Extension of Flow Behaviour and Damage Models for Cast Iron Alloys with Strain Rate Effect

Chuang Liu

Nanjing University of Science and Technology

Dongzhi Sun

Fraunhofer Institute for Mechanics of Materials: Fraunhofer-Institut für Werkstoffmechanik IWM

Xianfeng Zhang (✉ lynx@njust.edu.cn)

Nanjing University of Science and Technology School of Mechanical Engineering

Florence Andrieux

Fraunhofer Institute for Mechanics of Materials: Fraunhofer-Institut für Werkstoffmechanik IWM

Tobias Gerster

Fraunhofer Institute for High-Speed Dynamics Ernst-Mach-Institut: Fraunhofer-Institut für Kurzzeiddynamik Ernst-Mach-Institut EMI

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Extension of flow behaviour and damage models for cast iron alloys with strain rate effect

Chuang Liu^{a,b}, Dongzhi Sun^{a*}, Xianfeng Zhang^{b*}, Florence Andrieux^a, Tobias Gerster^c

a. Fraunhofer Institute for Mechanics of Materials, Wöhlerstr. 11, 79108 Freiburg, Germany

b. School of Mechanical Engineering, Nanjing University of Science and Technology, Xiaolingwei 200, 210094 Nanjing, China

c. Fraunhofer Institute for High Speed Dynamics, Ernst-Mach-Institute (EMI), Ernst-Zermelo-Strasse 4, 79104 Freiburg, Germany

Abstract

Cast iron alloys with low production cost and quite good mechanical properties are widely used in the automotive industry. To study the mechanical behavior of a typical ductile cast iron (GJS-450) with nodular graphite, uni-axial quasi-static and dynamic tensile tests at strain rates of 10^{-4} , 1, 10, 100, and 250 s^{-1} were carried out. In order to investigate the effects of stress state, specimens with various geometries were used in the experiments. Stress–strain curves and fracture strains of the GJS-450 alloy in the strain-rate range of 10^{-4} to 250 s^{-1} were obtained. A strain rate-dependent plastic flow law based on the Voce model is proposed to describe the mechanical behavior in the corresponding strain-rate range. The deformation behavior at various strain rates is observed and analyzed through simulations with the proposed strain rate-dependent constitutive model. The available damage model from Bai and Wierzbicki is extended to take the strain rate into account and calibrated based on the analysis of local fracture strains. The validity of the proposed constitutive model including the damage model was verified by the corresponding experimental results. The results show that the strain rate has obviously nonlinear effects on the yield stress and fracture strain of GJS-450 alloys. The

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* Corresponding author: E-mail address: lynx@njust.edu.cn (X.F. Zhang), dong-zhi.sun@iwmm.fraunhofer.de (D.Z. Sun)

predictions with the proposed constitutive model and damage models at various strain rates agree well with the experimental results, which illustrates that the rate-dependent flow rule and damage models can be used to describe the mechanical behavior of cast iron alloys at elevated strain rates.

Keywords: Dynamic behavior of materials; Strain rate dependency; Damage model; Voce model; Cast iron

1. Introduction

Cast iron with low production cost, excellent performance, low wear resistance, favourable vibration resistance and low gap sensitivity has become an important material in automotive industry. However, the cast iron components are inevitably subjected to dynamic loading at work conditions such as impact accident or metal forming process, during which a wide range of loading situations (strains, strain rates and stress state) may occur. To predict the security performance of cast iron components in crash accident involving dynamic loading, it is necessary to determine the complex deformation and damage behavior of the cast iron by experiments. Particularly, describing the strain rate dependency with a flexible material model is required for simulations of dynamic behavior under complex loading conditions. Extensively, as strain-rate is an important factor in the plastic instability (necking) [1] and failure [2] of the metallic materials, investigation on the influence of strain rate on mechanical response including deformation and damage should be carried out.

