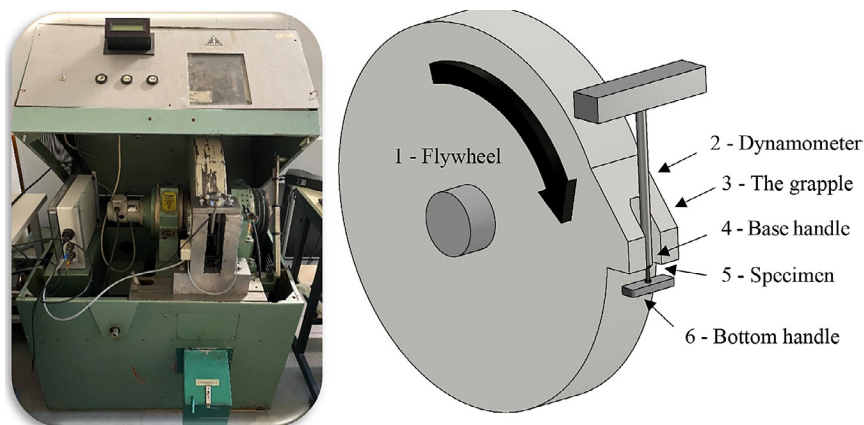


Figure 5. Rotary hammer test stand and its main components: 1 – flywheel, 2 – dynamometer, 3 –grapple, 4 – base handle, 5 – specimen, 6 – bottom handle

True characteristics as a function of plastic strain in austenitic steel

The relationship between the true stress σ_{true} and the nominal stress σ_{nom} is derived from the assumption that the volume of the tensile

specimen remains constant under tension, such that $l_0 A_0 = l A(F)$. Hence

$$\sigma_{true} = \frac{F}{A(F)} = \frac{F}{A_0} \frac{l}{l_0} = \sigma_{nom} \left(\frac{l}{l_0} \right) \quad (2)$$

Table 1. Overview of results obtained from rotary hammer tests

Specimen designation	φ	Measuring Length, L_0	Area, A_0	Breaking Force, F_m	Hammer Rotational Speed, n_{mola}	Strain Rate	True Dynamic Ultimate Strength, $R_{m, \text{true}}$
	mm	mm	mm ²	kN	m/s	s ⁻¹	MPa
Specimen_1	4.92	19.97	19.00	40.00	5	250	2105.263
Specimen_2	4.94	18.82	19.16	41.60	10	530	2171.19
Specimen_3	5.1	18.35	20.42	45.00	15	815	2203.722
Specimen_4	5.05	16.26	20.02	48.88	30	1845	2441.558
Specimen_5	4.94	19.08	19.16	49.20	40	2095	2567.85

Since

$$\frac{l}{l_0} = 1 + \varepsilon_{\text{nom}} \quad (3)$$

Therefore

$$\varepsilon_{\text{true}} = \ln(1 + \varepsilon_{\text{nom}}) \quad (4)$$

$$\sigma_{\text{true}} = \sigma_{\text{nom}}(1 + \varepsilon_{\text{nom}}) \quad (5)$$

The true strain $\varepsilon_{\text{true}}$ is composed of the sum of the elastic strain ε_{el} and the plastic strain ε_{pl} . Consequently, the plastic strain can be expressed as follows:

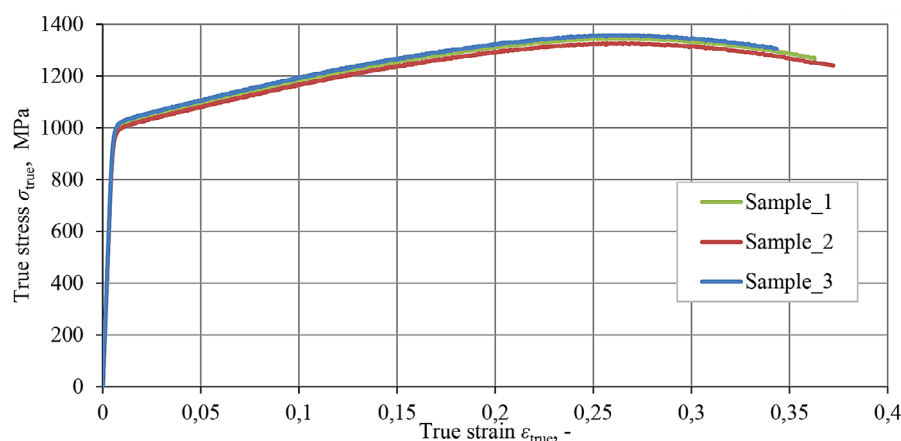
$$\varepsilon_{\text{pl}} = \varepsilon_{\text{true}} - \varepsilon_{\text{el}} = \varepsilon_{\text{true}} - \frac{\sigma_{\text{true}}}{E} \quad (6)$$

where: F – tensile force applied to the specimen, $A(F)$ – current cross-sectional area, A_0 – original cross-sectional area in the gauge section, l – current gauge length, l_0 – original gauge length, ε_{nom} – nominal strain, E – Young's modulus.

