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Report of Materials Provided by the Auto/Steel Partnership

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ABSTRACT

This is the final report for the effects of strain-rate, temperature, and stress-state on the yield stress and the strain hardening behavior of many common steels used in automobile construction were investigated. The yield and flow stresses were found to exhibit very high rate sensitivities for most of the steels while the hardening rates were found to be insensitive to strain rate and temperature at lower temperatures or at higher strain rates. This behavior is consistent with the observation that overcoming the intrinsic Peierls stress is shown to be the rate-controlling mechanism in these materials at low temperatures. The dependence of the yield stress on temperature and strain rate was found to decrease while the strain hardening rate increased. The Mechanical Threshold Stress (MTS) model was adopted to model the stress-strain behavior of the steels. Parameters for the constitutive relations were derived for the MTS model and also for the Johnson-Cook (JC) and the Zerilli-Armstrong (ZA) models. The results of this study substantiate the applicability of these models for describing the high strain-rate deformation of these materials. The JC and ZA models, however, due to their use of a power strain hardening law were found to yield constitutive relations for the materials which are strongly dependent on the range of strains for which the models were optimized.

I. INTRODUCTION

In this report a wide range of data on the steels chosen by the strain rate characterization

group subjected to high-strain-rate compression at various temperatures will be presented. The yield and flow stresses are shown to be sensitive to the changes in temperature and strain rate at low temperatures and/or high strain rates. A large Peierls stress in bcc materials has been proposed as the rate-controlling mechanism in this temperature and strain-rate regime^[7,9].

The availability of modern high-speed computers makes it possible to develop more sophisticated material constitutive model descriptions capable of modeling complex problems^[11-13]. An accurate description of a materials response over a wide range of loading environments, as well as having predictive capabilities outside the measured range, is in great demand. The material properties unique to bcc metals and alloys bring many challenges for the development of physically-based constitutive models. Several currently utilized constitutive models, namely the Mechanical Threshold Stress model^[14], the Johnson-Cook model^[15], and the Zerilli-Armstrong model^[16], are examples of constitutive models currently implemented in a range of finite element codes such as EPIC^[17], MESA^[18], and DYNA^[19], were examined. The same data set is used to derive the parameters for each model enabling direct comparisons between each model.

II. EXPERIMENTAL PROCEDURE

The materials used in the investigations were DQSK mild steel, HSLA steel (1 st project), IF steel, M190 steel, AKDQ mild steel of as received, and various prestrains, HSLA 1682, and a dual phase steel. The spec. sheets are available from National Steel (Dave Meuleman).

The mechanical responses of the steel materials were measured in compression using solid-cylindrical samples 3.81-mm in diameter by plate thickness in length, lubricated with molybdenum disulfide grease. Compression samples were machined from the plates in both the through-thickness and in-plane longitudinal orientations for the materials in the first phase of the A/SP / LANL interaction. Compression tests for the second phase of the investigation consisted only for through-thickness compression. Tensile tests were conducted on flat bars 3 inches long by 0.5 inches wide by the plate thickness. The reduced section of the sample was 2 inches long and 0.25 inches wide. The tensile tests at 0°, 45°, and 90° as well as 22° and 67° for the AKDQ material. Additionally, biaxial tests were conducted on as received 12 inch by 12 inch plates in the first phase of the project. Quasi-static compression tests were conducted at strain rates of 10^{-3} and 10^{-1} s^{-1} from 298 K to 573 K. Biaxial and tensile tests were conducted at a strain rate of 10^{-3} s^{-1} .

Dynamic tests at strain rates of $1000-8000 \text{ s}^{-1}$ were conducted from 298 K to 573 K in vacuum utilizing a Split-Hopkinson Pressure Bar^[21]. The inherent oscillations in the dynamic stress-strain curves and the lack of stress equilibrium in the specimens at low strains make the determination of yield inaccurate at high strain rates. We chose to focus our studies on the through thickness direction because of the assumed direction of impact. Biaxial and through-thickness tests have the same stress-state.

The shear modulus was calculated for body-centered cubic (bcc) for steels using the formula:

$$\mu = \frac{(C_{11} - C_{12} + C_{44})}{3} \quad (1)$$

where C_{ij} are the elastic constants^[22]. For simplicity, an empirical equation^[23] was used to fit the data to incorporate the temperature dependence of " μ " in the form of:

$$\mu = \mu_0 - \frac{D}{\exp\left(\frac{T_0}{T}\right) - 1} \quad (2)$$

where μ_0 , D and T_0 are fitting constants.

III. DESCRIPTION OF MODELS

The constitutive equations used in this study have the following forms:

A. *Johnson-Cook Model (JC)*^[15]:

$$\sigma = (A + B \cdot \epsilon_p^n)(1 + C \cdot \ln \dot{\epsilon}^*)(1 - T^{*m}) \quad (3)$$

where $\dot{\epsilon}^*$ is a non-dimensional strain rate value,

ϵ_p is the plastic strain, and T^* is $(T - T_{\text{Room}})/(T_{\text{Melt}} - T_{\text{Room}})$. T is in degrees Kelvin. A , B , n , C , and m are constants for this model.

B. Zerilli-Armstrong Model (ZA) for body-centered cubic materials^[16]:

$$\sigma = C_0 + C_1 \cdot \exp(-C_3 \cdot T + C_4 \cdot T \cdot \ln \dot{\epsilon}) + C_5 \cdot \epsilon_p^n \quad (4)$$

where C_0 , C_1 , C_3 , C_4 , C_5 , and n are constants for this model. The athermal stress term C_0 can be replaced with a Hall-Petch relation $\sigma_0 + k \cdot d^{-1/2}$, where d is the grain size, to address a grain size dependence on the yield stress^[16]. In the ZA model, it is presumed that the work hardening rate is independent of temperature and strain rate. Both of the above models use a power-law stress-strain relationship that exhibits continual work hardening without approaching a saturation in the flow stress at large strains.

For the JC, ZA models, computer programs were developed^[24] to optimize the fitting constants to the stress-strain data over a wide range of temperatures and strain rates. A range of corresponding constants is given to calculate the stress at a certain strain followed by comparing this value to the experimental values. This process is repeated for every curve of interest until the best agreement to the entire set of stress-strain data is achieved. A parameter indicating the degree of fit is defined as:

$$\delta = \frac{\sum_{i=1}^k \frac{|\sigma_{\text{calculated}}(\epsilon_i) - \sigma_{\text{experimental}}(\epsilon_i)|}{\sigma_{\text{experimental}}(\epsilon_i)}}{k} \quad (5)$$

Four points representing the characteristic hardening behavior for each stress-strain curve were taken to compare to the calculated stresses at the corresponding strain values. For the modeling results presented in this paper, fits with deviation parameters of better than 4% were achieved.

C. Mechanical Threshold Stress Model (MTS) :

The framework and detailed description of the mechanical threshold stress (MTS) model is given elsewhere^[14,25,26]. A summary of the MTS model is presented here to facilitate comparisons with the JC and ZA models and discussion of the results. Plastic deformation is known to be controlled by the thermally activated interactions of dislocations with obstacles. In the MTS model the current structure of a material is represented by an internal state variable, the mechanical threshold ($\hat{\sigma}$)^[27], which is defined as the flow stress at 0K. The mechanical threshold is separated into athermal and thermal components,

$$\hat{\sigma} = \hat{\sigma}_a + \sum \hat{\sigma}_t, \quad (6)$$

where the athermal component $\hat{\sigma}_a$ characterizes the rate independent interactions of dislocations with long-range barriers such as grain boundaries, dispersoids, or second phases. The thermal component $\hat{\sigma}_t$ characterizes the rate dependent interactions of dislocations with short range obstacles (forest dislocations, interstitial, solutes, Peierls barrier, etc.) that can be overcome with the assistance of thermal activation. The summation of the contributions from different obstacles doesn't need to be linear^[25]. The flow stress of a constant structure at a given deformation condition can be expressed in terms of the mechanical threshold as:

$$\frac{\sigma}{\mu} = \frac{\sigma_a}{\mu} + \sum \frac{\sigma_t}{\mu} = \frac{\sigma_a}{\mu} + \sum S(\dot{\epsilon}, T) \frac{\hat{\sigma}_t}{\mu_0}, \quad (7)$$

where the athermal component is a function of temperature only through the shear modulus, and the factor S specifies the ratio between the applied stress and the mechanical threshold stress. This factor is smaller than 1 for thermally activated controlled glide because the contribution of the thermal activation energy reduces the stress required to force a dislocation past an obstacle. In the thermally activated glide regime the interaction kinetics for short range obstacles are described by an Arrhenius expression of the form:

$$\dot{\epsilon} = \dot{\epsilon}_0 \exp\left(\frac{-\Delta G}{kT}\right). \quad (8)$$

The free energy (ΔG) is a function of stress and a phenomenological relation was chosen^[27]:

$$\Delta G = g_0 \mu b^3 \left[1 - \left(\frac{\sigma_i / \mu}{\hat{\sigma}_i / \mu_0} \right)^p \right]^q. \quad (9)$$

g_0 in units of μb^3 is the normalized activation energy for the dislocations to overcome the obstacles. It is also an indication of the sensitivity of overcoming this obstacle to changes in temperature and strain rate. p and q are parameters with the ranges $0 < p \leq 1$ and $1 \leq q \leq 2$. They detail the glide resistance profile in the higher and lower activation energy regions, respectively^[27]. Upon rearrangement, we have the following relation between the applied stress (σ_i) and the mechanical threshold stress ($\hat{\sigma}_i$) at a constant structure:

$$\frac{\sigma_i}{\mu} = \left[1 - \left(\frac{kT}{g_0 \mu b^3} \ln \frac{\dot{\epsilon}_0}{\dot{\epsilon}} \right)^{1/q} \right]^{1/p} \cdot \frac{\hat{\sigma}_i}{\mu_0}. \quad (10)$$

For single phase materials with cubic crystal structures, the thermal component (σ_i) consists of the linear summation of a term describing the thermal portion of the yield stress ($\sigma_i = \sigma_y - \sigma_a$) and a term describing the evolution of the dislocation structure σ_ϵ as a function of temperature, strain rate and strain. Equation (7) can be written as:

$$\frac{\sigma}{\mu} = \frac{\sigma_a}{\mu} + \frac{\sigma_i}{\mu} + \frac{\sigma_\epsilon}{\mu} = \frac{\sigma_a}{\mu} + S_i(\dot{\epsilon}, T) \frac{\hat{\sigma}_i}{\mu_0} + S_\epsilon(\dot{\epsilon}, T) \frac{\hat{\sigma}_\epsilon}{\mu_0}. \quad (11)$$

The second term on the right hand side of the equation describes the rate dependent portion of the yield stress mainly due to intrinsic barriers such as the strong Peierls stress in bcc materials at low temperatures or at high strain rates. It is further assumed that this term doesn't evolve after yielding. $\hat{\sigma}_\epsilon$ in equation (11) evolves with strain due to dislocation accumulation (work hardening) and annihilation (recovery). This structure evolution $\theta = d\hat{\sigma} / d\epsilon$ is written:

$$\theta = \theta_0 - \theta_r(T, \dot{\epsilon}, \hat{\sigma}), \quad (12)$$

where θ_0 is the hardening due to dislocation accumulation and θ_r is the dynamic recovery rate. The physical understanding of the work hardening behavior of polycrystals is still inadequate to unify this complex process and represent it entirely by physically-based parameters. Follansbee and Kocks^[14] have selected the following form to fit their experimental hardening data for Cu and the same form was found to provide a robust fit to hardening behavior in Ni^[26] and Ti-6Al-4V^[25]:

$$\theta = \theta_0 \left\{ 1 - \frac{\tanh \left[\alpha \frac{\hat{\sigma}_\epsilon}{\hat{\sigma}_{\epsilon s}(\dot{\epsilon}, T)} \right]}{\tanh(\alpha)} \right\}, \quad (13)$$

where α approaching zero represents a linear variation of strain hardening rate with stress (Voce law). The saturation threshold stress $\hat{\sigma}_{\epsilon s}$ is a function of temperature and strain rate. Kocks^[28] has proposed a description for $\hat{\sigma}_{\epsilon s}$ that has the same form as that proposed by Haasen^[29] for the beginning of dynamic recovery which in turn was based on calculations by Schoeck and Seeger^[30] of the stress dependence of the activation energy for cross slip in fcc metals. The relation is written:

$$\ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{\epsilon s 0}} = \frac{g_{0\epsilon s} \mu b^3}{kT} \ln \frac{\hat{\sigma}_{\epsilon s}}{\hat{\sigma}_{\epsilon s 0}}, \quad (14)$$

where $\dot{\epsilon}_{\epsilon s 0}$, $g_{0\epsilon s}$, and $\hat{\sigma}_{\epsilon s 0}$ are constants.

D. Cowper-Symonds, "modified" Johnson-Cook, and 10 parameter Models

The strain-rate sensitivity is described by the following equation:

Cowper-Symonds:
$$\sigma = \sigma_{stat.} \cdot \left(1 + \left(\frac{\dot{\epsilon}}{D} \right)^{1/p} \right) \quad (15)$$

“modified” Johnson-Cook:
$$\sigma = \sigma_{stat.} \cdot \left(1 + \frac{1}{p} \cdot \ln \left[\max \left(\frac{\dot{\epsilon}}{D}, 1 \right) \right] \right), \quad (16)$$

with the parameters for an IF steel listed in Table below.

For both models, the flow stress at higher strain rate is referenced to the stress-strain curve under quasi-static deformation condition ($\sigma_{stat.}$). For every testing temperature, this model uses a different set of ($\sigma_{stat.}$, D, p). If the simulation is done only at those three temperatures tested (−40, 22, and 80°C) then the model will provide reasonable material strength calculation. However when the testing temperature is different from those tested, this model can not provide a flow stress for a given strain rate and temperature. For example, if the temperature of interest is 43°C (=110°F, which is the average temperature in Phoenix during summer), then a set of ($\sigma_{stat.}$, D, p) needs to be derived for this particular temperature. One can image there is a need to simulate a car crash event at −20°C in Minnesota in winter, again another set of ($\sigma_{stat.}$, D, p) is required to describe the mechanical response.

Table: Parameters for German IF steel

	Cowper-Symonds		Johnson-Cook	
Temperature	p	D	p	D
−40°C	5.85	20.9	6.57	0.019
22°C	3.89	252.5	7.37	0.240
80°C	4.63	209.7	7.73	0.117

The 10-Parameter Model

In the German report, there is a constitutive model uses 10 parameters to describe the flow stress as a function of strain and strain rate in the following form:

$$\sigma(\epsilon, \dot{\epsilon}) = P_1 \cdot (1 + P_2 \cdot \epsilon^{P_3})^{P_4} \cdot (1 + \epsilon)^{P_5} \cdot (1 + \dot{\epsilon})^{P_6} \cdot (1 + P_7 \cdot \epsilon^{P_8} \cdot \dot{\epsilon}^{P_9})^{P_{10}} \quad (17)$$

with parameters listed for an IF steel in the next table.

	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}
-40°C	47.1	416.6	0.837	0.276	1.281	0.0096	0.0270	-0.155	0.060	23.89
22°C	178.4	64.86	0.942	0.283	0.498	0.0183	0.0180	-0.461	0.228	1.356
80°C	153.9	79.93	0.892	0.276	0.685	-0.030	0.0069	-0.199	0.288	8.73

An example of the model fit to the experimental data is shown in next figure for an IF steel tested at 22°C at various strain rates. The 10-parameter model is seen to capture the experimental data very well for the strain larger than 2%. The yield stress calculated from this model is twice the experimental value for the test at 225/s. Overshooting in the calculated yield stress is observed for other strain rate too. This overshooting will give a false initial response in the initial impact of the object of interest. This model will provide an accurate strain-hardening behavior for the conditions at the other two temperatures tested, namely -40°C and 80°C.