Phenomenological plastic constitutive models, including Johnson-Cook (J-C) [3], Khan-Huang (K-H) [4], Khan-Huang-Liang (K-H-L) [5], Fields-Backofen (F-B) [6], Molinari-Ravichandran (M-R) [7], Voce-Kocks (V-K) [8,9] and Arrhenius model [10], have been widely used in the simulation of metallic materials at high strain rates [11]. The J-C constitutive model are most widely used as a temperature, strain and strain rate dependent flow stress model, due to the simplicity and less requirement for material parameters. The success of application of J-

C model in simulation results from the simplicity and requirement of less model parameters. Khan and Huang [4] proposed a viscoplastic constitutive model to simulate the behavior of coarse-grained Al 1100 at a wide strain rate range. Fields-Backofen [6] proposed a simplified model with only three parameters to describe the strain sensitivity behavior. Molinari-Ravichandran model [7] is proposed based on a single internal variable, which has a better description for the flow behaviour of metals over a wide range of loading conditions. The Arrhenius equation [10] is widely used to describe the relationship between the strain-rate and flow stress at high temperatures. Voce [8] proposed a constitutive model for strain hardening, however, the formulation is strain rate and temperature insensitive.

As known to all, damage model is very important to describe the fracture characteristics of materials. Nowadays, damage models considering the effects of strain rate and stress state are beneficial for the crash simulation of automotive components. The failure strain can be defined as a function of the stress state (generally using the stress triaxiality and Lode parameter), the strain rate and the temperature. The damage models of Johnson-Cook (J-C) [12] and Bai-Wierzbicki (B-W) [13], for instance, are widely used in the crash simulations. The J-C damage model, a cumulative damage fracture model, was proposed based on a series of tests with OFHC copper, Armco iron, and 4340 steel, which takes the effects of strain rate, temperature and stress triaxiality into account. However, the Lode parameter, the second parameter in addition to triaxiality to define the stress state completely, is not included in the J-C model. Recently, Bai and Wierzbicki [14, 15] proposed a new model (B-W model) by combining the stress triaxiality with Lode parameter to achieve a better description of the damage characteristic [16, 17], which is validated by a series of experimental results. It explains well most experimental observations and is relatively easy to calibrate. Fracture is postulated to occur when the accumulated equivalent plastic strain reaches a critical value which is a function of the stress state (stress triaxiality and Lode parameter) [18, 19]. This stress state dependent damage model was validated by Basaran [20], Bai [21], Marzbanrad [22], Sandburg

[23] and Habib[24] with experiments on different materials. However, B-W damage model ignores the effects of strain rate and temperature, which are important factors for the mechanical properties of metal materials. Based on the tensile experiments with temperature ranging from 200°C to 480°C, Amours [25] extended the B-W damage model by taking the temperature into consideration, which was verified by relevant experimental results. Furthermore, the Gissmo damage model in the crash code LS-DYNA offers a possibility to define the failure strain as a function of triaxiality and Lode parameter in user mode through loading curves. Moreover, it is also possible to define a strain rate dependency model in a simple manner by giving a strain-rate dependent scaling factor.

In summary, for the application to cast iron materials, more attention should be paid to the following aspects: (1) Constitutive models with a better description of the effect of strain rate and temperature on flow stress should be investigated. (2) Damage model should be extended by taking stress state and strain rate into account. (3) Methods for determining the corresponding material damage parameters should be further investigated based on the experimental results.

In this paper, a systematic experimental investigation of GJS-450 cast iron with smooth, notched cylindrical and plane strain tensile specimens have been performed at the strain rates ranging from 10^{-4} to 250 s^{-1} . A plastic flow law based on Voce model was proposed to describe the behaviour of GJS-450 at various strain rates. Deformation behaviour at different strain rates were observed and analyzed through simulation. The B-W damage model was extended by taking the interaction of strain rate and stress state into account. The modified strain rate dependent model was defined in the commercial finite element software LS/DYNA via its material card of mat-add-erosion using the Gissmo option. Simulations of specimen tests at different stress states with different strain rates were conducted. The modified constitutive and damage models were validated by comparing the relevant experimental and numerical results.

2. Experimental characterization of strain-rate effects for cast iron alloys

2.1 Tensile tests on different specimens

The quasi-static and dynamic tensile tests on smooth cylindrical specimens with diameter of 4mm and gauge length of 20mm were performed with an electronic mechanical tensile machine, shown in Fig.1. The geometry of the smooth cylindrical tensile specimen is shown in Fig.2. Five strain rates, 10^{-4} , 1, 10, 100 and 250s^{-1} , were selected for the tensile experiments. The corresponding tensile velocities 0.002mm/s, 24mm/s, 240mm/s, 2400mm/s, 6000mm/s were determined according to the strain rates and the gauge length of the specimens, respectively. The force was recorded by the load cell on the test machine, and the displacement was measured by the digital image correlation (DIC). The engineering stress versus engineering strain curves for different strain rates were obtained.