Using the above equations, the true and plastic stress-strain curves were determined for the tested specimens of the investigated austenitic steel (Table 2) (Figure 6, 7).

Based on the material properties and the intended service conditions of the austenitic steel under investigation, a review of the literature [19] was conducted. It was determined that the material most similar to the one under study is an austenitic steel designated X7CrNiAl17-7. The chemical composition of this material is presented in Table 3.

In CAE software, the plastic behaviour of materials is commonly described using polynomial functions, where the true stress is expressed as a function of plastic strain, strain rate and temperature $\sigma_{\text{true}} = \sigma_{\text{true}}(\varepsilon_{\text{pl}}, \dot{\varepsilon}, \theta)$. A widely adopted approach, describing plastic behaviour of metals, is Johnson-Cook constitutive model [18, 20], in which the plastic Huber-Mises-Hencky (HMH) reduced stresses σ_{pl} are described by the following equation [12, 15, 18–22]:


Figure 6. True characteristics $\sigma_{\text{true}} - \varepsilon_{\text{true}}$ of investigated steel

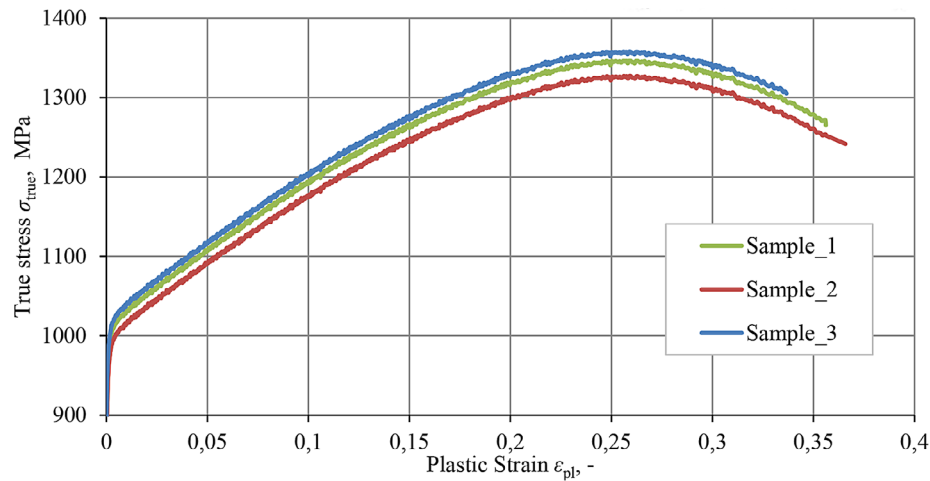


Figure 7. Plastic characteristics $\sigma_{true} - \epsilon_{pl}$ of investigated steel

Table 2. Summary of true material properties derived from Equations 2÷6

Sample designation	Young's modulus	Conventional Yield Strength (YS)	Strain at YS	Ultimate Tensile Strength (UTS)	Strain at UTS	Proportional limit
	E GPa	$R_{0.002}$ MPa	$\epsilon_{0.002}$ -	R_m MPa	ϵ_m -	$A=\sigma_{pl}=0$ MPa
Sample_1	191.05	987.80	0.007	1346.26	0.2630	908.02
Sample_2	188.93	980.66	0.007	1327.22	0.2620	895.06
Sample_3	195.65	1003.20	0.007	1357.70	0.2641	915.45
Average	191.87	990.55	0.007	1343.87	0.2630	906.18

Table 3. Percentage chemical composition of austenitic steel X7CrNiAl17-7 [19]

C	Si	Mn	P	S	Cr	Al	Ni
max. 0.09	max. 0.7	max. 1.0	max. 0.04	max. 0.015	16 to 18	0.7 to 1.5	6.5 to 7.8

$$\sigma_{pl} = (A + B\epsilon_{pl}^n) \left[1 + C \ln \left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right) \right] \left[1 - \left(\frac{\theta - \theta_0}{\theta_{top} - \theta_0} \right)^m \right] \quad (7)$$

where: A – elastic range of the material $\sigma_{pl} = 0$ (common simplification $A=R_e$); B – hardening parameter; n – hardening exponent; C – strain rate coefficient; ϵ_{pl} – true plastic strain; $\dot{\epsilon}$ – strain rate; $\dot{\epsilon}_0$ – quasi-static strain rate 0.0001 s^{-1} ; θ – current material temperature; θ_0 – ambient temperature; θ_{top} – melting temperature; m – thermal softening exponent.

The individual parameters of the Johnson-Cook model are determined based on experimental data. The values corresponding to the first

term of the equation are obtained from the results of static tensile tests. To identify the parameters related to the strain rate sensitivity in the second term of the model, data from rotary hammer dynamic tensile tests were utilized.