Very similar to the limitation explained for the Cowper-Symonds and Johnson-Cook Models, for every testing temperature, this model uses a different set of (P_1 - P_{10}) to describe the stress-strain response. If the simulation is done only at those temperatures tested (-40, 22, and 80°C) then the model will provide reasonable material strength calculation within the strain rates tested. However when the testing temperature is different from those tested, this model can not provide a flow stress for a given strain rate and temperature. Using the same example as above, if the temperature of interest is 43°C (=110°F, which is the average temperature in Phoenix during summer), then a set of (P_1 - P_{10}) needs to be derived for this particular temperature. Due to the complexity of the model which purely based on mathematical curve fitting, it is very difficult to "guess" a set of (P_1 - P_{10}) if one tries to interpolate the data between -40 and 80°C.

The following figure shows the same set of experimental data fitted to the Zerilli-Armstrong model. The model captures the yield and strain-hardening behavior very well. There is no over-prediction in the yield stress calculation. The strength of this model as well as other models (MTS, original Johnson-Cook) presented in this report is that the temperature sensitivity of the flow stress is built in as part of the constitutive model. With the data available at several temperatures, the parameters describing the temperature sensitivity in the model can be derived.

The following figure shows all experimental data compiled in the German report for an IF steel at three temperatures and at five strain rates.

It is seen that there are many overlapping curves in the above figure. Firstly, from the understanding of the thermal activation process of the plastic deformation, we can reduce the number of tests necessary to provide us essential information on the strain-rate and temperature sensitivities of the material. Secondly, we can select a constitutive model from the literature to unify the data such that the temperature and strain rate dependence of the flow stress can be described simultaneously. The following figure shows an example of the attempt using the Zerilli-Armstrong model.

It is seen that both the temperature and strain rate sensitivities are described very well by the Zerilli-Armstrong model. The parameters are derived for the testing conditions at the temperatures between -40 and 80°C, and at strain rates between 0.005/s to 225/s. It is confident that the model can accurately calculate the flow stress-strain curve at any given combination of strain rate and temperature that falls within the tested conditions. Furthermore, since this model is based on thermal activation theory, it is constructed that extrapolation to the deformation conditions outside experimental scope can be done with some degree of confidences.

To sum it up, the following schematic drawing shows the capabilities of the Cowper-Symonds, the modified Johnson-Cook, and the 10-Parameter models discussed in the German report and the models used in the current A/SP study. The models discussed in the German report can only describe a few discrete planes in the flow stress space of a material (upper part of the drawing). The models we currently use for this project are capable of describing the whole flow stress space as a function of strain, strain rate, and temperature (lower part of the drawing). There is no extra efforts need to be done in terms of testing matrix selection and constitutive model. On the contrary it requires even fewer number of tests and less efforts in constitutive modeling. In a car crash event, due to its high impact velocity, the material is under adiabatic deformation. The temperature increases during deformation. The magnitude of temperature increase depends on the strain rate and strain. It can range from a few degrees to a few hundred. It is expected that 10-30°C increase in temperature is possible during a crash event. It is therefore important to be able to describe the

flow stress accurately at any given initial temperature as well as having the capability to calculate the flow stress at different temperature to take the adiabatic heating into account during simulation.

IV. RESULTS AND ANALYSIS

A. Compression Test Results

The compressive stress-strain responses of the steels at 25 to 300°C as a function strain rate are shown in the accompanying power point filed titled Finaljc.ppt, Finalza.ppt, and Finalmts.ppt. These files are located in the folder asppptfiles on the CD. The tensile results for the phase two materials is also in this folder and is titled finaltension.ppt. The lower yield and flow stress levels in the most of the steels are seen to increase with increasing strain rate. As observed in many bcc materials at low temperature or at high strain rate, these materials show very high strain-rate sensitivities in their yield and flow stresses. However, the M190 steel shows little difference in the yield and flow stress behaviors for the range tested.

The effect of temperature and strain rate on mechanical properties of the steels was investigated through a series of stress-state tests at different temperatures and strain rates. The constitutive response shows less temperature sensitivity at higher temperatures as demonstrated by the curves for the phase one and the phase two materials. This behavior is primarily due to dislocations overcoming the intrinsic short range obstacle(s), such as a strong Peierls stress. The intrinsic barrier(s), that exhibits very high temperature and strain rate sensitivities, becomes transparent to dislocation motion at higher temperatures through thermal activation process. The dependence of the flow stress on temperature therefore dramatically decreases. However, the strain hardening behavior is essentially unchanged even when deformed at 1000°C at high rate as compared to that at room temperature and high strain rate.

B. An Introduction to Constitutive Modeling

Members of the Auto/Steel partnership have posed a question: Why use compression through-thickness and not in-plane or tensile data for the constitutive model fits? There are many possible answers to this question. First, we believe that this orientation will most likely represent the direction of deformation of the steel sheet that we have been testing. This is based on the comparisons we did of the biaxial tension tests and the compression tests. From elementary mechanics, we know that balanced biaxial in-plane tension has the same stress state as compression in the through-thickness direction. We believe that the stress state in the initial occurrence of crash is best represented by balanced biaxial tension in the steel sheet. That is the primary reason we measured the mechanical properties in the through-thickness direction. The temperature and strain rate sensitivity was measured for the material and we expect that they will remain the same with respect to the deformation path. The in-plane plane properties were measured in both compression and tensile tests. The tensile tests reveal differences with respect to the through-thickness properties. This difference is due to anisotropy as a result of the rolling process. With tests performed in through-thickness compression, in-plane tension, in-plane biaxial modes, and anisotropy measured using X-ray diffraction, the material properties are well characterized.

It is also possible to obtain the same information by measuring the mechanical properties using in-plane tensile tests and then calculating the balanced biaxial properties using continuum mechanics. However, due to the high cost and available testing techniques we chose to do

compression in the through-thickness direction which yielded direct measurements of the desired property (i.e. biaxial stress-state) of interest. Another reason is that the steel sheets do not have a "uniform" strength through thickness. When the samples are loaded in-plane they would behave more like a composite having a stronger outside edge relative to the center. The through-thickness orientation forces the steel to yield in the softer regions first.

I would like to first describe how the curves were fit and then mention what information can be gleaned from the various fitting techniques. In many cases we have data to approximately 20% strain. Typically two pair of data points are chosen to represent the stress-strain curves. The first pair being ~2% and ~13%, the second pair ~8% and 18%. These data are chosen such that when the points are connected they lie on top on the stress strain data for each strain rate and temperature and strain rate test to best represent the yield and strain hardening behaviors.

We have also modeled, on request, the effect of forcing the curves to fit the yield strength of the material, and also fit just the low and intermediate strain rate data (using a reference strain rate of 0.001/s as compared to the 1/s used in most of our analyses. To force the yield strength to match the data the first point in the first pair of fitting parameters (2% and 13% strain) was changed to 0% and 13%. The stress at zero strain had to be guessed at based on our knowledge of materials and the shape of the stress strain curve. (Hopkinson bar data typically cannot be used accurately for strains less than 2%).

Based on the fitting models and there responses to input we are confident in saying that our predictions of the data are accurate for all situations with perhaps two sets of parameters for each material. However, it must be stresses to the users of the data that best results will occur when the fitting parameters that one uses are predicted over the same strains range expected. This means that the ZA and JC model fits that use the yield strength are most accurate for low strains, typically less than 5%, The general fits will be better for strains from 3% to approximately 25% strain.

Johnson-Cook and Zerilli-Armstrong Models:

The basic approach to fitting the JC and ZA models is to select a wide range of data to represent the temperature and strain rate sensitivity as well as the hardening behavior of a given material. A range of corresponding parameters (A , B , n , C , and m in the JC model; C_0 , C_1 , C_3 , C_4 , C_5 , and n in the ZA model) varied by specified increments are then tested in a computer

optimization routine developed for the personal computer to compare the calculated and experimental stress levels at certain strains for all the data. Minimum deviation of the calculated stress from the experiment is used as a guideline to judge the fitting. This process is repeated and the range of the parameters is decreased as well as the increment for each parameter. In general, to calculate a few hundred thousand sets of parameters to fit ten stress-strain curves takes on the order of five minutes. Less than five adjustments to the parameter range and increment were found to give a best fit to the data. Since no single parameter is dominant or redundant, this optimization for the whole spectrum of data of interest does yield a best set of parameters without excessive prejudgment.

The fit to the ZA models for the various steels are shown in the finalza.ppt file. The experimental data at strains less than 0.2 was treated as an isothermal condition for all strain rates. The effect of adiabatic heating at high strains rate was neglected for low strains. In order to make an isothermal curve, a relation between temperature and stress has to be assumed, that may not be accurate and therefore introduce uncertainties to the stress levels. A possible approach in the future will be to assume there is not much temperature change at strains less than 0.2, then fit the data set as the isothermal condition. Once a better description between temperature and stress is obtained, this relation can be used to correct the original curves for adiabatic heating. Finally, the temperature-corrected curves can be refit to the model to derive the final fitting parameters. The temperature rise for tests at strain rates above 500 s^{-1} can be calculated assuming a certain percentage (Ψ) of the work of plastic deformation is converted into heat according to:

$$\Delta T = \frac{\Psi}{\rho C_p} \int \sigma(\epsilon) d\epsilon \quad (18)$$

where σ and ϵ are the true stress and strain, ρ is the density, and C_p is the heat capacity that can be written in the form of $A_0 + A_1 \cdot T + A_2 / T^2$ [33]. Adiabatic heating makes a large difference at higher strains under high-rate deformation.

The fit to the JC model to the same data set is in the power point file titled finaljc.ppt. The formulation of the JC model, equation (3), presumes that the stress-strain curves diverge upon increasing deformation after yield. However in this study we have shown that the strain hardening rate is insensitive to strain rate and temperature in steel within the range investigated. Substantial deviations of the model predictions from the experimental data for the strain-stress data from 25°C

to 300°C for the JC model are seen. The fitting parameters for the materials studied are listed in tables at the end of each file for the ZA and JC models.

Mechanical Threshold Model:

As stated in equation (11), the contribution to the flow stress arising from different obstacles has to be examined to achieve a physically-based modeling fit. The athermal stress depends on the temperature through the shear modulus only and it is a constant after being normalized by the shear modulus. The small fraction of the athermal stress with respect to the higher yield stress exhibited within the temperature range for the steels and the constitutive models applied to them makes an accurate selection of the athermal stress actually insignificant in the analysis. This is mainly used to take grain size effect into consideration. The second term on the right hand side of equation (11) represents the thermal contribution to the yield stress on top of the athermal contribution. (See fig. 1 of the file finalmts.ppt for an illustration of this description). It is further assumed that it does not evolve with strain. In well-annealed materials, the initial dislocation density is low enough so that the contribution from the strain hardening term at very low strains can be neglected. From the plot of the yield stress (σ_y) as a function of the normalized activation energy, the corresponding parameters which describe the deviation from the mechanical threshold ($\hat{\sigma}_i$) as a function of temperature and strain rate can be determined. The governing equations (10) and (11) can be rearranged as:

$$\left(\frac{\sigma_y - \sigma_a}{\mu} \right)^{p_i} = \left(\frac{\hat{\sigma}_i}{\mu_0} \right)^{p_i} - \left(\frac{kT}{g_{0i}\mu b^3} \ln \frac{\dot{\epsilon}_{0i}}{\dot{\epsilon}} \right)^{1/q_i} \cdot \left(\frac{\hat{\sigma}_i}{\mu_0} \right)^{p_i} \quad (19)$$

where $\dot{\epsilon}_{0i}$ is an adjustable parameter. An optimum value of $\dot{\epsilon}_{0i}$ will bring all the data at different temperatures and strain rates into a single curve. g_{0i} is the normalized activation energy for the dislocations to overcome the intrinsic barrier(s) or to unpin from impurities or solutes. It is also an indication of the sensitivity of overcoming this obstacle to changes in temperature and strain rate. p_i and q_i are parameters previously defined in equation (9).

The next step toward a complete constitutive relation for the MTS model is the description

of the strain hardening due to dislocation storage. The constants used in equations (10)-(14) are next determined from the experimental data. For each $\sigma(\varepsilon)$ curve, a corresponding mechanical threshold $\hat{\sigma}_\varepsilon(\varepsilon)$ is derived according to:

$$\hat{\sigma}_\varepsilon(\varepsilon) = \frac{\mu_0}{S_\varepsilon} \left(\frac{\sigma(\varepsilon)}{\mu} - \frac{\sigma_a}{\mu_0} - S_i \frac{\hat{\sigma}_i}{\mu_0} \right). \quad (20)$$

The constants used in the S_ε factor were $\dot{\varepsilon}_{0\varepsilon} = 10^7 \text{ s}^{-1}$, $g_{0\varepsilon} = 1.6$, $p_\varepsilon = 2/3$ and $q_\varepsilon = 1$, with $g_{0\varepsilon}$ the more critical parameter, based on previous experience with Cu^[14] and other materials^[25,26]. The hardening curve at 0K was fitted to equation (13) to obtain the saturation stress of the mechanical threshold. This saturation stresses at 0K was calculated for each test condition and the results were plotted according to equation (14) to derive the remaining parameters. Final model fitting results for the various steels tested are in the file named finalmts.ppt. The constants of the MTS model for the various steels are summarized in the tables in the report from October 22, 1998.

V. DISCUSSION

A. Description of Hardening Behavior in Constitutive Models

In general, material structure evolves as a result of the imposed external stresses. The description of structure evolution is important in constitutive models. One of the most commonly used equations for many decades to describe the stress-strain curves of polycrystalline metals is due to Ludwik^[38] in 1909. The stress increases according to a power function with respect to the strain in the following way:

$$\sigma = \sigma_0 + K \cdot \varepsilon^n \quad (21)$$

where σ_0 , K and n are material constants. This form of hardening behavior was adopted into the constitutive models by Johnson and Cook^[15], and Zerilli and Armstrong^[16]. It is generally accepted however, that at large strains most metallic materials tend to approach a finite "saturation

stress"[28] or approach a constant but small hardening rate at large strains (stage IV)[39,40]. Such a saturation is lacking in the form of equation (21). The MTS model contrarily uses a differential form as written in equation (13) to fit to the experimental data. The ill-defined integrated strain (from the entire previous deformation history) is thereby avoided. The parameter α determines how a material reaches saturation. With the saturation concept built in and a differential form of a hardening law in place, the data obtained under a well-controlled condition to a reasonable value of strain is sufficient to derive all the parameters needed in equation (13). Such data can be achieved through a series of reloading experiments to obtain isothermal stress-strain data to large strains. However, the lack of a saturation stress as an integral part of the JC and ZA models negates a satisfactory model fit at small strains if these two models were previously optimized for large-strain applications and vice versa. Utilization of either the ZA or JC models in large-scale system calculations where portions of the problem simultaneously span from low to high strains, particularly in the case of localization problems, make optimized fitting of these models nearly impossible. The yield stresses and the strain hardening behavior were described by this best set of parameters extremely well. However, the predictions at large strains suggest that continual hardening due to the absence of a saturation stress in these models, will predict high flow stresses at large strains. Stiffer mechanical properties were predicted by the JC and ZA models while the MTS model was closer to the experimental observations[41]. Mathematically, unless large-strain data are generated either through non-trivial reloading tests or calculated from an assumed hardening law, there is no unique set of constants to predict large-strain behavior from the small-strain data for the ZA and JC models.

Data Sets

As part of the fulfillment of the contract we are providing a compilation of all information generated from mechanical tests. In addition to the data sets provided as text files in the ASCII format we have also included the modeling fits, a directory containing progress reports, meeting overheads, and Kaleidagraph plots. In order to access the reports Microsoft Word is necessary, Microsoft PowerPoint for the presentations, and Kaleidagraph for the plots. If A/SP members are interested in accessing the Kaleidagraph files there is now a PC version of this program available. The CD containing the data also includes a list, "index", of the data sets for all the steels tested. The index is listed in appendix A and B of this report. Appendix A is the phase 1 materials and Appendix B is the Phase two materials. This listing is also included as a file named index.doc that is a duplicate of these

appendices. An additional file called JCZASummary.doc is a summary of the fits for the Johnson-Cook and Zerilli-Armstrong models.