Fig.1 Setup of tensile tests

Fig.2 Geometry of tensile specimens

2.2 Test results and discussions

Fig.3 Experiment results at different strain rates for cylindrical specimens

Fig.4 Experiment results for notched cylindrical specimens

Fig.5 Experiment results for notched flat plate

The engineering stress versus strain curves of GJS-450 cast iron at strain rates 10^{-4} , 1, 10, 100 and 250 s^{-1} are shown in Fig.3. The stress versus strain curves for notched specimens were shown in Fig.4 and Fig.5. As shown in Fig.3, Fig.4 and Fig.5, a significant strain rate hardening characteristic was indicated for the flow behavior of GJS-450 cast iron. The yield stresses at 0.2% plastic strain and ultimate tensile stresses at the different strain rates are reported in Fig.6. The normalized factor $\ln(\dot{\epsilon}_p/\dot{\epsilon}_{p0})$ is defined by the reference plastic strain rate $\dot{\epsilon}_{p0} = 10^{-4} \text{ s}^{-1}$. The dots in the figure are the experiment data.

According to the study of Yu [26], the exponential law given by Eq. (1) was chosen to describe the strain-rate dependency of plastic flow stress.

$$f(\dot{\epsilon}_p) = C + D e^{n \ln(\dot{\epsilon}_p/\dot{\epsilon}_{p0})} \text{ or } f(\dot{\epsilon}_p) = C + D (\dot{\epsilon}_p/\dot{\epsilon}_{p0})^n \quad (1)$$

where C , D and n are the material parameters, $\dot{\epsilon}_p$ is the strain rate and $\dot{\epsilon}_{p0}$ is the reference strain rate, here the $\dot{\epsilon}_{p0}$ is taken as 10^{-4} s^{-1} . The yield stress at the strain rate $\dot{\epsilon}_p$ is obtained.

$$\sigma(\dot{\epsilon}_p) = \sigma(\dot{\epsilon}_{p0}) \cdot f(\dot{\epsilon}_p) \quad (2)$$

Fig.6 The yield stress and ultimate tensile strength at various strain rates

Fig.7 Fracture strains at various strain rates

Four or more specimens for each strain rate were conducted in the experiment. The average fracture strains under the different strain rates are obtained from the experimental curves, which are illustrated in Fig. 7. Fig. 7 shows that the fracture strain increases with the increasing strain rate. The strain rate effect on fracture strain is obviously nonlinear with the logarithmic factor of strain rate.

3. Deformation and fracture behaviour for cast iron alloys

3.1 Plastic flow law

J-C plastic flow law was proposed in 1983 [3], and was extensively used to describe the rate-dependent behavior of various materials. The Johnson-Cook phenomenological equation, which contains four independent adjustable parameters (three of them are used to describe the static flow stress and one is to describe the strain rate effect), is widely used for high speed metal forming processes [27]. However, comparisons between the existing plastic flow models with the static experimental stress-strain data from Wagoner [28] and Mishra [29] showed that Voce [8] model is the best one to describe the flow behaviour for metallic materials. The good applicability of Voce model was also verified by Naderi [30] and Bressan [27]. In this work, a third-order Voce model is proposed to have a precise description of the static plastic flow characteristics. The static flow law is given by

$$\sigma(\dot{\epsilon}_{p0}) = Y_0 + \sum_{i=1}^3 A_i * (1 - \exp(-B_i * \epsilon^p)) \quad (3)$$

where $Y_0, A_1, A_2, A_3, B_1, B_2, B_3$ are the material parameters.

According to the results in Fig. 4 and the discussion in section 2.2, the correlation of the yield stress and the plastic strain rates can be described with an exponent function. Therefore, in order to describe the flow characteristic of cast iron, the Voce model is extended by taking strain rate into account by a multiplicative term given by the equation (1). Then the plastic flow law at different strain rate is obtained and shown in equation (4).