The determination of the Johnson-Cook model parameters A , B , C , n and m can be performed using several methods [23]. One commonly applied method is the so-called engineering method, in which the parameters in the first term of the model – A , B , n – are derived from static tensile test data using the following relationships:

- Based on the obtained nominal characteristic $\epsilon_{nom} - \sigma_{nom}$, parameters R_m , ϵ_m , E and as well as the value of parameter A – indicating the end of the proportionality limit – were determined;
- Subsequently, using Equations 4, 5 i 6 $R_{e,true}$, $R_{m,true}$, $\epsilon_{m,true}$, $\epsilon_{m,pl}$ were calculated;

$$\begin{aligned} A &= \sigma_{pl=0} \\ R_{m,true} &= R_m(1 + \varepsilon_m) \\ \varepsilon_{m,true} &= \ln(1 + \varepsilon_m) \end{aligned} \quad (8)$$

$$\varepsilon_{m,pl} = \varepsilon_{m,true} - \frac{R_{m,true}}{E}$$

- Determine the parameters B and n in accordance with the specified equations;

$$\begin{aligned} n &= \frac{R_{m,true} \cdot \varepsilon_{m,pl}}{R_{m,true} - A} \\ B &= \frac{R_{m,true} - A}{\varepsilon_{m,pl}^n} \end{aligned} \quad (9)$$

Utilizing the average values reported in Table 2, and applying Equations 8 and 9, the coefficients associated with the first term of the Johnson-Cook (JC) constitutive model were determined as follows:

$$A = 906.18 \text{ MPa}, B = 1277.32 \text{ MPa}, n = 0.786$$

Using the aforementioned values, the true characteristic was compared with the JC model prediction as shown in Figure 8.

Owing to significant discrepancies between the true characteristic and the JC model predictions, it was necessary to revise the parameters of the first term of the constitutive equation. The yield strength was adopted as parameter A, while the remaining coefficients were recalculated using Equations 9. As a result, agreement between the true curve and the JC model improved substantially, with a maximum deviation of approximately 6.3% (Figure 9).

The averaged true stress–strain data from the examined cases were used to plot the linear relationship for $\ln(\sigma - A)$ in accordance with equation (10). A linear regression model was fitted to the data, as shown in Figure 10.

$$\ln(\sigma - A) = n \ln \varepsilon + \ln B \quad (10)$$

A coefficient of determination (R^2) exceeding 0.976 was obtained for the final linear fit (Figure 10), indicating excellent agreement between the regression model and the data.

Finally, the coefficients for the first term of the Johnson–Cook constitutive model were determined from the data in Table 2 using Equation 9, as follows:

$$A = 990.55 \text{ MPa}, B = 1095.803 \text{ MPa}, n = 0.756$$

To determine the parameter C, it is essential to know the value of $R_{m,true}(\dot{\varepsilon})$ corresponding to a specific strain rate. The required data were obtained through dynamic tensile testing conducted using a rotary hammer, as shown in Table 4.

By transforming Equation 11, the following expression is derived:

$$C = \left(\frac{R_{m,true}(\dot{\varepsilon})}{R_{m,true}(\dot{\varepsilon}_0)} - 1 \right) / \ln \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \quad (11)$$

The calculated values of the constant C are summarized in Table 4. A constant value of $C = 0.044$ was adopted for further analysis. Figure 11 presents the true tensile strength as a function of strain rate $R_{m,true}(\dot{\varepsilon})$, based on the assumed value of the parameter C.