Table 1. Fitting parameters of the JC model for phase one and phase two materials
Johnson - Cook Model:

$$\sigma = (A + B \cdot \varepsilon_p^n)(1 + C \cdot \ln \dot{\varepsilon})(1 - [(T - 298)/(T_{melt} - 298)]^m)$$

JC model	A, MPa	B, MPa	n	C	m	T _m , K
DQSK	18	560	0.11	0.03	0.7	1808
DQSK-YS	230	360	.21	0.03	0.7	1808
DQSK-L,I	130	420	0.26	0.025	0.9	1808
HSLA	7.5	810	0.17	0.014	1.6	1808
HSLA-YS	330	560	0.39	0.012	1.7	1808
HSLA-L,I	347.5	405	0.36	0.009	0.9	1808
IF	280	550	0.396	0.042	0.65	1808
IF-YS	330	440	0.4	0.0455	0.6	1808
IF-L,I	210	450	0.4	0.023	0.05	1808
M-190	104	1960	0.053	0.0075	0.93	1808
M190-YS	1500	560	0.23	0.007	0.94	1808
M190-L,I	120	1600	0.02	0.000	0.01	1808
AKDQ 2%	250	430	0.31	0.05	0.6	1808
AKDQ 8%	260	350	0.13	0.038	0.6	1808
AKDQ 2x2	410	210	0.39	0.052	0.625	1808
AKDQ 4x4	370	330	0.39	0.054	0.6	1808
AKDQ 2x0	160	500	0.2	0.055	0.6	1808
AKDQ 8x0	420	220	0.41	0.05	0.7	1808
HSLA1682	400	600	0.38	0.02	0.8	1808
Dual Phase	300	1170	0.13	0.0075	1.0	1808

Table 2. Fitting parameters of the ZA model for phase one and phase two materials

Zerilli - Armstrong Model:

$$\sigma = C_0 + C_1 \cdot \exp(-C_3 \cdot T + C_4 \cdot T \cdot \ln \dot{\epsilon}) + C_5 \cdot \epsilon_p^n$$

ZA model	C ₀ , MPa	C ₁ , MPa	C ₃ , K ⁻¹	C ₄ , K ⁻¹ s ⁻¹	C ₅ , MPa	n
DQSK	2	1950	0.0095	0.0005	500	0.24
DQSK-YS	130	1650	0.009	0.0005	350	0.35
DQSK-L,I	110	2300	0.0115	0.000625	460	0.31
HSLA	10	1800	0.0145	0.00095	740	0.17
HSLA+YS	330	1600	0.0132	0.0009	630	0.58
HSLA+L,I	340	1400	0.01275	0.00065	400	0.36
IF	0.0	1175	0.0041	.00021	480	0.58
IF-YS	0	1140	0.0109	0.0007	600	0.27
IF-L,I	10	1200	0.0049	0.00012	510	0.51
M190	250	1540	0.0025	0.00006	1040	0.09
M190-YS	850	1475	0.0025	0.00006	450	0.23
M190-L,I	340	1000	0.0016	0.0000	750	0.04
AKDQ 2%	80	1075	0.006	0.00034	390	0.34
AKDQ 8%	200	1590	0.007	0.00032	240	0.4
AKDQ 2x2	130	1190	0.006	0.00034	350	0.4
AKDQ 4x4	130	1110	0.0055	0.0003	280	0.27
AKDQ 2x0	20	1170	0.0055	0.0003	420	0.29
AKDQ 8x0	190	1080	0.005	0.00028	280	0.63
HSLA1682	150	875	0.00525	0.00024	600	0.29
Dual Phase	10	2840	0.011	0.00033	1340	0.11

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APPENDIX A

INDEX AND DESCRIPTION OF DATA FILES FOR DQSK, HSLA, IF, M190 STEEL

Phase 1 LANL - Auto/Steel Partnership interaction.

Index of files for DQSK steel

This folder contains seven directories (or folders):

ADDITINF: based on special request or focus of Auto/steel partnership members.

DATA_P : experimental data files in the format of true plastic strain versus true stress [MPa].

JCMODEL : Final fits to the Johnson-Cook Model. The format is true plastic strain versus true stress [MPa]. The fits are under isothermal condition.

DQSKMTSMODEL : Final fits to the MTS Model. The format is true plastic strain versus true stress [MPa]. The fits are under isothermal condition.

RAW_DAT : experimental data files in the format of true strain versus true stress [MPa].

COMPRESS : Experimental data obtained from free compression tests.

HIGHRATE : Experimental data obtained from high-rate tests.

LOWRATE : Experimental data obtained from low-rate tests.

MEDRATE : Experimental data obtained from medium-rate tests.

TENSILE : Experimental data obtained from tensile tests.

ZAMODEL : Final fits to the ZA Model for BCC. The format is true plastic strain versus true stress [MPa]. The fits are under isothermal condition.

BESTFIT : Best fitting results to the strain hardening behavior of low to medium strain-rate tests.

HIGHRATE : Optimized to the hardening behavior exhibited by the data obtained at high strain rate using Hopkinson pressure bar.

YIELD : When the yield stresses were used as part of the input to derive the fitting parameters for DQSK. The hardening behavior of low to medium strain rate tests was used.

JCYSmolel9_10_98: Johnson-Cook fits to yield strength

For each directory and its sub-directories, the files are listed in alphabetical order with brief description for each file as below:

ADDITINF : additional information

dq : this folder contains the information used in the constitutive modeling using a reference strain rate of 0.001/s.

kgplots : this folder contains all kaleidagraph plots for DQSK steel.

restrike : This folder contains restrike data, and data predicting adiabatic heating using the MTS model.

DATA_P: (file format: true-plastic-strain true-stress[MPa])

DQ20433A.P - Testing temperature=200C, testing strain rate=4300/s, sample was machined from location A (see report for detail).

DQ40503A.P - 400C, 5000/s, location A

DQRT10-3.P - 25C, 0.001/s.

DQRT353A.P - 25C, 3500/s, location A.

DQRT500.P - 25C, 5/s.

DQSK100.P - 25C, 100/s.

DQSK12.P - 25C, 12/s.

DQSK5.P - 25C, 5/s.
 DQSK60.P - 25C, 60/s.
 DQSK60A.P - 25C, 60/s.
 DQSK70.P - 25C, 70/s.
 DQSK75.P - 25C, 75/s.
 DQSK85.P - 25C, 85/s.
 DQSK90.P - 25C, 90/s.
 LDQSKA1.P - 25C, 0.001/s.
 LDQSKA3.P - 25C, 0.1/s.
 LDQSKA3A.P - 25C, 0.1/s, repeat test.

JCMODEL : Modeling results for the Johnson-Cook Model

(file format : True-plastic-strain True-stress[MPa])

DQ20433A.JCF - Isothermal strain-stress fit of JC model to a test performed at temperature=200C and strain rate=4300/s.

DQ40503A.JCF - 400C, 5000/s.

DQRT10-3.JCF - 25C, 0.001/s.

DQRT353A.JCF - 25C, 3500/s.

DQRT500.JCF - 25C, 5/s.

DQSK100.JCF - 25C, 100/s.

DQSKJZ.JCF - Input file to calculate final fits to the JC model.

DQSKJZ - Model fit parameters for CM program

DQSKMTSMODEL : Modeling results for the MTS Model

(file format : True-plastic-strain True-stress[MPa])

DQ20433A.MTS - Isothermal strain-stress fit of MTS model to a test performed at temperature=200C and strain rate=4300/s.

DQ40503A.MTS - 400C, 5000/s.

DQRT10-3.MTS - 25C, 0.001/s.

DQRT353A.MTS - 25C, 3500/s.

DQRT500.MTS - 25C, 5/s.

DQSK100.MTS - 25C, 100/s.

DQSKMTS.MTS - Input file to calculate final fits to the MTS model.

DQSKMTS - Model fit parameters for CM program

RAW_DAT : Experimental data files

COMPRESS : Test under compression

HIGHRATE : Using Hopkinson Pressure Bar (strain rate greater than 1000/s)

DQ20433A.txt - 200C, 4300/s, location A

DQ40503A.txt - 400C, 5000/s, location A

DQ60433A.txt - 600C, 4300/s, location A

DQRT353A.txt - 25C, 3500/s, location A

LOWRATE : Quasi-static tests using Instron load frame,

(strain rates between 0.0001/s and 1/s).

L1PADQC.t - 25C, 0.001/s, in-plane, along rolling direction, location B.

L1PEDQC.t - 25C, 0.001/s, in-plane, perpendicular to rolling direction, loc. A.

L2PADQC.t - 25C, 0.001/s, in-plane, along rolling direction, loc. B, second test.

L2PEDQC.t - 25C, 0.001/s, in-plane, perpendicular to rolling direction, loc. A, second test.

L3PADQC.t - 25C, 0.001/s, in-plane, along rolling direction, loc. B, third test.

L3PEDQC.t - 25C, 0.001/s, in-plane, perpendicular to rolling direction, loc. A, third test.

L4PEDQC.t - 25C, 0.001/s, in-plane, perpendicular to rolling direction, loc. A, fourth test.

LDQSA1C.t - 25C, 0.001/s, thru-thickness, location A, first test.

LDQSA2C.t - 25C, 0.001/s, thru-thickness, location A, second test.

LDQSA3C.t - 25C, 0.1/s, thru-thickness, location A, first test.

LDQSA4C.t - 25C, 0.1/s, thru-thickness, location A, second test.
 LDQSA5C.t - -196C, 0.001/s, thru-thickness, location A, first test.
 LDQSA6C.t - -196C, 0.001/s, thru-thickness, location A, second test.
 LDQSB1C.t - 25C, 0.001/s, thru-thickness, location B, first test.
 LDQSB2C.t - 25C, 0.001/s, thru-thickness, location B, second test.
 LDQSB3C.t - 25C, 0.1/s, thru-thickness, location B, first test.
 LDQSB4C.t - 25C, 0.1/s, thru-thickness, location B, second test.
 LDQSB5C.t - -196C, 0.001/s, thru-thickness, location B, first test.
 LDQSB6C.t - -196C, 0.001/s, thru-thickness, location B, second test.

MEDRATE : Medium strain-rate tests using MTS test system,
 (strain rates between 5/s and 200/s).

DQRT20.DAT - 25C, 20/s.
 DQRT21.DAT - 25C, 12/s.
 DQRT522.DAT - 25C, 52/s, second test.
 DQRT500.P - 25C, 5/s.
 DQRT70.DAT - 25C, 70/s.
 DQSK100.P - 25C, 100/s.

TENSILE : Tests under tensile.

LTADQ1C.T - 25C, 0.001/s, location A, test no. 1.
 LTADQ2C.T - 25C, 0.001/s, location A, test no. 2.
 LTBDQ1C.t - 25C, 0.001/s, location B, test no. 1.
 LTBDQ2C.t - 25C, 0.001/s, location B, test no. 2.

BIAXIAL TENSION : Tests under biaxial loading.

DQSKBI1 - 25C, 0.001/s, 12" X 12" plate #1
 DQSKBI2 - 25C, 0.001/s, 12" X 12" plate #2

ZAMODEL : Modeling results for the Zerilli-Armstrong Model
 (file format : True-plastic-strain True-stress[MPa])

BESTFIT:

DQ20433A.ZBF - Isothermal strain-stress fit of ZA model to a test performed
 at temperature=200C and strain rate=4300/s.
 DQ40503A.ZBF - 400C, 5000/s.
 DQRT10-3.ZBF - 25C, 0.001/s.
 DQRT353A.ZBF - 25C, 3500/s.
 DQRT500.ZBF - 25C, 5/s.
 DQSK100.ZBF - 25C, 100/s.
 DQSKZA.ZBF - Input file to calculate final fits to the ZA model.
 DQSKZA - Model fit parameters for CM program

YIELD: Enforcing yield stresses.

DQ20433A.ZBF - Isothermal strain-stress fit of ZA model to a test performed
 at temperature=200C and strain rate=4300/s.
 DQ40503A.ZBF - 400C, 5000/s.
 DQRT10-3.ZBF - 25C, 0.001/s.
 DQRT353A.ZBF - 25C, 3500/s.
 DQRT500.ZBF - 25C, 5/s.
 DQSK100.ZBF - 25C, 100/s.
 DQSKJZYS.ZBF - Input file to calculate final fits to the ZA model.
 DQSKJZYS - Model fit parameters for CM program

Index of files for HSLA steel

This folder contains six directories (or folders):

ADDITINF based of special request or focus of interest.
DATA_P : experimental data files in the format of true plastic strain versus true stress [MPa].
JCMODEL : Final fits to the Johnson-Cook Model. The format is true plastic strain versus true stress [MPa]. The fits are under isothermal condition.
HSLAMTSMODEL : Final fits to the MTS Model. The format is true plastic strain versus true stress [MPa]. The fits are under isothermal condition.
RAW_DAT : experimental data files in the format of true strain versus true stress [MPa].
BIAXIAL : Experimental data obtained from biaxial bulge tests
COMPRESS : Experimental data obtained from free compression tests.
HIGHRATE : Experimental data obtained from high-rate tests.
LOWRATE : Experimental data obtained from low-rate tests.
MEDRATE : Experimental data obtained from medium-rate tests.
TENSILE : Experimental data obtained from tensile tests.
ZAMODEL : Final fits to the ZA Model for BCC. The format is true plastic strain versus true stress [MPa]. The fits are under isothermal condition.
BESTFIT : Best fitting results to the strain hardening behavior of low to medium strain-rate tests.
HIGHRATE : Optimized to the hardening behavior exhibited by the data obtained at high strain rate using Hopkinson pressure bar.
YIELD : When the yield stresses were used as part of the input to derive the fitting parameters for DQSK. The hardening behavior of low to medium strain rate tests was used.

For each directory and its sub-directories, the files are listed in alphabetical order with brief description for each file as below:

ADDITINF : additional information

Data :

HS201-1.P - 200C, 0.1/s, moly, MTS
HS301-1.P - 300C, 0.1/s, moly, MTS
HSLAI-3.P - 25C, 0.001/s, teflon/ moly, MTS
HSLNI-3.P - 77K, 0.001/s, Instron
HSLNI-3A.P - 77K, 0.001/s, Instron, repeat test.
HSLNI-3B.P - 77K, 0.001/s, Instron, repeat test.
HSRT-1.P - 25C, 0.1/s, teflon/ moly, MTS
HSRT-1A.P - 25C, 0.1/s, teflon/ moly, MTS, repeat test.
HSRT-1B.P - 25C, 0.1/s, teflon/ moly, MTS, repeat test.
HSRT-1C.P - 25C, 0.1/s, grease, MTS, repeat test
HSRT-1D.P - 25C, 0.1/s, grease, MTS, repeat test.
HSRTI-1.P - 25C, 0.1/s, grease, Instron
HSRTI-1B.P - 25C, 0.1/s, grease, Instron, repeat test.
HSRTI-1C.P - 25C, 0.1/s, grease, Instron, repeat test.
HSRTI-1D.P - 25C, 0.1/s, grease, Instron, repeat test.
HSRTI-1E.P - 25C, 0.1/s, grease, Instron, repeat test.
HSRTI-1F.P - 25C, 0.1/s, teflon/ moly, Instron, repeat test.
HSRTI-3.P - 25C, 0.001/s, Instron
HSRTI-3A.P - 25C, 0.001/s, grease, Instron, repeat test.
HSRTI-3B.P - 25C, 0.001/s, grease, Instron, repeat test.

kgplots : this folder contains all kaleidagraph plots on HSLA steel.

hs : This folder contains data and model fits for HSLA steel for a reference strain rate of 0.001/s.

DATA_P: (file format: true-plastic-strain true-stress[MPa])

HSLA7K2a.P - Testing temperature=200C, testing strain rate=7000/s.

HSLA4Ka.P - 25C, 4000/s.

HS200.P - 200C, 0.1/s.

HS300.P - 300C, 0.1/s.

HSLA001.P - 25C, 0.001/s.

HSLA1.P - 25C, 0.1/s.

HSLA20.P - 25C, 20/s.

HSLA50.P - 25C, 50/s.

HSLA01LN.P - 77K, 0.001/s.

JCMODEL : Modeling results for the Johnson-Cook Model

(file format : True-plastic-strain True-stress[MPa])

HSLA7K2.JCF - Isothermal strain-stress fit of JC model to a test performed at temperature=200C and strain rate=7000/s.

HSLA001.JCF - 25C, 0.001/s.

HSLA1.JCF - 25C, 0.1/s.

HSLA20.JCF - 25C, 20/s.

HSLA50.JCF - 25C, 50/s.