The modified plastic flow law is defined as

$$\sigma = [Y_0 + \sum_{i=1}^3 A_i * (1 - \exp(-B_i * \epsilon^p))] (C + D e^{n \ln(\dot{\epsilon}_p / \dot{\epsilon}_{p0})}) \quad (4)$$

Based on the present experimental results, the values of the parameters are obtained and listed in Table 1.

Table. 1. Parameters for the third order Voce flow law

Y_0 (MPa)	A_1 (MPa)	A_2 (MPa)	A_3 (MPa)	B_1	B_2	B_3	C	D	n
322.1	195.65	94.55	25.48	3.9	27.7	990	0.984	0.019	0.183

3.2 Material models

3.2.1 Deformation model

Fig.8 Normalized yield surfaces of two constitutive models

For the simulation, two yield criterion, the isotropy (MAT24 [31]) and anisotropy (MAT187 [32]) criterion, were selected and applied in the FE code for the simulation via the commercial finite element software LS-DYNA. MAT24, a classical yield criterion based on the von Mises criterion, is widely used in the simulations of steel components. As an isotropic, strain-rate dependent elastic-plastic material model, it is possible for MAT24 to define the stress

strain curves at different manner by users. A failure criterion was used in combination with MAT24. MAT187 uses an isotropic yield surface and is a strain-rate dependent elastic-plastic material model. The yield point of typical cast iron under tension is lower than under compression. For a better representation of material properties MAT187 was also applied. MAT187 uses separate stress-strain curves for compression, shear, uniaxial tension and bi-axial tension at different strain rates. Therefore, a lot of experimental investigations are necessary to be conducted. The yield surface contains several regions defined by the four load curves as shown in Fig. 8.

3.2.2 Failure model

The phenomenological Gissmo damage model, generalized incremental stress state dependant damage model, is proposed by Neukamm and Feucht [33, 34]. A simplified input of material parameters is intended to consider the instability or localization, as it is a crucial issue in simulations. However, instead of using an exponential function to describe the relationship between failure strain and the reference strain rate, a more general piece-wise function is used to define failure strain by taking triaxiality and Lode parameter into consideration. Also, the strain rate dependency is generalized, instead of using the logarithmic function proposed in J-C model, a strain rate factor is defined for different strain rates. It should be noted that the rate factors in both J-C and Gissmo model are constants and independent on the stress triaxiality. Furthermore, the B-W model [8] was proposed by taking stress triaxiality and Lode parameter into account and was verified by Basaran [35]. In the model, the locus for the failure strain at the reference strain rate is constructed in the 3D space of an equivalent fracture strain ϵ_f , stress triaxiality η , and the Lode angle parameter ξ , using the following equation:

$$\epsilon_f(\eta, \xi) = \left[\frac{1}{2}(D_1^- + D_1^+) - D_1^0 + \frac{1}{2}(D_2^- \exp(-D_3^- \eta) + D_2^+ \exp(-D_3^+ \eta)) - D_2^0 \exp(-D_3^0 \eta) \right] \xi^2 + \left[\frac{1}{2}(D_1^+ - D_1^-) + \frac{1}{2}(D_2^+ \exp(-D_3^+ \eta) - D_2^- \exp(-D_3^- \eta)) \right] \xi + D_1^0 + D_2^0 \exp(-D_3^0 \eta) \quad (5)$$

where the parameters of D_1^- , D_1^+ , D_1^0 , D_2^- , D_2^+ , D_2^0 , D_3^- , D_3^+ and D_3^0 can be obtained from the experiments under different stress states.

Specifically, for the axisymmetric tension $\xi=1$, plane strain or generalized shear $\xi=0$ and axisymmetric compression e.g. biaxial tension $\xi=-1$, Eq. (5) is reduced to the form of J-C model.

$$\begin{aligned}\varepsilon_f(\eta, \xi = 1) &= D_1^+ + D_2^+ \exp(-D_3^+ \eta) \\ \varepsilon_f(\eta, \xi = 0) &= D_1^0 + D_2^0 \exp(-D_3^0 \eta) \\ \varepsilon_f(\eta, \xi = -1) &= D_1^- + D_2^- \exp(-D_3^- \eta)\end{aligned}\tag{6}$$

3.3 Deformation behaviour of cast iron alloys

For the cast iron, the yield stress under compression is larger than that under tension. Also, the hardening behaviours under tension and compression are different as shown in Fig.9. The reason is that the graphites separate from the matrix under tension and act as pores. However, the graphites can bear compressive loading together with the matrix. Material model 187 in LS-DYNA [33] provides a solution by introducing yield curves under different stress states, which is shown in Fig. 8. However, it requires much more experimental efforts to determine the stress vs. strain curves under biaxial and uniaxial compression, shear, biaxial and uniaxial tension. Thus, both material models MAT24 and MAT187 are used to compare their applicability for simulations of specimen tests firstly.