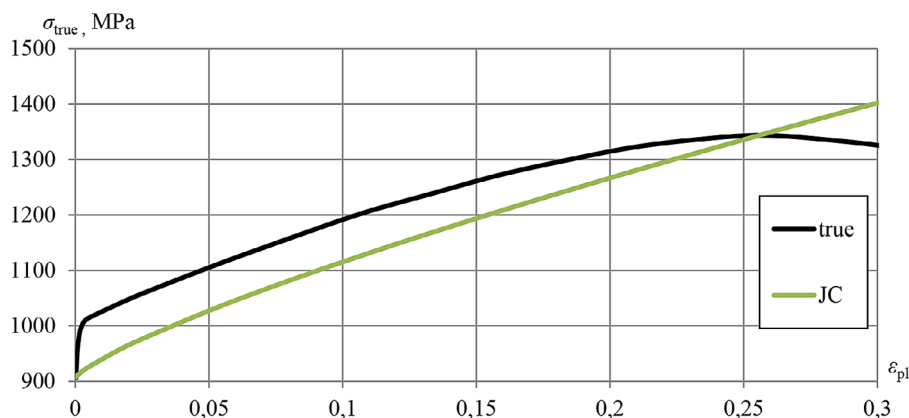


Figure 8. True characteristics and JC for the tested steel

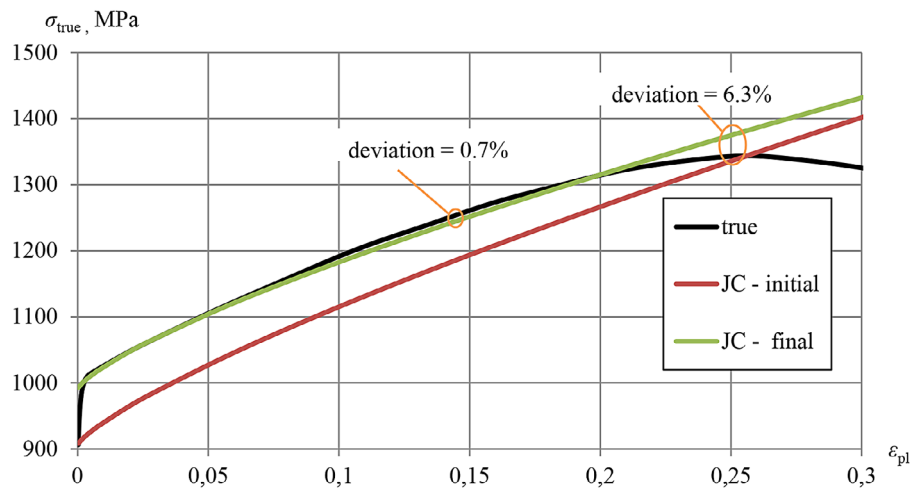


Figure 9. True characteristics with the initial and final JC model curves for the tested steel

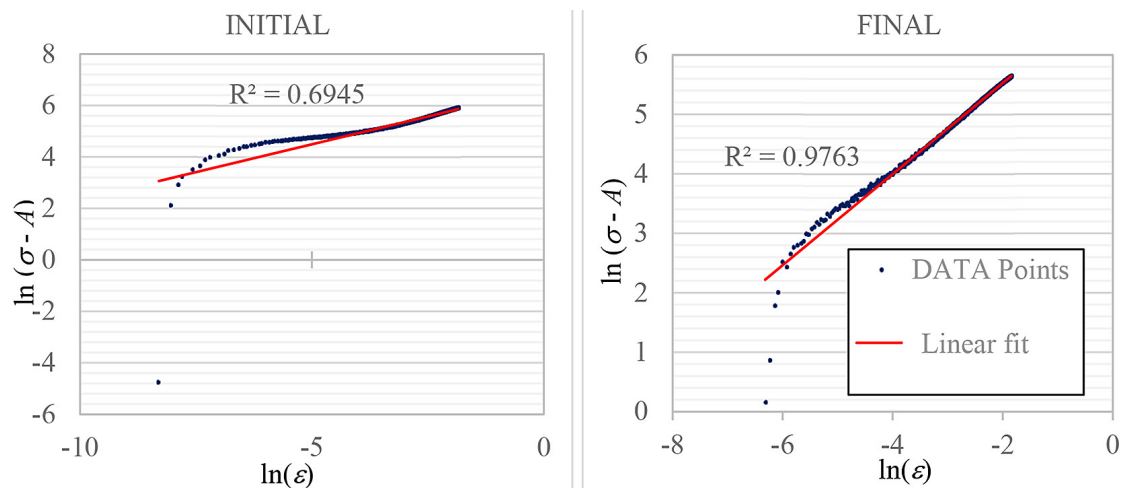


Figure 10. $\ln(\sigma - A)$ and $\ln \epsilon$ relationship under reference conditions for initial and final parameters

Table 4. Tensile strength corresponding to specific strain rates $R_m, \dot{\epsilon}$

Strain rate	$\dot{\epsilon} = 250 \text{ s}^{-1}$	$\dot{\epsilon} = 530 \text{ s}^{-1}$	$\dot{\epsilon} = 815 \text{ s}^{-1}$	$\dot{\epsilon} = 1845 \text{ s}^{-1}$	$\dot{\epsilon} = 2095 \text{ s}^{-1}$
$R_{m, \text{true}, \dot{\epsilon}}, \text{ MPa}$	2105.04	2171.55	2203.95	2441.62	2568.28
Coefficient C	0.03844754	0.039778	0.040217503	0.048824221	0.054047125

Figure 12 compares the JC plastic characteristics as a function of strain rate for the selected value of the strain rate coefficient C .

Figure 12 shows the influence of the Johnson–Cook strain-rate coefficient C on the material response as a function of strain rate, considering the first and second terms of Equation 7 and compares this with the experimental true stress–strain characteristic derived from Equation 5. The separation between the curves corresponding to different strain rates is approximately constant with plastic strain, which correctly reflects the trend

and scale of the strain rate effect, shifts the curves toward higher stress values.