HSLA4K.JCF - 25C, 4000/s.

HSLAjc.JCF - Input file to calculate final fits to the JC model.

HSLAjc - Model fit parameters for CM program

MTSMODEL : Modeling results for the MTS Model

(file format : True-plastic-strain True-stress[MPa])

HSLA7K2.MTS - Isothermal strain-stress fit of MTS model to a test performed at temperature=200C and strain rate=7000/s.

HSLA001.MTS - 25C, 0.001/s.

HSLA1.MTS - 25C, 0.1/s.

HSLA50.MTS - 25C, 50/s.

HSLA4Ka.MTS - 25C, 4000/s.

HSLAmts.MTS - Input file to calculate final fits to the MTS model.

HSLAjc - Model fit parameters for CM program

RAW_DAT : Experimental data files

COMPRESS : Test under compression

HIGHRATE : Using Hopkinson Pressure Bar (strain rate greater than 1000/s)

HSLA4KRT.DAT - 25C, 4000/s, second test.

HSLA7K200.DAT - 200C, 4000/s, third test.

LOWRATE : Quasi-static tests using Instron load frame,

(strain rates between 0.0001/s and 1/s).

HS2001C.DAT - 200C, 0.1/s, thru-thickness, teflon/moly lubricant, first test.

HS3001C.DAT - 300C, 0.1/s, thru-thickness, teflon/moly lubricant, first test.

HSLA11C.DAT - 25C, 0.1/s, thru-thickness, teflon/moly lubricant, first test.

HSLA12C.DAT - 25C, 0.1/s, thru-thickness, teflon/moly lubricant, second test.

HSLA13C.DAT - 25C, 0.1/s, thru-thickness, teflon/moly lubricant, third test

HSLA14C.DAT - 25C, 0.1/s, thru-thickness, teflon/moly lubricant, fourth test

HSLA15C.DAT - 25C, 0.1/s, thru-thickness, teflon/moly lubricant, fifth test

HSLA1C.DAT - 25C, 0.1/s, thru-thickness, moly lubricant, first test.

HSLA2SC.DAT - 25C, 0.001/s, thru-thickness, moly lubricant, second test.

HSLA3SC.DAT - 25C, 0.001/s, thru-thickness, moly lubricant, third test.

MEDRATE : Medium strain-rate tests using MTS test system,
(strain rates between 5/s and 200/s).

HSLA101.DAT - 25C, 100/s.
HSLA112.DAT - 25C, 112/s.
HSLA118.DAT - 25C, 118/s, second test.
HSLA140.DAT - 25C, 140/s.
HSLA21.DAT - 25C, 21/s.
HSLA37.DAT - 25C, 37/s.
HSLA50A.DAT - 25C, 50/s.
HSLA50B.DAT - 25C, 50/s.second test.
HSLA8.DAT - 25C, 8/s.

TENSILE : Tests under tensile.

LHSSTA1 - 25C, 0.001/s, location A, test no. 1.
LHSSTA2 - 25C, 0.001/s, location A, test no. 2.
LHSSTB1 - 25C, 0.001/s, location B, test no. 1.
LHSSTB2 - 25C, 0.001/s, location B, test no. 2.

BIAXIAL : Tests under biaxial loading.

biax1 - 25C, 0.001/s, 12" X 12" PLATE
biax2 - 25C, 0.001/s, 12" X 12" PLATE, test no. 2.

ZAMODEL : Modeling results for the Zerilli-Armstrong Model
(file format : True-plastic-strain True-stress[MPa])

BESTFIT:

HSLA7K2.ZBF - Isothermal strain-stress fit of ZA model to a test performed
at temperature=200C and strain rate=7000/s.

HSLA001.ZBF - 25C, 0.001/s.

HSLA1.ZBF - 25C, 0.1/s.

HSLA20.ZBF - 25C, 20/s.

HSLA50.ZBF - 25C, 50/s.

HSLA4K.ZBF - 25C, 4000/s.

HSLAza.ZBF - Input file to calculate final fits to the ZA model.

HSLAza - Model fit parameters for CM program

HSLAzays.ZBF - Input file to calculate final fits to the ZA model.

HSLAzays - Model fit parameters for CM program

Index of files for M-190 steel

This directory contains six sub-directories (or folders):

ADDITINF : additional information

DATA_P : experimental data files in the format of true plastic
strain versus true stress [MPa].

JCMODEL : Final fits to the Johnson-Cook Model. The format is true
plastic strain versus true stress [MPa]. The fits are under
isothermal condition.

MTSMODEL : Final fits to the MTS Model. The format is true plastic
strain versus true stress [MPa]. The fits are under
isothermal condition.

RAW_DAT : experimental data files in the format of true strain versus
true stress [MPa].

BIAXIAL : Experimental data obtained from biaxial bulge tests

COMPRESS : Experimental data obtained from free compression tests.

HIGHRATE : Experimental data obtained from high-rate tests.

LOWRATE : Experimental data obtained from low-rate tests.

MEDRATE : Experimental data obtained from medium-rate tests.

TENSILE : Experimental data obtained from tensile tests.
ZAMODEL : Final fits to the ZA Model for BCC. The format is true plastic strain versus true stress [MPa]. The fits are under isothermal condition.

For each directory and its sub-directories, the files are listed in alphabetical order with brief description for each file as below:

ADDITINF : additional information

kgplots : this folder contains all kaleidagraph plots on HSLA steel.

DATA.P: (file format: true-plastic-strain true-stress[MPa])

LOW RATE

RTP001.P - Testing temperature=25C, testing strain rate=0.001/s.

RTP1.P - 25C, 0.1/s.

M9100P1.P - 100C, 0.1/s.

M9200P1.P - 200C, 0.1/s.

M9300P1.P - 300C, 0.1/s.

MED RATE

RT10.P - 25C, 10/s, MTS

RT40.P - 25C, 40/s, MTS

RT80.P - 25C, 80/s, MTS

HIGH RATE

T2004KA.P - 200C, 4000/s, SHPB

T3006KA.P - 300C, 6000/s, SHPB.

T10035K.P - 100C, 3500/s, SHPB

RT2000.P - 25C, 2000/s, SHPB.

JCMODEL : Modeling results for the Johnson-Cook Model

(file format : True-plastic-strain True-stress[MPa])

M9300P1.JCF - Isothermal strain-stress fit of JC model to a test performed at temperature=300C and strain rate=0.1/s.

M9100P1.JCF - 100C, 0.1/s.

RT2000.JCF - 25C, 2000/s.

RT40.JCF - 25C, 40/s.

RTP001.JCF - 25C, 0.001/s.

T10035K.JCF - 100C, 3500/s.

T2004K.JCF - 200C, 4000/s.

M190jc.JCF - Input file to calculate final fits to the JC model.

M190jc - Model fit parameters for CM program

M190jc001.JCF - Input file to calculate final fits to the JC model with a reference strain rate of 0.001/s.

M190jc001 - Model fit parameters for CM program

MTSMODEL : Modeling results for the MTS Model

(file format : True-plastic-strain True-stress[MPa])

M9300P1.MTS - Isothermal strain-stress fit of JC model to a test performed at temperature=300C and strain rate=0.1/s.

M9100P1.MTS - 100C, 0.1/s.

RT2000.MTS - 25C, 2000/s.

RT40.MTS - 25C, 40/s.

RTP001.MTS - 25C, 0.001/s.

T10035K.MTS - 100C, 3500/s.

T2004K.MTS - 200C, 4000/s.

M190mts.MTS - Input file to calculate final fits to the MTS model.

M190mts - Model fit parameters for CM program

RAW.DAT : Experimental data files
COMPRESS : Test under compression
HIGHRATE : Using Hopkinson Pressure Bar (strain rate greater than 1000/s)
RT2000a.txt - 25C, 2000/s, first test.
T10035ka.txt - 100C, 3500/s, first test.
T2004ka.txt - 200C, 4000/s, second test.
T3006ka.txt - 300C, 6000/s, first test.

LOWRATE : Quasi-static tests using Instron load frame,
(strain rates between 0.0001/s and 1/s).
M9RTP1A.DAT - 25C, 0.1/s, thru-thickness, first test.
M9RTP1B.DAT - 25C, 0.1/s, thru-thickness, second test.
M9300P1.DAT - 300C, 0.1/s, thru-thickness, first test.
M9200P1A.DAT - 200C, 0.1/s, thru-thickness, first test.
M9200P1B.DAT - 200C, 0.1/s, thru-thickness, second test.
M9100P1.DAT - 100C, 0.1/s, thru-thickness, first test.

MEDRATE : Medium strain-rate tests using MTS test system,
(strain rates between 5/s and 200/s).
M190H1.DAT - 25C, 19/s.
M190H2A.DAT - 25C, 40/s.
M190H3.DAT - 25C, 50/s, second test.
M190H4.DAT - 25C, 80/s.
M190H5.DAT - 25C, 80/s, second test.
M190H6.DAT - 25C, 12/s.

TENSILE : Tests under tensile.
LM19A1 - 25C, 0.001/s, location A, test no. 1.
LM19A2 - 25C, 0.001/s, location A, test no. 2.
LM19B2 - 25C, 0.001/s, location B, test no. 1.
LM19B3 - 25C, 0.001/s, location B, test no. 2.

BIAXIAL : Tests under biaxial loading.
bim190L - 25C, 0.001/s, 12" X 12" PLATE, 0.08" thick.
bim190S - 25C, 0.001/s, 12" X 12" PLATE, 0.03 " thick.

ZAMODEL : Modeling results for the Zerilli-Armstrong Model
(file format : True-plastic-strain True-stress[MPa])

BESTFIT:
M9300P1.ZBf - Isothermal strain-stress fit of JC model to a test performed
at temperature=300C and strain rate=0.1/s.
M9100P1.ZBf - 100C, 0.1/s.
RT2000.ZBf - 25C, 2000/s.
RT40.ZBf - 25C, 40/s.
RTP001.ZBf - 25C, 0.001/s.
T10035K.ZBf - 100C, 3500/s.
T2004K.ZBf - 200C, 4000/s.
T3006K.ZBf - 300C, 6000/s.
M190za.ZBf - Input file to calculate final fits to the ZA model.
M190za - Model fit parameters for CM program

Index of files for IF steel

This directory contains six sub-directories (or folders):

ADDITINF : This folder contains additional information not used for constitutive modeling.

DATA_P : experimental data files in the format of true plastic strain versus true stress [MPa].

JCMODEL : Final fits to the Johnson-Cook Model. The format is true plastic strain versus true stress [MPa]. The fits are under isothermal condition.

MTSMODEL : Final fits to the MTS Model. The format is true plastic strain versus true stress [MPa]. The fits are under isothermal condition.

RAW_DAT : experimental data files in the format of true strain versus true stress [MPa].

BIAXIAL : Experimental data obtained from biaxial bulge tests

COMPRESS : Experimental data obtained from free compression tests.

HIGHRATE : Experimental data obtained from high-rate tests.

LOWRATE : Experimental data obtained from low-rate tests.

MEDRATE : Experimental data obtained from medium-rate tests.

TENSILE : Experimental data obtained from tensile tests.

ZAMODEL : Final fits to the ZA Model for BCC. The format is true plastic strain versus true stress [MPa]. The fits are under isothermal condition.

For each directory and its sub-directories, the files are listed in alphabetical order with brief description for each file as below:

ADDITINF : additional information

KGLOTS : this folder contains all kaleidagraph plots on HSLA steel.

DATA_P: (file format: true-plastic-strain true-stress[MPa])

IF1003.P - Testing temperature=100C, testing strain rate=0.001/s.

IFRTP1.P - 25C, 0.1/s.

IF2003.P - 200C, 0.001/s,

IFRTP3.P - 25C, 0.001/s,

IF3003.P - 300C, 0.001/s.

IFRT100.P - 25C, 100/s, MTS

IFRT50.P - 25C, 50/s, MTS

IF10653.P - 100C, 6500/s, SHPB

IFRT6K.P - 25C, 6000/s, SHPB.

IF20703.P - 200C, 7000/s, SHPB

IF30753.P - 300C, 7500/s, SHPB.

JCMODEL : Modeling results for the Johnson-Cook Model

(file format : True-plastic-strain True-stress[MPa])

IF10653.JCF - Isothermal strain-stress fit of JC model to a test performed at temperature=100C and strain rate=6500/s.

IF1003.JCf - 100C, 0.001/s

IF2003.JCF - 200C, 0.001/s.

IF20703.JCF - 200C, 7000/s.

IF30753.JCF - 300C, 7500/s.

IFRT100.JCf - 24C, 100/s

IFRT50.JCF - 25C, 50/s.

IFRT6K.JCF - 25C, 6000/s.

IFRTP1.JCF - 25C, 0.1/s.

IFRTP3.JCF - 25C, 0.001/s.

IF_jc.JCF - Input file to calculate final fits to the JC model.

IF_jc - Model fit parameters for CM program

IF_jc001.JCF - Input file to calculate final fits to the JC with 0.001/s as a reference strain rate.

IF_jc001 - Model fit parameters for CM program

MTSMODEL : Modeling results for the MTS Model

(file format : True-plastic-strain True-stress[MPa])

IF10653.MTS - Isothermal strain-stress fit of MTS model to a test
performed at temperature=100C and strain rate=6500/s.

IF1003.MTS - 100C, 0.001/s

IF20703.MTS - 200C, 7000/s.

IF30753.MTS - 300C, 7500/s.

IFRT100.MTS - 25C, 100/s.

IFRT6K.MTS - 25C, 6000/s.

IFRTP1.MTS - 25C, 0.1/s.

IFRTP3.MTS - 25C, 0.001/s.

IFmts.MTS - Input file to calculate final fits to the MTS model.

IFmts - Model fit parameters for CM program

RAW_DAT : Experimental data files

COMPRESS : Test under compression

HIGHRATE : Using Hopkinson Pressure Bar (strain rate greater than 1000/s)

IF10653a.dat - 100C, 6500/s, second test.

IF20703a.dat - 200C, 7000/s, first test.

IF30753a.dat - 300C, 7500/s, second test.

IFRT6Ka.dat - 25C, 6000/s, first test.

LOWRATE : Quasi-static tests using Instron load frame,

(strain rates between 0.0001/s and 1/s).

IF1003C.DAT - 100C, 0.001/s, thru-thickness, 0.08".

IF2003C.DAT - 200C, 0.001/s, thru-thickness, 0.08".

IF3003C.DAT - 300C, 0.001/s, thru-thickness, 0.08".

IFP1.DAT - 25C, 0.1/s, thru-thickness, 0.08".

IFTP1C.DAT - 25C, 0.1/s, thru-thickness, 0.08".

IFSP1C.DAT - 25C, 0.1/s, thru-thickness, 0.063".

IFTP3AC.DAT - 25C, 0.001/s, thru-thickness, 0.08".

P0018AC.T - 25C, 0.001/s, thru-thickness, compliance corrected L80IF3LU.

P0018BC.T - 25C, 0.001/s, thru-thickness, compliance corrected L80IF4LU.

P0018CC.T - 25C, 0.001/s, thru-thickness, compliance corrected L80IF8LU.

P0018DC.T - 25C, 0.001/s, thru-thickness, compliance corrected L80IF9LU.

P0018EC.T - 25C, 0.001/s, thru-thickness, compliance corrected L8010LU.

P0018FC.T - 25C, 0.001/s, thru-thickness, compliance corrected L8011LU.

P00163AC.T - 25C, 0.001/s, thru-thickness, compliance corrected L63IF1LU.

P00163BC.T - 25C, 0.001/s, thru-thickness, compliance corrected L63IF2LU.

MEDRATE : Medium strain-rate tests using MTS test system,

(strain rates between 5/s and 200/s).

IFSC100.DAT - 25C, 100/s, short stack, load cell.

IFSW100.DAT - 25C, 100/s, short stack, load washer.

IFTD20AC.DAT - 25C, 20/s, tall stack.

IFTW100.DAT - 25C, 100/s, tall stack.

IFTD20BC.DAT - 25C, 20/s, tall stack, second test.

IFTD50AC.DAT - 25C, 50/s, tall stack.

IFTD50BC.DAT - 25C, 50/s, tall stack, second test.

TENSILE : Tests under tensile.