Fig.9 Flow behaviour of the cast iron material GJS 450 under uniaxial tension and compression

In order to verify the proposed rate-dependent plastic flow model, tensile tests on smooth cylindrical specimen, notched cylindrical specimen and notched flat plate were simulated. The new developed plastic flow model was applied with LS-DYNA via the flexible material model. To improve computational efficiency, a quarter of the models was established with an element

size of 0.5mm. Hexahedron solid elements with constant stress are used for the simulations.

The models are shown in Fig. 10.

Fig.10 Models for simulations (a) Smooth specimen (b) Specimen with notch radius of 1mm (c) Specimen with notch radius of 4mm (d) Flat specimen with notch radius of 2mm

Fig.11 Comparison of experiment and simulation for smooth tension

Fig.12 Simulation results with notched specimen under (a) quasi-static load (b) dynamic load

The calculated engineering stress-strain curves at five strain rates are compared with the experimental data, as shown in Fig. 11. The numerical results at four strain rates are in excellent agreement with the experimental data. As shown in Fig. 12, for the notched specimens, the simulation results with material model of MAT24 agree well with the experimental data under

both quasi-static and dynamic loads, except the cylindrical specimen with notch radius of 1mm. The main reason of discrepancy occurring in Fig. 12 is that the von Mises yield criterion is used in different stress state for MAT24. However, the plastic flow behaviour of GJS-450 cast iron are different under tension and compression. This characteristics accord with MAT187 in which different flow stress are adopted under different stress state.

It is obtained that the pressure dependent material model MAT187 is more applicable for GJS-450 cast iron according to the experimental results. It is shown in Fig. 10(a) and Fig. 10(b) that in the case of the specimen with notch radius of 1mm, simulation results with MAT187 are in excellent agreement with experimental results. However, due to the interpolation between curves at different stress states and strain rates, the material model MAT187 works in a time-consuming way, which can result in inefficient calculations. Therefore, for the analysis of the damage process of cast iron, the material model of MAT24 and MAT187 are both applied in the simulation.

3.4 Modelling of fracture behaviour

3.4.1 Fracture strains of smooth round specimens

Fig.13 Equivalent plastic strain distribution with increasing global engineering strain at strain rate 10^{-4}s^{-1}

Deformation process of a smooth cylindrical specimen is shown in Fig. 11. Local effective plastic strains versus global engineering strain in the specimen under strain rate of 10^{-4}s^{-1} are shown in Fig. 13. Fig.13 and Fig.14 show that the local effective plastic strain ε_p and the global engineering strain ε are almost the same until the global engineering strain ε reaches 0.17. When the global engineering strain exceeds 0.17, a strain gradient due to necking of the specimen occurs and a sharply increase in the local effective plastic strain ε_p can be observed. It can be found that the element near the centre of the specimen has a larger plastic strain than that of the remaining part of element. Therefore, for the smooth cylindrical tensile specimen, the fracture occurs firstly near the central axis.

Fig.14 Local plastic strain vs. engineering strain
for strain rate 10^{-4}s^{-1}

Fig.15 local plastic strain vs. engineering strain for
different strain rates

The evolution of the local plastic strain in the middle of the specimen and the global engineering strain for different strain rates are shown in Fig.15. As shown in Fig.14 and Fig.15, the local plastic strain ε_p linearly increases with the strain at the low engineering strain ε and a sharply increase occurs after the inflection point, while the inflection point of the curve increases with the strain rate. This means that an increase of strain rate results in a delay of onset of necking. Combining the experimental data of engineering fracture strain and the curves of local plastic strains versus engineering strains for different strain rates, the plastic fracture strains can be obtained, which are shown in Fig.16.