The third term of the equation accounts for the influence of temperature on the material's plastic behaviour. To determine the parameter m , static tensile tests should be conducted at elevated temperatures to obtain the tensile strength at the test temperature $R_m(\theta)$. In addition, the material's melting point, θ_{top} , is required. The required values were obtained from the literature [24–27]. The following values were selected for the analysis:

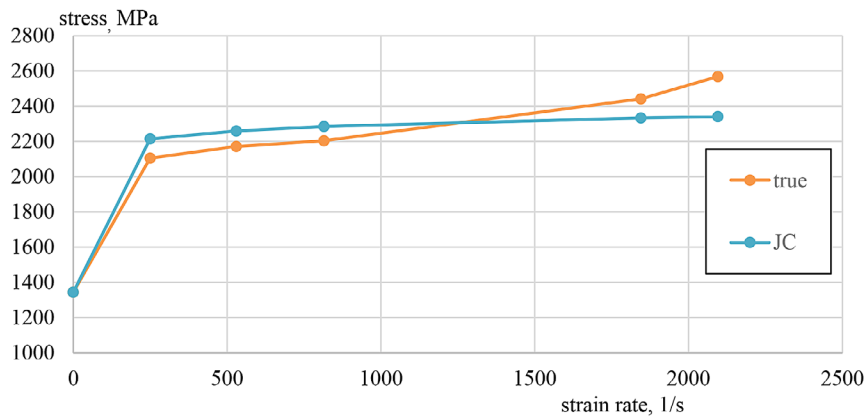


Figure 11. True tensile strength R_m as a function of strain rate for $C = 0.044$

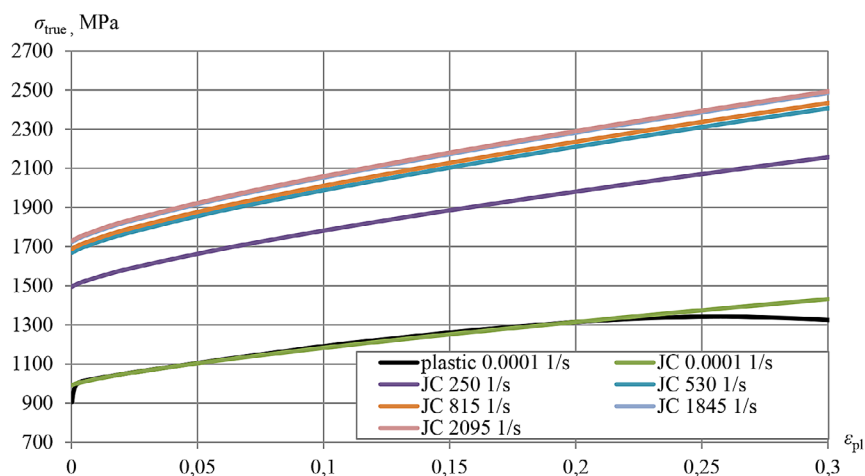


Figure 12. JC Model for austenitic steel as a function of strain rate with $C = 0.044$

Melting point $\theta_{\text{top}} = 1653.15 \text{ K}$; Tensile strength $R_m = 648 \text{ MPa}$ at a temperature of 698.15 K ; Tensile strength $R_m = 469 \text{ MPa}$ at a temperature of 1003.15 K .

Using the relationship between the tensile strength at elevated temperature and the tensile strength at room temperature for a strain rate of 0.0001 s^{-1} , as defined by the following equation:

$$R_{m,\theta} = R_{m,0} \cdot \left[1 - \left(\frac{\theta - \theta_0}{\theta_{\text{top}} - \theta_0} \right)^m \right] \quad (12)$$

After applying the transformation, the following expression is obtained:

$$m = \frac{\ln \left(1 - \frac{R_{m,\theta}}{R_{m,0}} \right)}{\ln \left(\frac{\theta - \theta_0}{\theta_{\text{top}} - \theta_0} \right)} \quad (13)$$

Substituting the relevant data into the equation yielded the values of the thermal plasticity

exponent m at the temperatures considered. These values are summarised in Table 5.

Figure 13 illustrates the temperature-dependent behaviour of the steel at strain rate of 0.0001 s^{-1} .

Failure model for austenitic steel

Plastic failure is governed by the existing stress state, commonly characterised by the tri-axiality factor η_{TRIAX} [21, 28, 29]. This parameter depends on the orientation of the forces applied to the structural element. For uniaxial tension, a tri-axiality factor of $1/3$ was adopted [30]. The

Table 5. Values of parameter m calculated for selected temperatures

Temperature, K	Value of parameter, m
698.15 (425°C)	0.77
1003.15 (730°C)	0.88
Average value m	0.83

the material. The value $d = 0$ denotes the state at which the (flow) stress has reached the ultimate tensile strength R_m , but no degradation has occurred, whereas $d = 1$ corresponds to complete degradation of the material. The state of damage evolution is expressed as a function of the plastic displacement μ_{pl} , defined as follows [24]:

$$u_{pl} = L \varepsilon_{pl} \quad (15)$$

where: L is the characteristic length of the FEM element.