LIFAT1E - 25C, 0.001/s, location A, test no. 1.

LIFAT2E - 25C, 0.001/s, location A, test no. 2.

LIFAT3E - 25C, 0.001/s, location A, test no. 3.

LIFBT1E - 25C, 0.001/s, location B, test no. 1.

LIFBT2E - 25C, 0.001/s, location B, test no. 2.

BIAXIAL : Tests under biaxial loading.

IF biaxial - 25C, 0.001/s, 12" X 12" PLATE

ZAMODEL : Modeling results for the Zerilli-Armstrong Model

(file format : True-plastic-strain True-stress[MPa])

BESTFIT:

IF10653.JCF - Isothermal strain-stress fit of ZA model to a test performed
at temperature=100C and strain rate=6500/s.

IF2003.ZBF - 200C, 0.001/s.

IF1003.ZBF - 100C, 0.001/s.

IF20703.ZBF - 200C, 7000/s.

IF30753.ZBF - 300C, 7500/s.

IF3003.ZBF - 300C, 0.001/s.

IFRT50.ZBF - 25C, 50/s.

IFRT100.ZBF - 25C, 100/s.

IFRT6K.ZBF - 25C, 6000/s.

IFRTP1.ZBF - 25C, 0.1/s.

IFRTP3.ZBF - 25C, 0.001/s.

IF _za.ZBF - Input file to calculate final fits to the ZA model.

IF _za - Model fit parameters for CM program

IF _za001.ZBF - Input file to calculate final fits to the ZA with a reference strain rate of 0.001/s.

IF _za001 - Model fit parameters for CM program

Additionally there is a Microsoft word document titled DOSKpub3/23/98. It is a paper submitted for publication on the mild steel.

Another folder is the epsfiles. It includes the enhanced post script data for the actual constitutive model fits.

APPENDIX B

INDEX AND DESCRIPTION OF DATA FILES FOR AKDQ, PRESTRAINED AKDQ, HSLA (2), AND A DUAL PHASE STEEL.

Phase 2. LANL - Auto/Steel Partnership interaction.

There are three primary folders in this phase.

DATA: consisting of the raw data, constitutive model fits, and kaleidagraph plots. Data files beginning with
HE____.dat or MB____.dat are high strain rate tests. All other files are intermediate or low strain rate tests.

EPSCM: consists of the enhanced post script plots of the results of the constitutive models.

Reports2: consists of progress reports and presentations

DATA: consists of primary folders.

AKDQARd: AKDQ mild steel, as received

ARsumm.qpc: Kaleidagraph file summarizing compression_data for phase 1 and 2__mild steels

RAW: data files

AKDQ01C.DAT: Strain rate = 0.001/s, Temperature = 23C (time, extensometer, load, strain,
stress)

AKDQ02C.DAT: Jump test 0.001/s to 0.1/s, 23C

AKDQ03C.DAT: 1/s, 23C

AKHR1AC.DAT: 61/s, 23C

HE0233W1.DAT: 2100/s, 23C (strain rate, strain, stress)

AKDQ2%: AKDQ mild steel 2% axial prestrain.

2Asumm.qpc: Kaleidagraph file summarizing compression_data at room temperature.

2Asumml1_4_97.qpc: Kaleidagraph file summarizing compression data for temperature and strain rate.

RAWcompdata: raw compression data.

AKD12AC.DAT: 0.001 to 0.1/s, 23C (time, extensometer, load, strain, stress) “
AKD12BC.DAT: 0.001 to 0.1/s, 23C “
AKDQ04C.DAT: 0.001 to 0.1/s, 23C “
AKDQ05C.DAT: 0.001 to 0.1/s, 23C “
AKDQ06C.DAT: 0.001 to 0.1/s, 23C “
AKDQ07C.DAT: 0.001 to 0.1/s, 23C “
AKDQ08C.DAT: 1/s, 23C “
AKDQ09C.DAT: 1/s, 23C “
AKDQ10C.DAT: 1/s, 23C “
AKDQ11C.DAT: 1/s, 23C “
AKDQ19C.DAT: 1/s, 200C “
AKDQ20C.DAT: 1/s, 200C “
AKDQ21C.DAT: 1/s, 200C “
AKDQ37C.DAT: 1/s, 100C “
AKDQ38C.DAT: 1/s, 100C “
AKDQ39C.DAT: 1/s, 100C “
AKHR3C.DAT: 76/s, 23C “
AKHR5C.DAT: 87/s, 23C “
HE0229.DAT: 2100/s, 23C (strain rate, strain, stress) “
HE0230.DAT: 800/s, 23C “
HE0231W1.DAT: 1900/s, 23C “
HE0232W1.DAT: 1800/s, 23C “
MB0060W1.DAT: 10500/s, 200C “
MB0061W1.DAT: 5000/s, 200C “
MB0062W1.DAT: 3750/s, 200C “
MB0063W1.DAT: 3750/s, 100C “
MB0064W1.DAT: 2800/s, 100C “
MB0065W1.DAT: 3350/s, 100C “

CM2A: consttutive model 2% axial

2p001rt.p: two column Stress/Strain data
2p001rt.p.JCf: Johnson-Cook representation of this data
2p001rt.p.MTSf: MTS representation of this data
2p001rt.p.ZBf: Zerilli-Armstrong representation of this data
2p1100.p: two column Stress/Strain data
2p1100.p.JCf: Johnson-Cook representation of this data
2p1100.p.MTSf: MTS representation of this data
2p1100.p.ZBf: Zerilli-Armstrong representation of this data
2p1200.p: two column Stress/Strain data
2p1200.p.JCf: Johnson-Cook representation of this data
2p1200.p.MTSf: MTS representation of this data
2p1200.p.ZBf: Zerilli-Armstrong representation of this data
2p19krt.p: two column Stress/Strain data
2p19krt.p.JCf: Johnson-Cook representation of this data
2p19krt.p.MTSf: MTS representation of this data
2p19krt.p.ZBf: Zerilli-Armstrong representation of this data
2p1rt.p: two column Stress/Strain data
2p1rt.p.JCf: Johnson-Cook representation of this data
2p1rt.p.MTSf: MTS representation of this data
2p1rt.p.ZBf: Zerilli-Armstrong representation of this data
2p1rt2.p: two column Stress/Strain data
2p35k100.p: two column Stress/Strain data
2p35k100.p.JCf: Johnson-Cook representation of this data
2p35k100.p.MTSf: MTS representation of this data
2p35k100.p.ZBf: Zerilli-Armstrong representation of this data
2p37k200.p: two column Stress/Strain data

2p37k200.p.JCf: Johnson-Cook representation of this data
 2p37k200.p.MTSf: MTS representation of this data
 2p37k200.p.ZBf: Zerilli-Armstrong representation of this data
 2p85rt.p: two column Stress/Strain data
 2p85rt.p.JCf: Johnson-Cook representation of this data
 2p85rt.p.MTSf: MTS representation of this data
 2p85rt.p.ZBf: Zerilli-Armstrong representation of this data
 AK2jc: fitting format (JC model)
 AK2jc.JC25
 AK2jc.JCF: final fit JC parameters
 AK2jc.JZA
 AK2za: fitting format (ZA model)
 AK2za.ZB25
 AK2za.ZBF: final fit ZA parameters
 AK2za.JZA
 DQSK2amts: fitting format (MTS model)
 DQSK2aMTS.doc
 DQSK2amts.eps: enhanced post script results of constitutive model (MTS)
 DQSK2amts.MTS25
 DQSK2amts.MTSF: final fit MTS parameters
 Jc2a.eps: enhanced post script results of constitutive model (Johnson-Cook)
 Za2a.eps: enhanced post script results of constitutive model (Zerilli-Armstrong)
 Data for cm: Copy of data files (.dat) used in the constitutive modeling

AKDQ8%: AKDQ mild steel 8% axial prestrain.

8Asumm.qpc: Kaleidagraph file summarizing compression data at room temperature.

8Asumm11_4_97.qpc: Kaleidagraph file summarizing compression data for temperature and strain rate.

RAW: raw compression data.

AKDQ13C.DAT: 0.001 to 0.1/s, 23C (time, extensometer, load, strain, stress)

AKDQ14C.DAT: 0.001 to 0.1/s, 23C

AKDQ15C.DAT: 0.001 to 0.1/s, 23C

AKDQ17C.DAT: 1/s, 23C

AKDQ18C.DAT: 1/s, 23C

AKDQ22C.DAT: 1/s, 200C

AKDQ23.DAT: 1/s, 200C

AKDQ23C.DAT: 1/s, 200C

AKDQ24C.DAT: 1/s, 200C

AKDQ40C.DAT: 1/s, 100C

AKDQ41C.DAT: 1/s, 100C

AKDQ42C.DAT: 1/s, 100C

AKHR6C.DAT: 83/s, 23C

AKHR7C.DAT: 89/s, 23C

AKHR8C.DAT: 86/s, 23C

AKS1S2WC.DAT: 1.2/s, 23C

AKS1SWC.DAT: 3.2/s, 23C

AKS1TWC.DAT: .87/s, 23C

HE0234.DAT: 1700/s, 23C, (strain rate, strain, stress)

HE0235.DAT: 2100/s, 23C

HE0236W1.DAT: 2000/s, 23C

MB0066W1.DAT: 4250/s, 200C

MB0067W1.DAT: 4250/s, 200C

MB0068W1.DAT: 3750/s, 200C

MB0069W1.DAT: 3400/s, 100C

MB0070W1.DAT: 3250/s, 100C

MB0071W1.DAT: 3500/s, 100C

CM8A: consttutive model 8% axial prestrain

8p001rt.p: two column Stress/Strain data

8p001rt.p.JCf: Johnson-Cook representation of this data
 8p001rt.p.MTSf: MTS representation of this data
 8p001rt.p.ZBf: Zerilli-Armstrong representation of this data
 8p1100.p: two column Stress/Strain data
 8p1100.p.JCf: Johnson-Cook representation of this data
 8p1100.p.MTSf: MTS representation of this data
 8p1100.p.ZBf: Zerilli-Armstrong representation of this data
 8p1200.p: two column Stress/Strain data
 8p1200.p.JCf: Johnson-Cook representation of this data
 8p1200.p.MTSf: MTS representation of this data
 8p1200.p.ZBf: Zerilli-Armstrong representation of this data
 8p2krt.p: two column Stress/Strain data
 8p2krt.p.JCf: Johnson-Cook representation of this data
 8p2krt.p.MTSf: MTS representation of this data
 8p2krt.p.ZBf: Zerilli-Armstrong representation of this data
 8p1rt.p: two column Stress/Strain data
 8p1rt.p.JCf: Johnson-Cook representation of this data
 8p1rt.p.MTSf: MTS representation of this data
 8p1rt.p.ZBf: Zerilli-Armstrong representation of this data
 8p1rt2.p: two column Stress/Strain data
 8p34k100.p: two column Stress/Strain data
 8p34k100.p.JCf: Johnson-Cook representation of this data
 8p34k100.p.MTSf: MTS representation of this data
 8p34k100.p.ZBf: Zerilli-Armstrong representation of this data
 8p4k200.p: two column Stress/Strain data
 8p4k200.p.JCf: Johnson-Cook representation of this data
 8p4k200.p.MTSf: MTS representation of this data
 8p4k200.p.ZBf: Zerilli-Armstrong representation of this data
 8p83rt.p: two column Stress/Strain data
 8p83rt.p.JCf: Johnson-Cook representation of this data
 8p83rt.p.MTSf: MTS representation of this data
 8p83rt.p.ZBf: Zerilli-Armstrong representation of this data
 AK8jz: fitting format (JC model)
 AK8jz.JC25
 AK8jz.JCF: final fit JC parameters
 AK8jz.JZA
 AK8jz: fitting format (ZA model)
 AK8jz.ZB25
 AK8jz.ZBF: final fit ZA parameters
 DQSK8amts: fitting format (MTS model)
 DQSK8amts.doc
 DQSK8amts.eps: enhanced post script results of constitutive model (MTS)
 DQSK8amts.MTS25
 DQSK8amts.MTSF: final fit MTS parameters
 Jc8a.eps: enhanced post script results of constitutive model (Johnson-Cook)
 Za8a.eps: enhanced post script results of constitutive model (Zerilli-Armstrong)
 cddata : Copy of data files (.dat) used in the constitutive modeling

AKDQ4x4: AKDQ mild steel 4x4 biaxial prestrain.

4X4summ11_4_97.qpc: Kaleidagraph file summarizing compression data for temperature and strain rate.

RAW: raw compression data.

AKDQ25C.DAT: 0.001 to 0.1/s, 23C (time, extensometer, load, strain, stress)	
AKDQ26C.DAT: 0.001 to 0.1/s, 23C	"
AKDQ27C.DAT: 0.001 to 0.1/s, 23C	"
AKDQ43.DAT: 1/s, 23C	"
AKDQ43C.DAT: 1/s, 23C	"
AKDQ44C.DAT: 1/s, 23C	"

AKDQ8x0: AKDQ mild steel 8x0 plain prestrain.
8x0summ11_4_97.qpc: Kaleidagraph file summarizing compression data for temperature and strain rate.

AKDQ28C.DAT: 0.001 to 0.1/s, 23C	(time, extensometer, load, strain, stress)
AKDQ29C.DAT: 0.001 to 0.1/s, 23C	“
AKDQ30C.DAT: 0.001 to 0.1/s, 23C	“
AKDQ46C.DAT: 1/s, 23C	“
AKDQ47C.DAT: 1/s, 23C	“
AKDQ48.DAT: 1/s, 23C	“
AKDQ61C.DAT: 1/s, 200C	“
AKDQ62C.DAT: 1/s, 200C	“
AKDQ63C.DAT: 1/s, 200C	“
AKDQ64C.DAT: 1/s, 100C	“
AKDQ65C.DAT: 1/s, 100C	“
AKDQ66C.DAT: 1/s, 100C	“
AKHR9C.DAT: 75/s, 23C	“
AKHR10C.DAT: 77/s, 23C	“
AKHR11C.DAT: 68/s, 23C	“

HE0241W1.DAT: 1900/s, 23C, (strain rate, strain, stress)	
HE0242W1.DAT: 2100/s, 23C	"
HE0243W1.DAT: 2000/s, 23C	"
MB0090W1.DAT: 3700/s, 200C	"
MB0091W1.DAT: 3850/s, 200C	"
MB0092W1.DAT: 3750/s, 200C	"
MB0093W1.DAT: 3250/s, 100C	"
MB0094W1.DAT: 3400/s, 100C	"
MB0095W1.DAT: 3300/s, 100C	"

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P801rt.p.MTSf: MTS representation of this data
 P801rt.p.ZBf: Zerilli-Armstrong representation of this data
 P8033100.p: two column Stress/Strain data
 P8033100.p.JCf: Johnson-Cook representation of this data
 P8033100.p.MTSf: MTS representation of this data
 P8033100.p.ZBf: Zerilli-Armstrong representation of this data
 P8037200.p: two column Stress/Strain data
 P8037200.p.JCf: Johnson-Cook representation of this data
 P8037200.p.MTSf: MTS representation of this data
 P8037200.p.ZBf: Zerilli-Armstrong representation of this data
 P8075rt.p: two column Stress/Strain data
 P8075rt.p.JCf: Johnson-Cook representation of this data
 P8075rt.p.MTSf: MTS representation of this data
 P8075rt.p.ZBf: Zerilli-Armstrong representation of this data
 AK80jz: fitting format (JC model)
 AK80jz.JC25
 AK80jz.JCF: final fit JC parameters
 AK80jz.JZA
 AK80jz: fitting format (ZA model)
 AK80jz.ZB25
 AK80jz.ZBF: final fit ZA parameters
 AK80jz2: fitting format (ZA model)
 AK80jz2.JZA
 AK80jz2.ZB25
 AK80jz2.ZBF: final fit ZA parameters
 DQSK80mts: fitting format (MTS model)
 DQSK80MTS.doc
 DQSK80mts.eps: enhanced post script results of constitutive model (MTS)
 DQSK80mts.MTS25
 DQSK80mts.MTSF: final fit MTS parameters
 Jc80eps : enhanced post script results of constitutive model (Johnson-Cook)
 Za80.eps: enhanced post script results of constitutive model (Zerilli-Armstrong)
 cmdata : Copy of data files (.dat) used in the constitutive modeling

AKDQ2x2: AKDQ mild steel 2x2 biaxial prestrain.