Fig.16 Fracture strains at different strain rates

Fig.17 Fitting failure strains under smooth tension at different strain rates

Fig.18 Parameters for damage model at different strain rates

The local loading paths (plastic strain as function of triaxiality) in the specimen centre during the tensile process are obtained from the simulations which are shown in Fig.17. Taking the quasi-static tensile failure damage curve as reference and the function $f(\dot{\epsilon}, \eta)$ as modified parameter, fracture strains for different strain rate is obtained as Eq. (7).

$$\epsilon_f(\eta, \xi, \dot{\epsilon}) = \epsilon_f(\eta, \xi, \dot{\epsilon}_{p0}) * f(\dot{\epsilon}, \eta) \quad (7)$$

where $\epsilon_f(\eta, \xi, \dot{\epsilon}_{p0})$ is the fracture strain for quasi-static load, $f(\dot{\epsilon}, \eta)$ is the function for strain rate and triaxiality.

The values of function $f(\dot{\epsilon}, \eta)$ versus logarithmic strain rate are shown in Fig.18. Fig.18 reveals that the fracture strain no longer decreases linearly with the increase of logarithmic

strain rate as assumed by the J-C model. Here, a secondary polynomial term is introduced to describe the strain-rate effect.

$$f(\dot{\epsilon}, \eta = 0.33) = E + F \ln(\dot{\epsilon}_p / \dot{\epsilon}_{p0}) + G (\ln(\dot{\epsilon}_p / \dot{\epsilon}_{p0}))^2 \quad (8)$$

where the parameters ($E=1$, $F=-0.067$, $G=0.0029$) are obtained by combining the experimental data and simulation results.

In general, the local fracture strain decreases with increasing strain rate due to the earlier necking of the specimen at low strain rate. However, the local fracture strain increases slightly with the increase of strain rate in the region of strain rate greater than 10s^{-1} , which is consistent with the model of Johnson-Cook at larger strain rates.

3.4.2 Fracture strains of notched specimens

To investigate the effect of the triaxiality on fracture strain, analysis of tests on flat plane with notch radius of 2mm (plane strain specimen) and cylindrical specimens with notch radius of 1mm and 4mm were performed in a similar way as described in section 3.4.1. The parameters for the modified damage model were obtained by inverse simulation of all specimen tests. It is shown in Fig.19-21 that the influence of strain rate on failure strain is different under different triaxialities.

Fig.19 Fitting damage curve for notched flat plate

Fig.20 Fitting damage curve for cylindrical specimens with a notch radius of 4mm

Fig.21 Fitting Gissmo damage curve for cylindrical specimens with a notch radius of 1mm

Fig.22 Factor of strain rate depending on failure strain for different triaxialities

Fig.22 illustrates that the strain rate factor for failure $f(\dot{\epsilon}, \eta)$ shows a linear increasing trend with the triaxiality, then turns to a stable value if the small difference in strain rate is ignored. Accordingly, the function for strain rate dependency for different triaxialities can be written as:

$$f(\dot{\epsilon} = 10, \eta) = \begin{cases} 0.6 & \eta \leq 0.33 \\ n * \eta + m & 0.33 < \eta < 0.72 \\ 1 & \eta \geq 0.72 \end{cases} \quad (9)$$

where $m=0.27$, $n=1.03$ can be obtained by fitting the determined failure strains at strain rate of 10/s and quasi-static loading.

4 Fracture behaviour of cast iron alloys with modified damage model

4.1 Modified damage model

Based on the above analysis and references [36], it is plausible that ϵ_f is not constant under different loading conditions. The fracture strain of cast iron GJS-450 is sensitive to strain rates and triaxiality. Combining the Eq. (5) and Eq. (7), a modified function $f(\dot{\epsilon}, \eta)$ is proposed in order to take the coupling effect of strain rate and triaxiality into account. The strain-rate dependent fracture strain can be written as

$$\epsilon_f(\eta, \xi, \dot{\epsilon}) = \left\{ \left[\frac{1}{2} (D_1^- + D_1^+) - D_1^0 + \frac{1}{2} (D_2^- \exp(-D_3^- \eta) + D_2^+ \exp(-D_3^+ \eta)) D_2^0 \exp(-D_3^0 \eta) \right] \xi^2 \right. \\ \left. + \left[\frac{1}{2} (D_1^+ - D_1^-) + \frac{1}{2} (D_2^+ \exp(-D_3^+ \eta) - D_2^- \exp(-D_3^- \eta)) \right] \xi + D_1^0 + D_2^0 \exp(-D_3^0 \eta) \right\} * f(\dot{\epsilon}, \eta) \quad (10)$$