The progression of material degradation is described by the damage-evolution coefficient. In CAE practice, three alternative formulations are commonly used: linear, exponential, and tabulated. The linear form is defined as the ratio of plastic displacement u_p to failure displacement $u_{failure}$ [29]

$$d = \frac{u_{pl}}{u_{failure}} \quad (16)$$

Table 6 summarises the characteristic points shown in Figure 14 that were used to determine the material's failure parameters.

Determination of failure parameters for austenitic steel for $\eta_{TRIAX} = 0.33$ (uniaxial tension) where L defines the size of the FEM mesh.

In summary, all parameters characterising the tested steel can be effectively described by the Johnson-Cook model.

$$\sigma = (990.55 + 1095.803 \cdot \varepsilon^{0.756}) \cdot \left[1 + 0.044 \cdot \ln \left(\frac{\dot{\varepsilon}}{0.0001} \right) \right] \cdot \left[1 - \left(\frac{\theta - 293.15}{1360} \right)^{0.83} \right]$$

Failure parameters: $d = 0.1648$; $\varepsilon_{failure} = 1.334$; $\eta_{TRIAX} = 0.33$; $A = 990.55$ MPa; $B = 1095.803$ MPa; $n = 0.756$; $m = 0.83$; $C = 0.044$; $\theta_0 = 293.15$ K; $\theta_{top} = 1653.15$ K; Young's modulus – $E = 1.91 \cdot 10^{11}$ Pa; Poisson's ratio – $\nu = 0.28$; Density – $\rho = 7880$ kg/m³; Ultimate tensile strength – $R_m = 1343.87$ MPa; Yield strength – $R_e = 990.55$ MPa.

Reproduction of the experiment using numerical simulation

Based on the calibrated material parameters, a numerical analysis was performed using the ABAQUS – Dynamic Explicit procedure to compare the experimental results with the simulation responses. The specimen geometry from the rotary hammer was accurately reproduced using 62,510 linear eight-node hexahedral elements, defined by 67,402 nodes. The characteristic element size was

$$\begin{aligned} \varepsilon_{failure} &= \varepsilon_4 - \varepsilon_7 = 1.59 - 0.256 = 1.334 \\ d\bar{\sigma} &= \sigma_5 - \sigma_3 = 1478.69 - 1234.97 = 243.72 \text{ MPa} \\ \text{since } \sigma &= (1 - d)\bar{\sigma} \text{ so, } d = 1 - \frac{\sigma}{\bar{\sigma}} = 1 - \frac{1234.97}{1478.69} = 0.1648 \\ E' &= (1 - d)E = (1 - 0.1648) \cdot 191.87 = 160.24 \text{ GPa} \\ u_{failure} &= 1.334 \cdot L \end{aligned}$$

Table 6. Summary of values used to calculate failure parameters based on Figure 14

Point No.	Strain	Stress	Description
	ε_e , -	σ_{true} , MPa	
H	0.0049	906.19	Limit of the proportionality $\sigma_H = \sigma_{pl=0}$
1	0.007	990.55	Yield strength R_e
2	0.263	1343.87	Tensile strength R_m
3	0.3595	1234.197	Fracture point
4	1.59	0.0	Total material degradation $d = 1$
5	0.3595	1478.69	Stress behaviour in a damage-free material model
6	0.3517	0.0	Strain after fracture
7	0.256	0.0	Strain after reaching the ultimate tensile strength R_m , $d = 0$

set at $L = 0.5$ mm. The following boundary conditions were applied: the upper end of the specimen was fully fixed in all degrees of freedom, while the lower end was constrained against lateral displacements and subjected to a prescribed axial kinematic condition to achieve the target engineering strain rate. No grips were modelled. The axial motion was applied directly to the end face of the specimen. Therefore, no surface-to-surface contact or friction was defined. The total simulated time was set as 2×10^{-3} s for $\dot{\epsilon} = 250$ s $^{-1}$ and 2×10^{-4} s for $\dot{\epsilon} = 2095$ s $^{-1}$. The explicit time-step size was limited by the smallest element size and the elastic (acoustic) wave propagation velocity in the tested material. In this case, the maximum time-step size was 2.36×10^{-8} s.

The previously developed Johnson-Cook material model, including the failure model, was assigned to the reconstructed specimen geometry. Subsequently, both static and dynamic tensile tests on the rotary hammer were simulated, applying strain rates of $\dot{\epsilon} = 250$ s $^{-1}$ and $\dot{\epsilon} = 2095$ s $^{-1}$. The results for $\dot{\epsilon} = 250$ s $^{-1}$ are presented in Figure 15.

The numerical simulation results are shown in Figure 16.