2X2summ11_4_97.qpc: Kaleidagraph file summarizing compression data for temperature and strain rate.

RAW: raw compression data.

AKDQ31C.DAT: 0.001 to 0.1/s, 23C (time, extensometer, load, strain, stress)
 AKDQ32C.DAT: 0.001 to 0.1/s, 23C "
 AKDQ33C.DAT: 0.001 to 0.1/s, 23C "
 AKDQ49.DAT: 1/s, 23C "
 AKDQ50C.DAT: 1/s, 23C "
 AKDQ51C.DAT: 1/s, 23C "
 AKDQ67C.DAT: 1/s, 200C "
 AKDQ68C.DAT: 1/s, 200C "
 AKDQ69C.DAT: 1/s, 200C "
 AKDQ70C.DAT: 1/s, 100C "
 AKDQ71C.DAT: 1/s, 100C "
 AKDQ72C.DAT: 1/s, 100C "
 AKHR15C.DAT: 95/s, 23C "
 AKHR16C.DAT: 96/s, 23C "
 AKHR17C.DAT: 95/s, 23C "
 AKHR21C.DAT: 77/s, 23C "
 MB0160W1.DAT: 2600/s, 23C, (strain rate, strain, stress)
 MB0161W1.DAT: 2700/s, 23C "
 MB0162W1.DAT: 2700/s, 23C "

MB0072W1.DAT: 4250/s, 200C "
 MB0073W1.DAT: 4000/s, 200C "
 MB0074W1.DAT: 3300/s, 200C "
 MB0075W1.DAT: 3150/s, 100C "
 MB0076W1.DAT: 3300/s, 100C "
 MB0077W1.DAT: 3400/s, 100C "
 CM2X2: consttutive model 2x2 biaxial prestrain
 P22001rt.p: two column Stress/Strain data
 P22001rt.p.JCf: Johnson-Cook representation of this data
 P22001rt.p.MTSf: MTS representation of this data
 P22001rt.p.ZBf: Zerilli-Armstrong representation of this data
 P221100.p: two column Stress/Strain data
 P221100.p.JCf: Johnson-Cook representation of this data
 P221100.p.MTSf: MTS representation of this data
 P221100.p.ZBf: Zerilli-Armstrong representation of this data
 P221200.p: two column Stress/Strain data
 P221200.p.JCf: Johnson-Cook representation of this data
 P221200.p.MTSf: MTS representation of this data
 P221200.p.ZBf: Zerilli-Armstrong representation of this data
 P2227krt.p: two column Stress/Strain data
 P2227krt.p.JCf: Johnson-Cook representation of this data
 P2227krt.p.MTSf: MTS representation of this data
 P2227krt.p.ZBf: Zerilli-Armstrong representation of this data
 P221rt.p: two column Stress/Strain data
 P221rt.p.JCf: Johnson-Cook representation of this data
 P221rt.p.MTSf: MTS representation of this data
 P221rt.p.ZBf: Zerilli-Armstrong representation of this data
 P2234100.p: two column Stress/Strain data
 P2234100.p.JCf: Johnson-Cook representation of this data
 P2234100.p.MTSf: MTS representation of this data
 P2234100.p.ZBf: Zerilli-Armstrong representation of this data
 P2233200.p: two column Stress/Strain data
 P2233200.p.JCf: Johnson-Cook representation of this data
 P2233200.p.MTSf: MTS representation of this data
 P2233200.p.ZBf: Zerilli-Armstrong representation of this data
 P2295rt.p: two column Stress/Strain data
 P2295rt.p.JCf: Johnson-Cook representation of this data
 P2295rt.p.MTSf: MTS representation of this data
 P2295rt.p.ZBf: Zerilli-Armstrong representation of this data
 AK22jz: fitting format (JC model)
 AK22jz.JC25
 AK22jz.JCF: final fit JC parameters
 AK22jz.JZA
 AK22jz: fitting format (ZA model)
 AK22jz.ZB25
 AK22jz.ZBF: final fit ZA parameters
 DQSK22mts: fitting format (MTS model)
 DQSK22MTS.doc
 DQSK22mts.eps: enhanced post script results of constitutive model (MTS)
 DQSK22mts.MTS25
 DQSK22mts.MTSF: final fit MTS parameters
 Jc22.eps: enhanced post script results of constitutive model (Johnson-Cook)
 Za22.eps: enhanced post script results of constitutive model (Zerilli-Armstrong)
 cmdata : Copy of data files (.dat) used in the constitutive modeling

AKDQ2x0: AKDQ mild steel 8x0 plain prestrain.

2x0summ11_4_97.qpc: Kaleidagraph file summarizing compression data for temperature and strain rate.

RAW: raw compression data.

AKDQ34C.DAT: 0.001 to 0.1/s, 23C (time, extensometer, load, strain, stress)

AKDQ35C.DAT: 0.001 to 0.1/s, 23C

AKDQ36C.DAT: 0.001 to 0.1/s, 23C

AKDQ52C.DAT: 1/s, 23C

AKDQ53C.DAT: 1/s, 23C

AKDQ54.DAT: 1/s, 23C

AKDQ73C.DAT: 1/s, 200C

AKDQ74C.DAT: 1/s, 200C

AKDQ75C.DAT: 1/s, 200C

AKDQ76.DAT: 1/s, 100C

AKDQ76C.DAT: 1/s, 100C

AKDQ77C.DAT: 1/s, 100C

AKDQ78C.DAT: 1/s, 100C

AKHR18C.DAT: 75/s, 23C

AKHR19C.DAT: 77/s, 23C

AKHR20C.DAT: 68/s, 23C

AKHR22C.DAT: 68/s, 23C

MB0157W1.DAT: 5750/s, 23C, (strain rate, strain, stress)

MB0158W1.DAT: 4500/s, 23C

MB0159W1.DAT: 3300/s, 23C

MB0084W1.DAT: 4000/s, 200C

MB0085W1.DAT: 3750/s, 200C

MB0086W1.DAT: 3600/s, 200C

MB0087W1.DAT: 3500/s, 100C

MB0088W1.DAT: 3400/s, 100C

MB0089W1.DAT: 3350/s, 100C

CM2X0: consttutive model 2x0 plain prestrain

P20001rt.p: two column Stress/Strain data

P20001rt.p.JCf: Johnson-Cook representation of this data

P20001rt.p.MTSf: MTS representation of this data

P20001rt.p.ZBf: Zerilli-Armstrong representation of this data

P201100.p: two column Stress/Strain data

P201100.p.JCf: Johnson-Cook representation of this data

P201100.p.MTSf: MTS representation of this data

P201100.p.ZBf: Zerilli-Armstrong representation of this data

P201200.p: two column Stress/Strain data

P201200.p.JCf: Johnson-Cook representation of this data

P201200.p.MTSf: MTS representation of this data

P801200.p.ZBf: Zerilli-Armstrong representation of this data

P2033krt.p: two column Stress/Strain data

P2033krt.p.JCf: Johnson-Cook representation of this data

P2033krt.p.MTSf: MTS representation of this data

P2033krt.p.ZBf: Zerilli-Armstrong representation of this data

P201rt.p: two column Stress/Strain data

P201rt.p.JCf: Johnson-Cook representation of this data

P201rt.p.MTSf: MTS representation of this data

P201rt.p.ZBf: Zerilli-Armstrong representation of this data

P2035100.p: two column Stress/Strain data

P2035100.p.JCf: Johnson-Cook representation of this data

P2035100.p.MTSf: MTS representation of this data

P2035100.p.ZBf: Zerilli-Armstrong representation of this data

P2036200.p: two column Stress/Strain data

P2036200.p.JCf: Johnson-Cook representation of this data

P2036200.p.MTSf: MTS representation of this data

P2036200.p.ZBf: Zerilli-Armstrong representation of this data

P2095rt.p: two column Stress/Strain data

P2095rt.p.JCf: Johnson-Cook representation of this data

P2095rt.p.MTSf: MTS representation of this data
 P2095rt.p.ZBf: Zerilli-Armstrong representation of this data
 AK20jz: fitting format (JC model)
 AK20jz.JC25
 AK20jz.JCF: final fit JC parameters
 AK20jz.JZA
 AK20jz: fitting format (ZA model)
 AK20jz.ZB25
 AK20jz.ZBF: final fit ZA parameters
 DQSK20mts: fitting format (MTS model)
 DQSK20MTS.doc
 DQSK20mts.eps: enhanced post script results of constitutive model (MTS)
 DQSK20mts.MTS25
 DQSK20mts.MTSF: final fit MTS parameters
 Jc20eps : enhanced post script results of constitutive model (Johnson-Cook)
 Za20.eps: enhanced post script results of constitutive model (Zerilli-Armstrong)
 cmdata : Copy of data files (.dat) used in the constitutive modeling

HSLA1682:.

HSLAsumm.qpc: Kaleidagraph file summarizing compression data for temperature and strain rate.

RAW: raw compression data.

HSLAPIA.DAT: 1/s, 23C, (time-incorrect for this strain rate, LVDT, extensometer, load)
 HSLAPIAC.DAT: 1/s, 23C, compliance corrected, (extensometer, load, strain, stress)
 HSLAPIB.DAT: 1/s, 23C, (time-incorrect for this strain rate, LVDT, extensometer, load)
 HSLAPIBC.DAT: 1/s, 23C, compliance corrected, (extensometer, load, strain, stress)
 HSLAPIC.DAT: 1/s, 23C, (time-incorrect for this strain rate, LVDT, extensometer, load)
 HSLAPICC.DAT: 1/s, 23C, compliance corrected, (extensometer, load, strain, stress)
 HSLA001C.DAT: 0.001/s, 23C, compliance corrected, (time, extensometer, load, strain, stress)
 HSLB001.DAT: 0.001/s, 23C, (time, LVDT, extensometer, load)
 HSLB001C.DAT: 0.001/s, 23C, compliance corrected, (extensometer, load, strain, stress)
 HSLC001.DAT: 0.001/s, 23C, (time, LVDT, extensometer, load)
 HSLC001C.DAT: 0.001/s, 23C, compliance corrected, (extensometer, load, strain, stress)
 HS2001.DAT: 1/s, 200C, (time-incorrect for this strain rate, LVDT, extensometer, load)
 HS2001C.DAT: 1/s, 200C, compliance corrected, (extensometer, load, strain, stress)
 HS2002.DAT: 1/s, 200C, (time-incorrect for this strain rate, LVDT, extensometer, load)
 HS2002C.DAT: 1/s, 200C, compliance corrected, (extensometer, load, strain, stress)
 HS1001.DAT: 1/s, 100C, (time-incorrect for this strain rate, LVDT, extensometer, load)
 HS1001C.DAT: 1/s, 100C, compliance corrected, (extensometer, load, strain, stress)
 HS1002.DAT: 1/s, 100C, (time-incorrect for this strain rate, LVDT, extensometer, load)
 HS1002C.DAT: 1/s, 100C, compliance corrected, (extensometer, load, strain, stress)
 HSHR21C.DAT: 75/s, 23C, (time, extensometer, load, strain, stress)
 HSHR22C.DAT: 75/s, 23C, (time, extensometer, load, strain, stress)
 HSHR23C.DAT: 74/s, 23C, (time, extensometer, load, strain, stress)
 HSHR24C.DAT: 123/s, 23C, (time, extensometer, load, strain, stress)
 HSHR25C.DAT: 134/s, 23C, (time, extensometer, load, strain, stress)
 HSHR26C.DAT: 130/s, 23C, (time, extensometer, load, strain, stress)
 HSHR28C.DAT: 20/s, 23C, (time, extensometer, load, strain, stress)
 MB0163.DAT: 5750/s, 23C, (strain rate, strain, stress)
 MB0163a.DAT: 5750/s, 23C "
 MB0163W1.DAT: 5750/s, 23C "
 MB0164W1.DAT: 4500/s, 23C "
 MB0165W1.DAT: 3300/s, 23C "
 MB0096W1.DAT: 4000/s, 200C "
 MB0097W1.DAT: 3750/s, 200C "
 MB0098W1.DAT: 3600/s, 200C "
 MB0099W1.DAT: 3500/s, 100C "
 MB0100W1.DAT: 3400/s, 100C "

MB0101W1.DAT: 3350/s, 100C
 CM: constitutive model HSLA1682 steel
 Hsla001.p: two column Stress/Strain data
 Hsla001.p.JCf: Johnson-Cook representation of this data
 Hsla001.p.MTSf: MTS representation of this data
 Hsla001.p.ZBf: Zerilli-Armstrong representation of this data
 hs1001.p: two column Stress/Strain data
 hs1001.p.JCf: Johnson-Cook representation of this data
 hs1001.p.ZBf: Zerilli-Armstrong representation of this data
 hs2001.p: two column Stress/Strain data
 hs2001.p.JCf: Johnson-Cook representation of this data
 hs2001.p.MTSf: MTS representation of this data
 hs2001.p.ZBf: Zerilli-Armstrong representation of this data
 Mb0163.p: two column Stress/Strain data
 Mb0163.p.JCf: Johnson-Cook representation of this data
 Mb0163.p.MTSf: MTS representation of this data
 Mb0163.p.ZBf: Zerilli-Armstrong representation of this data
 Hsla1c.p: two column Stress/Strain data
 Hsla1c.p.JCf: Johnson-Cook representation of this data
 Hsla1c.p.MTSf: MTS representation of this data
 Hsla1c.p.ZBf: Zerilli-Armstrong representation of this data
 Mb0099.p: two column Stress/Strain data
 Mb0099.p.JCf: Johnson-Cook representation of this data
 Mb0099.p.MTSf: MTS representation of this data
 Mb0099.p.ZBf: Zerilli-Armstrong representation of this data
 Mb0097.p: two column Stress/Strain data
 Mb0097.p.JCf: Johnson-Cook representation of this data
 Mb0097.p.MTSf: MTS representation of this data
 Mb0097.p.ZBf: Zerilli-Armstrong representation of this data
 Hshr22.p: two column Stress/Strain data
 Hshr22a.p: two column Stress/Strain data
 Hshr22.p.JCf: Johnson-Cook representation of this data
 Hshr22a.p.MTSf: MTS representation of this data
 Hshr22.p.ZBf: Zerilli-Armstrong representation of this data
 hslajz: fitting format (JC model)
 hslajz.JC25
 hslajz.JCF: final fit JC parameters
 hslajz.JZA
 hslajz: fitting format (ZA model)
 hslajz.ZB25
 hslajz.ZBF: final fit ZA parameters
 HSLA2mts: fitting format (MTS model)
 HSLA2MTS.doc
 HSLA2mts.eps: enhanced post script results of constitutive model (MTS)
 HSLA2mts.MTS25
 HSLA2mts.MTSF: final fit MTS parameters
 Hslajc.eps : enhanced post script results of constitutive model (Johnson-Cook)
 Hslaza.eps: enhanced post script results of constitutive model (Zerilli-Armstrong)

Dual Phase.

RAW: raw compression data.