The parameters are taken as $D_1^- = 0.2$, $D_1^+ = 0.09$, $D_1^0 = 0.08$, $D_2^- = 1.9$, $D_2^+ = 0.8$, $D_2^0 = 0.45$, $D_3^- = 3$, $D_3^+ = 3$, $D_3^0 = 3$, which are from the study of Sun [37].

It is assumed that the effect of strain rate and triaxiality on the fracture strain $f(\dot{\epsilon}, \eta)$ is continuous. Besides, $f(\dot{\epsilon} = 0.0001, \eta) = 1$, $f(\dot{\epsilon}, \eta > 0.72) = 1$ and Eq. (8), Eq. (9) are taken as the boundary conditions for the function. According to the method of spatial stereo geometry, the function $f(\dot{\epsilon}, \eta)$ can be defined as

$$f(\dot{\epsilon}, \eta) = [1 - E - F \ln(\dot{\epsilon}_p / \dot{\epsilon}_{p0}) - G(\ln(\dot{\epsilon}_p / \dot{\epsilon}_{p0}))^2] * (\eta - H) / I + 1 \quad (11)$$

where the parameters are $E=1$, $F=-0.067$, $G=0.0029$, $H=0.72$, $I=0.39$.

According to Eq. (10), the surface for function $f(\dot{\epsilon}, \eta)$ is obtained, which is shown in Fig.23.

Combining Eq. (9) and Eq. (10), the damage surface for different strain rate and the damage curves for GJS-450 at different strain rate are obtained, which are shown in Fig.24- Fig.28.

Fig. 23 The modified damage surface at different strain rate

Fig. 24 The modified damage curves for smooth tension at different strain rates

Fig. 25 Damage surface for strain rate 0.0001/s

Fig. 26 Damage surface for strain rate 10/s

Fig. 28 Damage surface for strain rate 250/s

4.2 Simulation with the modified Gissmo damage model

In order to verify the new rate-dependent damage model, simulations of tension tests on smooth cylindrical specimen, notched cylindrical specimen and notched flat plate (plane strain) were conducted. The new modified damage model was realized with the commercial finite element software LS-DYNA.

Fig.29 Comparison of experiment and simulation for smooth tension

Fig.30 Comparison of experiment and simulation for notched tension(a) Quasi-static loading (b)

Dynamic loading

Simulation results with the modified Gissmo damage model in combination with MAT24 for smooth tensile specimens at different strain rates are shown in Fig.29. It shows that the fracture strains at different strain rates are in excellent agreement with the experimental data. Moreover, the simulation results for notched specimens under quasi-static load and dynamic load are shown in Fig.30(a) and Fig.30(b), respectively. The calculated fracture strains of round notched specimens (R1, R4) and flat-notched specimens R2 agree well with the corresponding experimental results, which indicates that the modified damage model has a good description of the damage characteristics of GJS-450 at different strain rates.

5 Conclusions

Quasi-static and dynamic tensile experiments for GJS-450 cast iron at strain rates ranging from 10^{-4} to 250 s^{-1} were performed on smooth and notched specimens with radius of 1mm and 4mm, respectively. A significant strain-rate dependent mechanical behaviour is observed in deformation and failure of the material. A strain rate dependent plastic flow law based on Voce model and a modified damage model based on Basaran model were proposed to describe the mechanical behaviour of GJS-450 at different strain rates. Simulations on different specimen tests were conducted to verify the validity of the proposed models. The main conclusions are as follows:

(1) The yield strength and damage characteristics of GJS-450 cast iron have an obvious relationship with strain rates. The necking phenomenon was more pronounced at low strain rates. The influences of strain rate on engineering strain and local strain are quite different, which should be considered in the development of material models.

(2) Based on the experimental results, the Voce model is extended to describe strain-rate dependency of plastic flow behaviour. Simulation results with modified plastic flow law agree

well with the experimental results. The modified plastic flow model can be used to describe the mechanical behaviour of GJS-450 cast iron.