The principal stress values obtained for the simulated strain rates are consistent with those predicted by the JC model. The simulated material

strength is approximately 9% higher than the values recorded in the dynamic tensile test at a strain rate of $\dot{\epsilon} = 250$ s $^{-1}$, and approximately 6.5% higher than those from the static tensile test.

This discrepancy is primarily attributed to the use of an average value of the parameter C within the tested strain rate range (Figure 11), as well as geometric simplifications arising from the discretisation of the specimen. It should be noted that, in the case of static loading, a more accurate representation could be achieved by using data obtained directly from the measuring equipment of the testing machine.

Additionally, the strength of the specimen in the simulation performed at a strain rate $\dot{\epsilon} = 2095$ s $^{-1}$, using the assumed JC model coefficients, is approximately 12% lower than the values obtained from the dynamic tensile test. As shown in Figure 16, an increase in strain rate leads to a wave-like pattern of stress propagation and noticeable heterogeneity in material hardening. Despite these dynamic effects, the results are within an acceptable range, confirming that the developed JC model is suitable for simulating more demanding structures made from the tested material.

The simulation was conducted using two different mesh discretisation methods, as illustrated in Figure 17. The choice of discretisation significantly influences the distribution

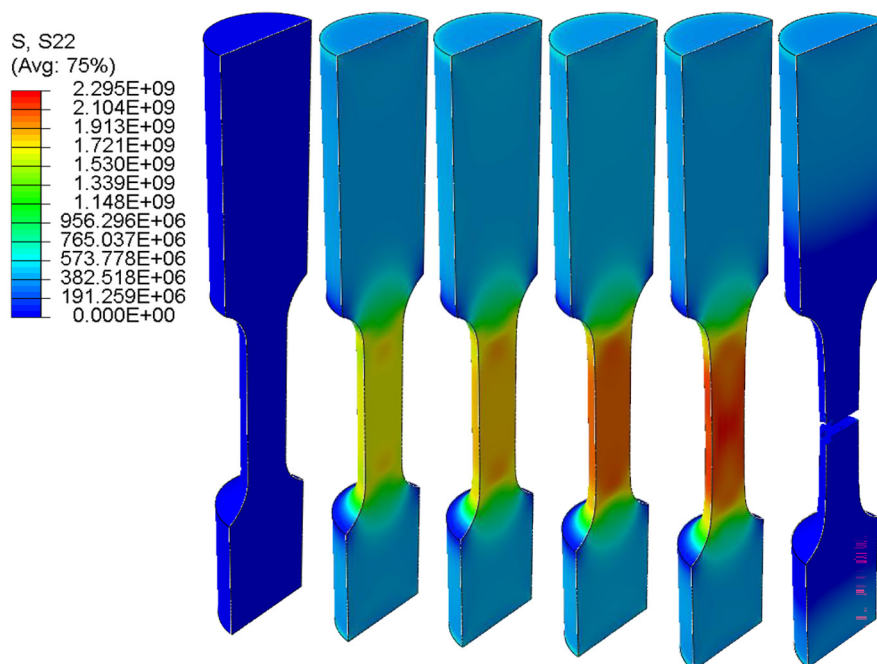


Figure 15. Principal stresses S22 in the tensile specimen at a strain rate of $\dot{\epsilon} = 250$ s $^{-1}$

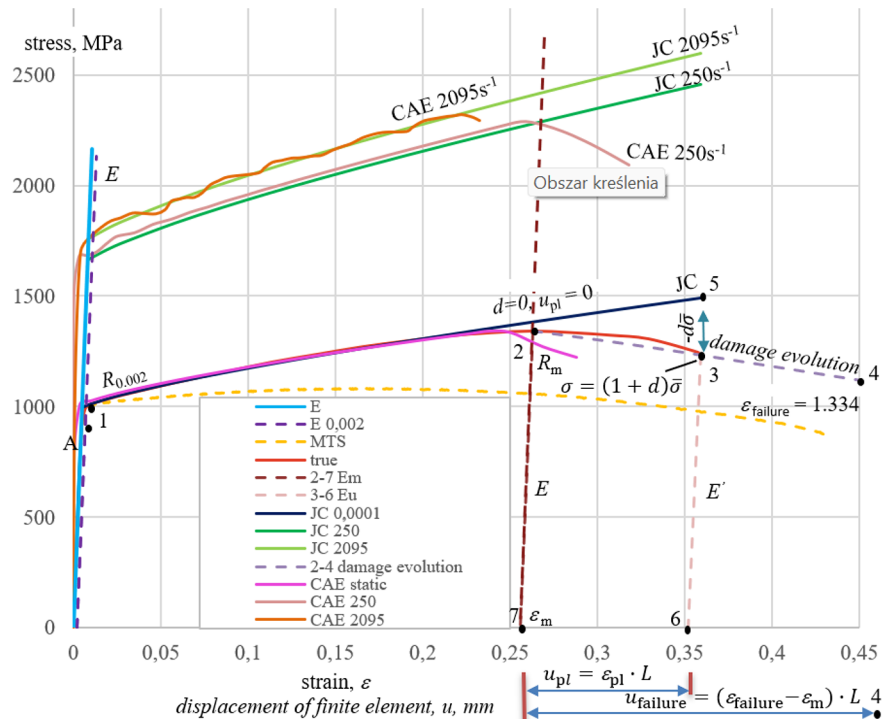


Figure 16. Failure model from CAE simulations overlaid on true stress-strain characteristics