DPRT1B.DAT: 1/s, 23C, (time-incorrect for this strain rate, LVDT, extensometer, load)
 DPRT1BC.DAT: 1/s, 23C, compliance corrected, (extensometer, load, strain, stress)
 DPRT1C.DAT: 1/s, 23C, (time-incorrect for this strain rate, LVDT, extensometer, load)
 DPRT1CC.DAT: 1/s, 23C, compliance corrected, (extensometer, load, strain, stress)
 DPRP3A.DAT: 0.001/s, 23C, (time, LVDT, extensometer, load)
 DPRP3AC.DAT: 0.001/s, 23C, compliance corrected, (extensometer, load, strain, stress)

Mb0257.p.MTSf: MTS representation of this data
 Mb0257.p.ZBf: Zerilli-Armstrong representation of this data
 Mb0259.p: two column Stress/Strain data
 Mb0259.p.JCf: Johnson-Cook representation of this data
 Mb0259.p.MTSf: MTS representation of this data
 Mb0259.p.ZBf: Zerilli-Armstrong representation of this data
 Dphr72.p: two column Stress/Strain data
 Dphr72a.p: two column Stress/Strain data
 Dphr72.p.JCf: Johnson-Cook representation of this data
 Dphr72a.p.MTSf: MTS representation of this data
 Dphr72.p.ZBf: Zerilli-Armstrong representation of this data
 dpjz: fitting format (JC model)
 dpjz.JC25
 dpjz.JCF: final fit JC parameters
 dpjz.JZA
 dpjz: fitting format (ZA model)
 dpjz.ZB25
 dpjz.ZBF: final fit ZA parameters
 DPmts: fitting format (MTS model)
 DPMTS.doc
 DPmts.eps: enhanced post script results of constitutive model (MTS)
 DPmts.MTS25
 DPmts.MTSF: final fit MTS parameters
 dpjc.eps: enhanced post script results of constitutive model (Johnson-Cook)
 dpza.eps: enhanced post script results of constitutive model (Zerilli-Armstrong)

Tensile: Tensile test results for phase two materials

Data folder:

L0AKD1.DAT: AKDQ as received, 0 degrees #1
 L0AKD2.DAT: AKDQ as received, 0 degrees #2
 L0AXI1.DAT: AKDQ 2% axial, 0 degrees #1
 L0AXI2.DAT: AKDQ 2% axial, 0 degrees #2
 L0BIX1.DAT: AKDQ 4x4, 0 degrees #1
 L0BIX2.DAT: AKDQ 4x4, 0 degrees #2
 L0HSL2.DAT: HSLA 1682, 0 degrees #1
 L0HSL3.DAT: HSLA 1682, 0 degrees #2
 L1AXI0.DAT: AKDQ 2% axial, 0 degrees #1
 L1AXI45.DAT: AKDQ 2% axial, 0 degrees #1
 L1AXI90.DAT: AKDQ 2% axial, 0 degrees #1
 L1PLA0.DAT: AKDQ 8x0, 0 degrees #1
 L1PLA45.DAT: AKDQ 8x0, 45 degrees #1
 L1PLA90.DAT: AKDQ 8x0, 90 degrees #1
 L2001.DAT: AKDQ 2x0, 0 degrees #1
 L2002.DAT: AKDQ 2x0, 0 degrees #2
 L20451.DAT: AKDQ 2x0, 45 degrees #1
 L20452.DAT: AKDQ 2x0, 45 degrees #2
 L20901.DAT: AKDQ 2x0, 90 degrees #1
 L20902.DAT: AKDQ 2x0, 90 degrees #2
 L2201.DAT: AKDQ 2x2, 0 degrees #1
 L2202.DAT: AKDQ 2x2, 0 degrees #2
 L22451.DAT: AKDQ 2x2, 45 degrees #1
 L22452.DAT: AKDQ 2x2, 45 degrees #2
 L22901.DAT: AKDQ 2x2, 90 degrees #1
 L22902.DAT: AKDQ 2x2, 90 degrees #2
 L22AKD1.DAT: AKDQ as received, 22 degrees #1
 L22AKD2.DAT: AKDQ as received, 22 degrees #2
 L2AXI0.DAT: AKDQ 2% axial, 0 degrees #2
 L2AXI45.DAT: AKDQ 2% axial, 45 degrees #2

L2AXI90.DAT: AKDQ 2% axial, 90 degrees #2
 L2PLA0.DAT: AKDQ 8x0, 0 degrees #2
 L2PLA45.DAT: AKDQ 8x0, 45 degrees #2
 L2PLA90.DAT: AKDQ 8x0, 90 degrees #2
 L45AKD1.DAT: AKDQ as received, 45 degrees #1
 L45AKD2.DAT: AKDQ as received, 45 degrees #2
 L45AXI1.DAT: AKDQ 8% axial, 45 degrees #1
 L45AXI2.DAT: AKDQ 8% axial, 45 degrees #2
 L45BIX1.DAT: AKDQ 4x4, 45 degrees #1
 L45BIX2.DAT: AKDQ 4x4, 45 degrees #2
 L45HSL1.DAT: HSLA 1682, 45 degrees #1
 L45HSL2.DAT: HSLA 1682, 45 degrees #2
 L67AKD1.DAT: AKDQ as received, 67 degrees #1
 L67AKD2.DAT: AKDQ as received, 67 degrees #2
 L90AKD1.DAT: AKDQ as received, 90 degrees #1
 L90AKD2.DAT: AKDQ as received, 90 degrees #2
 L90AXI1.DAT: AKDQ 8% axial, 90 degrees #1
 L90AXI2.DAT: AKDQ 8% axial, 90 degrees #2
 L90BIX1.DAT: AKDQ 4x4, 90 degrees #1
 L90BIX2.DAT: AKDQ 4x4, 90 degrees #2
 L90HSL1.DAT: HSLA 1682, 90 degrees #1
 L90HSL2.DAT: HSLA 1682, 90 degrees #2
 LDP01.DAT: Dual Phase, 0 degrees #1
 LDP02.DAT: Dual Phase, 0 degrees #2
 LDP451.DAT: Dual Phase, 45 degrees #1
 LDP452.DAT: Dual Phase, 45 degrees #2
 LDP901.DAT: Dual Phase, 90 degrees #1
 LDP902.DAT: Dual Phase, 90 degrees #2

Kgplots: Results of tensile tests

Ak22.qpc: Biaxial 2x2 perstrain tensile plot
 Ak2a.qpc: axial 2% perstrain tensile plot
 Ak2p.qpc: plane 2x0 perstrain tensile plot
 Ak44bi.qpc: Biaxial 4x4 perstrain tensile plot
 Ak8a.qpc: axial 8% perstrain tensile plot
 Ak8p.qpc: plane 8x0 perstrain tensile plot
 Akasrec.qpc: As received tensile plot
 Dpten.qpc: Dual Phase tensile plot
 HSLA1682.qpc: HSLA 1682 tensile plot

EPSCM: constitutive model results

Dpjc.eps: Dual Phase Johnson-Cook results
 DPmts.eps: Dual Phase MTS results
 Dpza.eps: Dual Phase Zerilli-Armstrong results
 DQSK20mts.eps: Mild steel 2x0 prestrain MTS results
 DQSK22mts.eps: Mild steel 2x2 prestrain MTS results
 DQSK2amts.eps: Mild steel 2% axial prestrain MTS results
 DQSK44mts.eps: Mild steel 4x4 prestrain MTS results
 DQSK80mts.eps: Mild steel 8x0 prestrain MTS results
 DQSK8amts.eps: Mild steel 8% axial prestrain MTS results
 HSLA2mts.eps: HSLA 1682 steel MTS results
 hslajc.eps: HSLA 1682 steel Johnson-Cook results
 hslaza.eps: HSLA 1682 steel Zerilli-Armstrong results
 Ifjcsfix.eps: Interstitial free, yield strength, Johnson-Cook fit
 Ifysfix.eps: Interstitial free, yield strength fit
 Jc20.eps: Mild steel 2x0 prestrain Johnson-Cook results
 Jc22.eps: Mild steel 2x2 prestrain Johnson-Cook results
 Jc2a.eps: Mild steel 2% axial prestrain Johnson-Cook results

Jc44.eps: Mild steel 4x4 prestrain Johnson-Cook results
Jc80.eps: Mild steel 8x0 prestrain Johnson-Cook results
Jc8a.eps: Mild steel 8% axial prestrain Johnson-Cook results
za20.eps: Mild steel 2x0 prestrain Zerilli-Armstrong results
za22.eps: Mild steel 2x2 prestrain Zerilli-Armstrong results
za2a.eps: Mild steel 2% axial prestrain Zerilli-Armstrong results
za44.eps: Mild steel 4x4 prestrain Zerilli-Armstrong results
za80.eps: Mild steel 8x0 prestrain Zerilli-Armstrong results
za8a.eps: Mild steel 8% axial prestrain Zerilli-Armstrong results

Reports2: Reports and presentations made to the Auto/steel partnership

Progrep3_12_97: word document
A/S-P Prog4_21_97: word document
Steel5_8_97: powerpoint Document
Steel6_25_97.ppt: powerpoint Document
Steel8_5_97.ppt: powerpoint Document
Steel11_5_97.ppt: powerpoint Document
Steel1_29_98.ppt: powerpoint Document
Steel5_6_98.ppt: powerpoint Document
Steel1_7_97.ppt: powerpoint Document

DQSK-low, intermediate S.R., ref. S.R. = 0.001/s, JC

HSLA-low, intermediate S.R., ref. S.R. = 0.001/s, JC

IF-low, intermediate S.R., ref. S.R. = 0.001/s, JC

M190-low, intermediate S.R., ref. S.R. = 0.001/s, JC

DQSK Johnson-Cook updated parameters

Los Alamos

DQSK Johnson-Cook YS parameters

Los Alamos

$$\sigma = (A + B \cdot \epsilon_p^n) (1 + C \cdot \ln \dot{\epsilon}) (1 - [(T - T_{Room}) / (T_{Melt} - T_{Room})]^m)$$

HSLA Johnson-Cook updated parameters

HSLA Johnson-Cook YS parameters

Los Alamos

IF Johnson-Cook updated parameters

JC fit for fixed yield point - IF steel

Los Alamos

$$\sigma = (A + B \cdot \epsilon_p^n)(1 + C \cdot \ln \dot{\epsilon})(1 - [(T - T_{Room}) / (T_{Melt} - T_{Room})]^m)$$

M190 Johnson-Cook updated parameters

M190 Johnson-Cook YS parameters

2% prestrain Johnson - Cook

8% Johnson - Cook

2x2% Johnson - Cook

Los Alamos

$$\sigma = (A + B \cdot \epsilon_p^n) (1 + C \cdot \ln \dot{\epsilon}) (1 - [(T - T_{Room}) / (T_{Melt} - T_{Room})]^m)$$

4x4% Johnson - Cook

Los Alamos

$$\sigma = (A + B \cdot \epsilon_p^n) (1 + C \cdot \ln \dot{\epsilon}) (1 - [(T - T_{Room}) / (T_{Melt} - T_{Room})]^m)$$

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MST-5: Materials Research and Processing Science

Dynamic Properties

2x0% Johnson - Cook

Los Alamos

8x0% Johnson - Cook

Los Alamos

$$\sigma = (A + B \cdot \epsilon_p^n) (1 + C \cdot \ln \dot{\epsilon}) (1 - [(T - T_{Room}) / (T_{Melt} - T_{Room})]^m)$$

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Dynamic Properties

HSLA 1682 Johnson - Cook

Los Alamos

Dual Phase Johnson - Cook

Los Alamos

Los Alamos National Laboratory

MST-5: Materials Research and Processing Science

Dynamic Properties

Equation and Parameters for JC Model Using Low and Intermediate Strain Rates

$$\sigma = (A + B \cdot \epsilon^n) \cdot (1 + C \ln \dot{\epsilon}) \cdot (1 - T^{*m}); \quad T^* = \frac{T - 298}{T_{melt} - 298}$$

JC model	A, MPa	B, MPa	n	C	m	T _{melt} , K
DQSK	130	420	0.26	0.025	0.9	1808
HSLA	347.5	405	0.36	0.009	0.9	1808
M-190	210	450	0.4	0.023	0.023	1808
IF	120	1600	0.02	0.0	0.01	1808

Equation and Parameters for JC Model, Phase 1

$$\sigma = (A + B \cdot \varepsilon^n) \cdot (1 + C \ln \dot{\varepsilon}) \cdot (1 - T^{*m}); \quad T^* = \frac{T - 298}{T_{melt} - 298}$$

JC model	A, MPa	B, MPa	n	C	m	T _{melt} , K
DQSK	18	560	0.11	0.03	0.7	1808
HSLA	7.5	810	0.17	0.014	1.6	1808
M-190	104	1960	0.053	0.00775	0.93	1808
IF	280	550	0.396	0.042	0.65	1808

Equation and Parameters for JC Model, Phase 2

$$\sigma = (A + B \cdot \varepsilon^n) \cdot (1 + C \ln \dot{\varepsilon}) \cdot (1 - T^{*m}); \quad T^* = \frac{T - 298}{T_{melt} - 298}$$

JC model	A, MPa	B, MPa	n	C	m	T _{melt} , K
AKDQ 2%	250	430	0.31	0.05	0.6	1808
AKDQ 8%	260	350	0.13	0.038	0.6	1808
AK 2x2%	410	210	0.39	0.052	0.625	1808
AK 4x4%	370	330	0.39	0.054	0.6	1808
AK 2x0	160	500	.2	0.055	0.6	1808
AK 8x0	420	220	0.41	0.05	0.7	1808
HSLA 1682	400	600	0.38	0.02	0.8	1808
Dual Phase	300	1170	0.13	0.0075	1.00	1808

DQSK-low, intermediate S.R., ZA

HSLA-low, intermediate S.R., ZA

IF-low, intermediate S.R., ZA

M190-low, intermediate S.R., ZA

DQSK Zerilli-Armstrong updated parameters

DQSK Zerilli-Armstrong updated yield strength parameters

HSLA Zerilli-Armstrong updated parameters

HSLA Zerilli-Armstrong updated yield strength parameters

IF Zerilli-Armstrong updated parameters

ZA fit for fixed yield point - IF Steel

Los Alamos

$$\sigma = C_0 + C_1 \cdot \exp(-C_3 \cdot T + C_4 \cdot T \cdot \ln \dot{\epsilon}) + C_5 \cdot \epsilon_p^n$$

M190 Zerilli-Armstrong updated parameters

M190 Zerilli-Armstrong updated YS parameters

2% Zerelli - Armstrong

Los Alamos

$$\sigma = C_0 + C_1 \cdot \exp(-C_3 \cdot T + C_4 \cdot T \cdot \ln \dot{\epsilon}) + C_5 \cdot \dot{\epsilon}^n$$

#	C ₀	C ₁	C ₃	C ₄	C ₅	n
F	80.0	1075.0	0.00600	0.0003400	390.0	0.3400

AK2Za

1900/s, 298K
3500/s, 373K
85/s, 298K
3700/s, 473K
1/s, 298K
1/s, 373K
0.001/s, 298K
1/s, 473K

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Dynamic Properties

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8% Zerelli - Armstrong

Los Alamos

Los Alamos National Laboratory

Dynamic Properties

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2x2% Zerelli - Armstrong

Los Alamos

$$\sigma = C_0 + C_1 \cdot \exp(-C_3 \cdot T + C_4 \cdot T \cdot \ln \dot{\epsilon}) + C_5 \cdot \dot{\epsilon}^n$$

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Dynamic Properties

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4x4% Zerelli - Armstrong

Los Alamos

$$\sigma = C_0 + C_1 \cdot \exp(-C_3 \cdot T + C_4 \cdot T \cdot \ln \dot{\epsilon}) + C_5 \cdot \epsilon_p^n$$

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Dynamic Properties

2x0% Zerelli - Armstrong

Los Alamos

$$\sigma = C_0 + C_1 \cdot \exp(-C_3 \cdot T + C_4 \cdot T \cdot \ln \dot{\epsilon}) + C_5 \cdot \epsilon_p^n$$

3300/s, 298K
 3500/s, 373K
 95/s, 298K
 3600/s, 473K
 1/s, 298K
 1/s, 373K
 0.001/s, 298K
 1/s, 473K

8x0% Zerelli - Armstrong

Los Alamos

$$\sigma = C_0 + C_1 \cdot \exp(-C_3 \cdot T + C_4 \cdot T \cdot \ln \dot{\epsilon}) + C_5 \cdot \epsilon_p^n$$

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Dynamic Properties

HSLA 1682 Zerelli - Armstrong

Los Alamos

$$\sigma = C_0 + C_1 \cdot \exp(-C_3 \cdot T + C_4 \cdot T \cdot \ln \dot{\epsilon}) + C_5 \cdot \epsilon_p^n$$

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MST-5: Materials Research and Processing Science

Dynamic Properties

Dual Phase Zerelli - Armstrong

Los Alamos

Equation and Parameters for ZA Model Using Low and Intermediate Strain Rates

$$\sigma = C_0 + C_1 \cdot \exp(-C_3 \cdot T + C_4 \cdot T \cdot \ln \dot{\epsilon}) + C_5 \cdot \epsilon_p^n$$