(3) Damage parameters were determined based on the observation of the deforming process and inverse simulations of the experimental results. The calculated engineering fracture strains with the new developed strain-rate dependent damage model agrees well with the experimental results. The strain rate effect on failure depends on stress state. The extended rate dependent damage model can be used to describe the damage behaviour of GJS-450 cast iron.

Availability of data and materials

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Competing interests

The authors declare that they do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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Authors' contributions

Chuang Liu: Data curation, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing.

Dongzhi Sun: Funding acquisition, Writing - review & editing, Project administration.

Xianfeng Zhang: Validation, Supervision, Writing - review & editing.

Florence Andrieux: Methodology, Formal analysis, Writing - review & editing.

Tobias Gerster: Data curation, Investigation.

Authors' Information

Chuang Liu born in 1990, is currently an postdoctor at Nanjing University of of Science and Technology, China. He received his Ph.D. degree from Nanjing University of of Science and Technology, China, in 2020. His main research interests is impact dynamics.

Dongzhi Sun born in 1953, is currently an researcher at Fraunhofer Institute for Mechanics of Materials, Germany. He received her Ph.D. degree from Institute of Ferrous Metallurgy of Aachen University, Germany, in 1987. His main research interests include mechanisms and new methods for crash and production process simulations.

Xianfeng Zhang born in 1978, is currently an professor at Nanjing University of of Science and Technology, China. He received his Ph.D. degree from Nanjing University of of Science and Technology, China, in 2005. His main research interests is impact dynamics.

Florence Andrieux born in 1967, is currently an researcher at Fraunhofer Institute for Mechanics of Materials, Germany. She received her Ph.D. degree from University of Technologie of Compiègne (UTC), FRANCE, in 1991. Her main research interests include Crash simulation accounting for manufacturing processes and forming and influence of strain hardening and damage.

Tobias Gerster is currently an researcher at Fraunhofer Institute for High Speed Dynamics, Ernst-Mach-Institute (EMI), Germany. His main research interests is impact dynamics.

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Figures

Figure 1

Setup of tensile tests

Figure 2

Geometry of tensile specimens

Figure 3

Experiment results at different strain rates for cylindrical specimens

Figure 4

Experiment results for notched cylindrical specimens

Figure 5

Experiment results for notched flat plate

Figure 6

The yield stress and ultimate tensile strength at various strain rates

Figure 7

Fracture strains at various strain rates

Figure 8

Normalized yield surfaces of two constitutive models

Figure 9

Flow behaviour of the cast iron material GJS 450 under uniaxial tension and compression

Figure 10

Models for simulations (a) Smooth specimen (b) Specimen with notch radius of 1mm (c) Specimen with notch radius of 4mm (d) Flat specimen with notch radius of 2mm

Figure 11

Comparison of experiment and simulation for smooth tension

Figure 12

Simulation results with notched specimen under (a) quasi-static load (b) dynamic load

Figure 13

Equivalent plastic strain distribution with increasing global engineering strain at strain rate 10^{-4}s^{-1}

Figure 14

Local plastic strain vs. engineering strain for strain rate 10^{-4}s^{-1}

Figure 15

local plastic strain vs. engineering strain for different strain rates

Figure 16

Fracture strains at different strain rates

Figure 17

Fitting failure strains under smooth tension at different strain rates

Figure 18

Parameters for damage model at different strain rates

Figure 19

Fitting damage curve for notched flat plate

Figure 20

Fitting damage curve for cylindrical specimens with a notch radius of 4mm

Figure 21

Fitting Gissmo damage curve for cylindrical specimens with a notch radius of 1 mm

Figure 22

Factor of strain rate depending on failure strain for different triaxialities

Figure 23

The modified damage surface at different strain rate

Figure 24

The modified damage curves for smooth tension at different strain rates

Figure 25

Damage surface for strain rate 0.0001/s

Figure 26

Damage surface for strain rate 10/s

Figure 27

Damage surface for strain rate 250/s

Figure 28

Comparison of experiment and simulation for smooth tension

Figure 29

Comparison of experiment and simulation for notched tension(a) Quasi-static loading (b) Dynamic loading