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An enhanced Johnson–Cook strength model for splitting strain rate and temperature effects on lower yield stress and plastic flow

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ABSTRACT

This paper introduces a new 'strength model', named Split Johnson–Cook (SJC). The model is a generalization of classical Johnson–Cook (JC) and provides a much improved coherence for the plastic material description. Specifically, the new model tackles the issue that the effects of equivalent plastic strain rate and temperature shall not be taken as equal for each equivalent plastic strain, avoiding then heavy modeling errors on the lower yield stress and on the subsequent plastic flow.

The salient features of the original JC model are shortly reviewed first, paying specific attention to possible modeling incoherencies. Two main shortcoming issues are framed and discussed. Further, a review on several modifications of the JC model from the literature is outlined. Then, the new SJC model is introduced in such a framework and thoroughly described. A comprehensive discussion on its calibration strategies follows, by developing three alternative calibration approaches.

The new model is then applied to the material description of three real material cases (a structural steel, a commercially pure metal and a stainless steel), by considering literature sets of hardening functions recorded at different equivalent plastic strain rates and temperatures. SJC predicted trends are checked against experimental data, for each calibration strategy, by evaluating the material prediction on both lower yield stress and plastic flow. Obtained results are also compared to those provided by plain JC.

The SJC model shows the capability to remarkably improve the material description, as compared to plain JC. Moreover, the fact of presenting a form very similar to that of the original JC model allows to possibly reusing some of the JC material parameters, which may be already known from available calibrations. Also, the SJC model keeps the same computational appeal of the original JC model and need of experimental data toward calibration, while heaviness of calibration and computational weight remain almost unchanged.

1. Introduction

The present paper proposes a modification of the so-called Johnson–Cook (JC) strength model [39], namely a hardening function describing the material yield stress as a function of equivalent plastic strain, equivalent plastic strain rate and temperature. The new strength model consists in a generalization of the original JC model, toward achieving a better modeling coherence.

The present enhanced model allows to better describe the effects of equivalent plastic strain rate and temperature on the lower yield stress and on the plastic flow. The resulting strength model aims at providing much better results comparing to those achievable from the plain JC model, by working in the same computational framework and by adopting the same type of experimental data available for calibration.

Notice that Johnson and Cook defined also a model for predicting fracture phenomena [40]. However, fracture effects are not considered in this paper so far, which focuses on strength models only. On the other hand, a large strain framework is considered. Basic contexts, concepts and notations adopted in the paper follow preliminary earlier work on a doctoral dissertation [19] and results complement those on plain JC produced in a companion paper [21].

The JC hardening function fits in the classic elastoplastic framework (see, [29,43,13,6]), by handling the stress deviator evolution only, while a separate equation of state rules the volumetric behavior. On this, computational implementation issues may be found in Wilkins [98,99], and in Benson [5]. Also, for a discussion on issues related to constitutive model objectivity in computational implementations, see Gambirasio et al. [20].

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Before introducing the new strength model, a short introduction on the original JC model is presented next, in order to recall some key aspects that take a central role for the subsequent definitions in the enhanced model. Such discussion mainly relies on what exposed in companion paper Gambirasio and Rizzi [21], in which a wider discussion on the JC model and on its calibration strategies may be found, together with a review on the bulge of the extensive literature devoted to that.

Subsequently, Section 1.1 briefly outlines the framework in which the Johnson-Cook model is conceived and its main shortcomings. Section 2 presents a mini review on several modifications of the JC model proposed in the literature, useful for collocation of the present enhanced model and for appreciating its novelty. Then, Section 3 presents the new Split Johnson–Cook model and widely discusses its calibration, outlined on three real material cases, by showing much improved performance with respect to plain JC. Finally, Section 4 outlines the closing considerations and lists the crucial points of this study.

1.1. Johnson–Cook model framework and shortcomings

Johnson and Cook [39], introduced a strength model for describing elastoplastic hardening under large strains, within certain ranges of equivalent plastic strain rates and temperatures. One main target of the JC model was making it suitable for FEM implementation and computational use. Hardening outcomes were exposed in terms of Cauchy stress vs. true strain (logarithmic strain measure). In the JC model, the yield stress is expressed as a power function of the equivalent plastic strain and as a natural logarithmic variation of the yield stress on the dimensionless equivalent plastic strain rate $\dot{\bar{\varepsilon}}^*$

$$\dot{\bar{\varepsilon}}^* = \frac{\dot{\bar{\varepsilon}}_p}{\dot{\bar{\varepsilon}}_p^0}, \tag{1}$$

where $\dot{\bar{\varepsilon}}_p$ is the current equivalent plastic strain rate and $\dot{\bar{\varepsilon}}_p^0$ a fixed reference value of it. Concerning temperature effects, a power dependence of the yield stress on the homologous or homogeneous temperature T^* is assumed

$$T^* = \frac{T - T_0}{T_m - T_0}, \tag{2}$$

where T_m is the melting temperature and T_0 a reference fixed value of temperature.