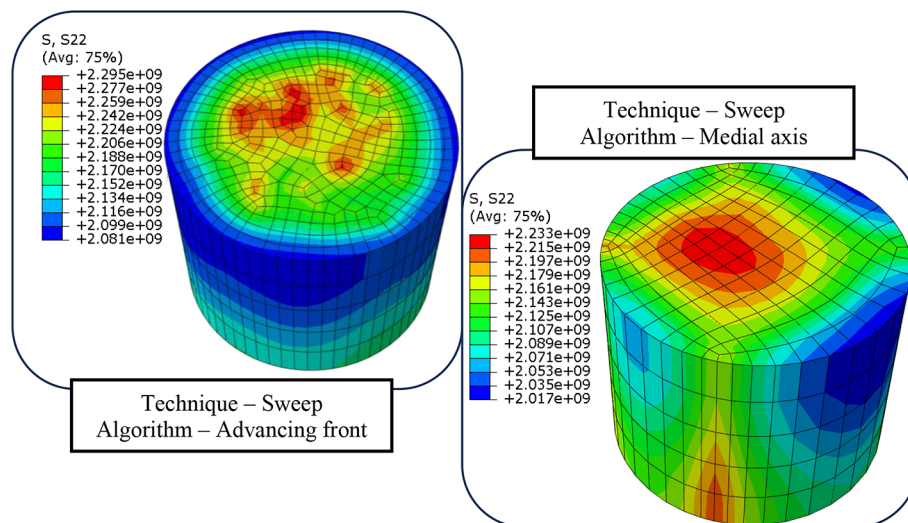


Figure 17. Results for different mesh discretisation methods at a strain rate of $\dot{\epsilon} = 250 \text{ s}^{-1}$

of stress concentrations. In the case of uniaxial tension, the stress values should be relatively uniform around the entire circumference of the specimen. The observed discrepancies indicate that, for the present case, the advancing front meshing algorithm yields better agreement. This method constructs the mesh by progressively generating elements from the boundaries inward, resulting in a more uniform and physically realistic stress distribution.

CONCLUSIONS

Based on static and dynamic tensile tests performed using a rotary hammer, the mechanical properties of austenitic steel were determined and a corresponding material model was developed in line with CAE software conventions for strain rates ranging from $0 \div 2100 \text{ s}^{-1}$. This model facilitates the simulation of rapidly evolving phenomena relevant to impact events, ballistic resistance

and shock-wave effects (e.g., explosion-induced pressure) in the tested structures.

Finite element method (FEM) simulations enable the detailed calculation of field variables at any node within the analysed structure during loading. Such capabilities are essential for the accurate assessment of dynamic and high strain rate events. Moreover, reliable characterisation of the material's behaviour enables the simulations to produce results closely aligned with those obtained in physical experiments.

The comparison of numerical simulation results with experimental data demonstrated deviations of approximately 6.5%, 9% and 12% at the respective strain rates, which are within acceptable limits and confirm the validity of the developed model and its underlying material description.

The resulting material model is suitable for more complex simulations involving intricate geometries or assemblies, thereby reducing the need for costly physical crash tests during the design and development phases. This research expands the materials database for high strain-rate conditions.

Enhancement of the model's predictive reliability requires expansion of both the experimental dataset and the constitutive formulation. Results for E250 steel [1] indicate that combining tests spanning a broad range of stress triaxialities, temperatures, and strain rates - together with validation under independent loading configurations - markedly improves predictive accuracy. In the present work, the baseline Johnson–Cook model is employed, but it does not capture triaxiality-dependent void nucleation and growth or post-necking softening. Accordingly, the scope is limited to identifying damage parameters for uniaxial tension (η_{triax}). Limited material availability precluded a larger test matrix that would have enabled identification at other values of the triaxiality coefficient. Calibration and validation were carried out in uniaxial tension at a single temperature, without accounting for adiabatic self-heating at high strain rates, which affects the material response. An additional contributor to discrepancies between simulations and experiments is the adoption of a single, averaged value of the Johnson–Cook strain-rate sensitivity parameter C over the entire rate range considered. Despite these limitations, the study provides a sound basis for further work, including extension to other stress states and temperatures, explicit incorporation of thermal effects, and more precise calibration of strain-rate-dependent parameters.

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