According to these assumptions, the JC model was multiplicatively represented by the following hardening equation, expressed as the von Mises yield stress as a function of equivalent plastic strain, dimensionless equivalent plastic strain rate and homologous temperature

$$\bar{s} = (A + B \cdot \bar{\varepsilon}_p^n) \cdot \left(1 + C \cdot \ln \frac{\dot{\bar{\varepsilon}}_p}{\dot{\bar{\varepsilon}}_p^0}\right) \cdot \left(1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right), \tag{3}$$

with eight JC material parameters A, B, n, C, $\dot{\bar{\varepsilon}}_p^0$, T_0, T_m, m of dimensions and possible units as reported in Table 1. Appropriate experimental tests are needed for their calibration.

The JC strength model conceives a multiplicative decomposition of the current yield stress in the three terms visible in Eq. (3). They set, respectively: a power hardening law (quasi-static term), a log function on the dimensionless equivalent plastic strain rate (strain rate term), a power variation on the homologous temperature (temperature term). Regarding the latter, when the melting temperature is reached, the temperature term vanishes, so that the material loses its deviatoric strength. Above the melting temperature the yield stress may be set to zero or a different strength function may be considered, appropriate for describing the arising material phases.

Table 1
JC parameters dimensions and possible units.

A	Stress (MPa)	n	Dimensionless	$\dot{\bar{\varepsilon}}_p^0$	Strain rate (s^{-1})	T_m	Temperature (K)
B	Stress (MPa)	C	Dimensionless	T_0	Temperature (K)	m	Dimensionless

The JC model has been largely used by several authors, for successfully modeling of different materials. As instances, the JC model has been adopted for the modeling of Ti–6Al–4V titanium alloy [54,55,48,2,50], structural steel [4], XC48 steel [53], HSLA-65 steel [70], sheet steel [86], mild steels [85], ultra-fine-grained copper [67], Hastelloy X [1], 304 stainless steel [14], quenched and self-tempered reinforcing steel [10], 2024-T351 aluminum [89] and advanced high-strength steel sheets [81]. Among the many applications of the JC model, quite a few consider the modeling of structures under high velocity impacts and blast loadings (see, e.g., [75,95,93]).

The formulation of the JC model starts from an empirical basis and provides a fairly simple model, which may not always give precise predictions of the material hardening behavior. This aspect was somehow indicated also in Johnson and Cook [39]. Anyway, this simplicity entails several positive points. In fact, it achieves a reasonable compromise between modeling simplicity, prediction coherency, quest of dedicated experimental data and computational requirements. Regarding negative aspects, it may be said that the simplicity of the JC strength model is paid by introducing some drawbacks in the formulation. In particular, *two main flaws may be identified*:

- The first flaw consists in the fact that the log variation of the yield stress on the dimensionless equivalent plastic strain rate may not be suitable to fit the strain rate sensitivity of some materials. Analogously, the yield stress power function of the homologous temperature may present the same shortcoming. These aspects might lead to heavy modeling errors in some practical cases.
- The second flaw consists in the fact the effects of equivalent plastic strain, equivalent plastic strain rate and temperature on the yield stress are totally independent from each other. This is a direct consequence of the choice of adopting a hardening function designed in a multiplicative way, in which the three factors independently represent the three effects on the yield stress. For instance, for a given equivalent plastic strain, its effect on the yield stress is the same whatever values the equivalent plastic strain rate and temperature assume. This may imply heavy modeling errors, either on the lower yield stress or on the subsequent plastic flow, or even on both. Thus, this simplistic approach may lead to considerable modeling errors, which actually add to the ones due to the first flaw.

The next section aims at better evaluating the magnitude of these two main detrimental issues of plain JC, inspiring then and motivating the present further proposed SJC modification later outlined in Section 3.

2. Assessment of modeling incoherencies of the plain JC model and critical review on several proposed modifications

Considering what stated at the end of Section 1, there arise questions about the relevance of the identified flaws, i.e. how much they may negatively affect the coherence of the JC strength model. It appears that, due to its nature, the JC model may occasionally be incapable to coherently predict the hardening material behavior, in particular over wide ranges of equivalent plastic strain rate and