ZA model	C ₀ , MPa	C ₁ , MPa	C ₃ , K ⁻¹	C ₄ , K ¹ s ⁻¹	C ₅ (Mpa)	n
DQSK	110	2300	0.0115	0.00063	460	0.31
HSLA	340	1400	0.0127	0.00065	400	0.36
M-190	340	1000	0.0016	0.0	750	0.04
IF	10	120	0.0049	0.00012	510	0.51

Equation and Parameters for ZA Model, Phase 1

$$\sigma = C_0 + C_1 \cdot \exp(-C_3 \cdot T + C_4 \cdot T \cdot \ln \dot{\epsilon}) + C_5 \cdot \epsilon_p^n$$

ZA model	C_0 , MPa	C_1 , MPa	C_3 , K ⁻¹	C_4 , K ⁻¹	C_5 , MPa	n
DQSK	2	1950	0.0095	0.0005	500	0.24
DQSK+ys	130	1650	0.009	0.0005	350	0.35
HSLA	10	1800	0.0145	0.00095	740	0.17
HSLA+ys	330	1600	0.0132	0.0009	630	0.58
M-190	250	1540	0.0025	0.00006	1040	0.09
IF	0.0	1175	0.0041	0.00021	480	0.58

Equation and Parameters for ZA Model, Phase 2

$$\sigma = C_0 + C_1 \cdot \exp(-C_3 \cdot T + C_4 \cdot T \cdot \ln \dot{\epsilon}) + C_5 \cdot \epsilon_p^n$$

ZA model	C ₀ , MPa	C ₁ , MPa	C ₃ , K ⁻¹	C ₄ , K ⁻¹ s ⁻¹	C ₅ , MPa	n
AKDQ 2%	80	1075	0.006	0.00034	390	0.34
AKDQ 8%	200	1590	0.007	0.00032	240	0.4
AKDQ 2x2%	130	1190	0.006	0.00034	350	0.4
AKDQ 4x4%	130	1110	0.0055	0.0003	280	0.27
AKDQ 2x0%	20	1170	0.0055	0.0003	420	0.29
AKDQ 8x0%	190	1080	0.005	0.00028	280	0.63
HSLA 1682	150	875	0.00525	0.00024	600	0.29
Dual Phase	10.0	2840	0.011	0.00033	1340	0.11

Mechanical Threshold Stress (MTS) Model

$$\frac{\sigma}{\mu} = \frac{\sigma_a}{\mu} + S_i(\dot{\epsilon}, T) \frac{\hat{\sigma}_i}{\mu_0} + S_\epsilon(\dot{\epsilon}, T) \frac{\hat{\sigma}_\epsilon}{\mu_0}$$

- A linear summation of three stress components, each of which has a significance in terms of dislocation interactions, constructs the constitutive relations for most pure and single-phase materials.
- 1st Term: An athermal friction or internal stress resulting from dislocation interactions with, for instance, grain boundaries.
- 2nd Term: Attributed to intrinsic dislocations and defects and describes the strain rate and temperature effects on yield.
- 3rd Term: The result of dislocation interactions from deformation which accounts for strain rate and temperature effects on work hardening.

DQSK MTS updated parameters

HSLA MTS updated parameters

IF MTS updated parameters

M190 MTS updated parameters

Equations and Parameters for DQSK Fitted to MTS Model

$$\bullet \frac{\sigma}{\mu} = \frac{\sigma_a}{\mu} + S_i(\dot{\epsilon}, T) \frac{\hat{\sigma}_i}{\mu_0} + S_\epsilon(\dot{\epsilon}, T) \frac{\hat{\sigma}_\epsilon}{\mu_0}$$

Where: $\frac{\sigma_a}{\mu} = 0.002$

$$\bullet \mu = \mu_0 - \frac{2910 \text{ MPa}}{\exp \frac{-204 \text{ K}}{T}} - 1$$

Where: $\mu_0 = 7.146 \times 10^4 \text{ MPa}$

$$\bullet S_i(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0i}} \ln \frac{\dot{\epsilon}_{0i}}{\dot{\epsilon}} \quad \forall q_i \quad \forall p_i$$

Where: $\frac{k}{b^3} = 0.90474 \text{ MPa / K}, \quad k = 1.38 \times 10^{-23} \text{ Joule/K}, \quad b = 2.48 \times 10^{-10} \text{ m}$
 $\dot{\epsilon}_{0i} = 1 \times 10^7 \text{ s}^{-1}, \quad g_{0i} = 0.1276,$
 $q_i = 1.75, \quad p_i = 0.5, \quad \frac{\hat{\sigma}_i}{\mu_0} = 0.0195 \text{ (or } \hat{\sigma}_i = 1393 \text{ MPa)}$

$$\bullet S_\epsilon(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0\epsilon}} \ln \frac{\dot{\epsilon}_{0\epsilon}}{\dot{\epsilon}} \quad \forall q_\epsilon \quad \forall p_\epsilon$$

Where: $\dot{\epsilon}_{0\epsilon} = 1 \times 10^7 \text{ s}^{-1},$
 $g_{0\epsilon} = 1.6, \quad q_\epsilon = 1, \quad p_\epsilon = 2/3$

$$\bullet \frac{d\hat{\sigma}_\epsilon}{d\epsilon} = \theta_0(\dot{\epsilon}, T) - 1 - \frac{\tanh \alpha \frac{\hat{\sigma}_\epsilon}{\hat{\sigma}_{\epsilon s}(\dot{\epsilon}, T)}}{\tanh(\alpha)}$$

Where: $\alpha = 2.0$
 $\theta_0 = 4500; \text{ MPa}$

$$\bullet \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{0\epsilon s}} = \frac{\mu b^3 g_{0\epsilon s}}{kT} \ln \frac{\hat{\sigma}_{\epsilon s}}{\hat{\sigma}_{\epsilon s 0}}$$

Where: $g_{0\epsilon s} = 1.25, \quad \hat{\sigma}_{\epsilon s 0} = 360 \text{ MPa}, \quad \dot{\epsilon}_{0\epsilon s} = 1 \times 10^7 \text{ s}^{-1}$

$$\bullet \Delta T = \frac{\Psi}{\rho C_p} \sigma(\epsilon) d\epsilon; \text{ when } \dot{\epsilon} \geq 500 \text{ s}^{-1}$$

Where: $\Psi = 0.95, \quad \rho = 7.86 \text{ Mg/m}^3$
 $C_p = 0.0928 + 7.45 \times 10^{-4} T + \frac{12404}{T^2}; \text{ MPa m}^3/\text{Mg/K}$

Equations and Parameters for HSLA Fitted to MTS Model

$$\frac{\sigma}{\mu} = \frac{\sigma_a}{\mu} + S_i(\dot{\epsilon}, T) \frac{\hat{\sigma}_i}{\mu_0} + S_\epsilon(\dot{\epsilon}, T) \frac{\hat{\sigma}_\epsilon}{\mu_0}$$

Where: $\frac{\sigma_a}{\mu} = 0.002$

$$\mu = \mu_0 - \frac{2910 \text{ MPa}}{\exp \frac{-204 \text{ K}}{T}} - 1$$

Where: $\mu_0 = 7.146 \times 10^4 \text{ MPa}$

$$S_i(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0i}} \ln \frac{\dot{\epsilon}_{0i}}{\dot{\epsilon}} \quad \forall q_i \quad \forall p_i$$

Where: $\frac{k}{b^3} = 0.90474 \text{ MPa / K}$, $k = 1.38 \times 10^{-23} \text{ Joule/K}$, $b = 2.48 \times 10^{-10} \text{ m}$

$\dot{\epsilon}_{0i} = 1 \times 10^6 \text{ s}^{-1}$, $q_i = 1.5$, $p_i = 0.5$,

for $G_{\text{norm}} X < 0.105$ $g_{0i} = 0.0974$, $\frac{\hat{\sigma}_i}{\mu_0} = 0.0182$ (or $\hat{\sigma}_i = 1300 \text{ MPa}$)

for $G_{\text{norm}} X \geq 0.105$ $g_{0i} = 0.5564$, $\frac{\hat{\sigma}_i}{\mu_0} = 0.006853$ (or $\hat{\sigma}_i = 490 \text{ MPa}$)

$$G_{\text{norm}} X = \frac{kT}{\mu b^3} \ln \frac{\dot{\epsilon}_{0i}}{\dot{\epsilon}} \quad \forall q_i$$

$$S_\epsilon(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0\epsilon}} \ln \frac{\dot{\epsilon}_{0\epsilon}}{\dot{\epsilon}} \quad \forall q_\epsilon \quad \forall p_\epsilon$$

Where: $\dot{\epsilon}_{0\epsilon} = 1 \times 10^7 \text{ s}^{-1}$,

$g_{0\epsilon} = 1.6$, $q_\epsilon = 1$, $p_\epsilon = 2/3$

$$\frac{d\hat{\sigma}_\epsilon}{d\epsilon} = \theta_0(\dot{\epsilon}, T) - 1 - \frac{\tanh \alpha \frac{\hat{\sigma}_\epsilon}{\hat{\sigma}_{\epsilon 0}(\dot{\epsilon}, T)}}{\tanh(\alpha)}$$

Where: $\alpha = 2.0$

$\theta_0 = 2800 \text{ MPa}$

$$\ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{0\epsilon s}} = \frac{\mu b^3 g_{0\epsilon s}}{kT} \ln \frac{\hat{\sigma}_{\epsilon s}}{\hat{\sigma}_{\epsilon s 0}}$$

Where: $g_{0\epsilon s} = 1.25$, $\hat{\sigma}_{\epsilon s 0} = 560 \text{ MPa}$, $\dot{\epsilon}_{0\epsilon s} = 1 \times 10^7 \text{ s}^{-1}$

$$\Delta T = \frac{\Psi}{\rho C_p} \sigma(\epsilon) d\epsilon; \text{ when } \dot{\epsilon} \leq 500 \text{ s}^{-1}$$

Where: $\Psi = 0.95$, $\rho = 7.86 \text{ Mg/m}^3$

$C_p = 0.0928 + 7.45 \times 10^{-4} T + \frac{12404}{T^2}$; $\text{MPa m}^3/\text{Mg/K}$

Equations and Parameters for IF Fitted to MTS Model

$$\bullet \quad \frac{\sigma}{\mu} = \frac{\sigma_a}{\mu} + S_i(\dot{\epsilon}, T) \frac{\hat{\sigma}_i}{\mu_0} + S_\epsilon(\dot{\epsilon}, T) \frac{\hat{\sigma}_\epsilon}{\mu_0}$$

$$\text{Where: } \frac{\sigma_a}{\mu} = 0.002$$

$$\bullet \quad \mu = \mu_0 - \frac{2910 \text{ MPa}}{\exp \frac{-204 \text{ K}}{T}} - 1$$

$$\text{Where: } \mu_0 = 7.146 \times 10^4 \text{ MPa}$$

$$\bullet \quad S_i(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0i}} \ln \frac{\dot{\epsilon}_{0i}}{\dot{\epsilon}} \quad \forall q_i \quad \forall p_i$$

$$\text{Where: } \frac{k}{b^3} = 0.90474 \text{ MPa / K}, \quad k = 1.38 \times 10^{-23} \text{ Joule/K}, \quad b = 2.48 \times 10^{-10} \text{ m}$$

$$\dot{\epsilon}_{0i} = 1 \times 10^7 \text{ s}^{-1}, \quad q_i = 1.5, \quad p_i = 0.5,$$

$$g_{0i} = 0.155, \quad \frac{\hat{\sigma}_i}{\mu_0} = 0.0158 \text{ (or } \hat{\sigma}_i = 1129 \text{ MPa)}$$

$$\bullet \quad S_\epsilon(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0\epsilon}} \ln \frac{\dot{\epsilon}_{0\epsilon}}{\dot{\epsilon}} \quad \forall q_\epsilon \quad \forall p_\epsilon$$

$$\text{Where: } \dot{\epsilon}_{0\epsilon} = 1 \times 10^7 \text{ s}^{-1},$$

$$g_{0\epsilon} = 1.6, \quad q_\epsilon = 1, \quad p_\epsilon = 2/3$$

$$\bullet \quad \frac{d\hat{\sigma}_\epsilon}{d\epsilon} = \theta_0(\dot{\epsilon}, T) - 1 - \frac{\tanh \alpha \frac{\hat{\sigma}_\epsilon}{\hat{\sigma}_{\epsilon s}(\dot{\epsilon}, T)}}{\tanh(\alpha)}$$

$$\text{Where: } \alpha = 2.0$$

$$\theta_0 = 3500 \text{ MPa}$$

$$\bullet \quad \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{0\epsilon s}} = \frac{\mu b^3 g_{0\epsilon s}}{kT} \ln \frac{\hat{\sigma}_{\epsilon s}}{\hat{\sigma}_{\epsilon s 0}}$$

$$\text{Where: } g_{0\epsilon s} = 1.55, \quad \hat{\sigma}_{\epsilon s 0} = 420 \text{ MPa}, \quad \dot{\epsilon}_{0\epsilon s} = 1 \times 10^7 \text{ s}^{-1}$$

$$\bullet \quad \Delta T = \frac{\Psi}{\rho C_p} \sigma(\epsilon) d\epsilon; \text{ when } \dot{\epsilon} \sim 500 \text{ s}^{-1}$$

$$\text{Where: } \Psi = 0.95, \quad \rho = 7.86 \text{ Mg/m}^3$$

$$C_p = 0.0928 + 7.45 \times 10^{-4} T + \frac{12404}{T^2}; \text{ MPa m}^3/\text{Mg/K}$$

Equations and Parameters for M190 Fitted to MTS Model

$$\bullet \frac{\sigma}{\mu} = \frac{\sigma_a}{\mu} + S_i(\dot{\epsilon}, T) \frac{\hat{\sigma}_i}{\mu_0} + S_\epsilon(\dot{\epsilon}, T) \frac{\hat{\sigma}_\epsilon}{\mu_0}$$

Where: $\frac{\sigma_a}{\mu} = 0.002$

$$\bullet \mu = \mu_0 - \frac{2910 \text{ MPa}}{\exp \frac{-204 \text{ K}}{T}} - 1$$

Where: $\mu_0 = 7.146 \times 10^4 \text{ MPa}$

$$\bullet S_i(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0i}} \ln \frac{\dot{\epsilon}_{0i}}{\dot{\epsilon}} \quad \psi_{q_i} \quad \psi_{p_i}$$

Where: $\frac{k}{b^3} = 0.90474 \text{ MPa / K}, \quad k = 1.38 \times 10^{-23} \text{ Joule/K}, \quad b = 2.48 \times 10^{-10} \text{ m}$
 $\dot{\epsilon}_{0i} = 1 \times 10^6 \text{ s}^{-1}, \quad q_i = 1.5, \quad p_i = 0.5,$
 $g_{0i} = 1.86, \quad \frac{\hat{\sigma}_i}{\mu_0} = 0.0248 \text{ (or } \hat{\sigma}_i = 1772 \text{ MPa)}$

$$\bullet S_\epsilon(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0\epsilon}} \ln \frac{\dot{\epsilon}_{0\epsilon}}{\dot{\epsilon}} \quad \psi_{q_\epsilon} \quad \psi_{p_\epsilon}$$

Where: $\dot{\epsilon}_{0\epsilon} = 1 \times 10^7 \text{ s}^{-1},$
 $g_{0\epsilon} = 1.6, \quad q_\epsilon = 1, \quad p_\epsilon = 2/3$

$$\bullet \frac{d\hat{\sigma}_\epsilon}{d\epsilon} = \theta_0(\dot{\epsilon}, T) - 1 - \frac{\tanh \alpha \frac{\hat{\sigma}_\epsilon}{\hat{\sigma}_{\epsilon s}(\dot{\epsilon}, T)}}{\tanh(\alpha)}$$

Where: $\alpha = 2.0$
 $\theta_0 = 5500 \text{ MPa}$

$$\bullet \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{0\epsilon s}} = \frac{\mu b^3 g_{0\epsilon s}}{kT} \ln \frac{\hat{\sigma}_{\epsilon s}}{\hat{\sigma}_{\epsilon s 0}}$$

Where: $g_{0\epsilon s} = 1.45, \quad \hat{\sigma}_{\epsilon s 0} = 580 \text{ MPa}, \quad \dot{\epsilon}_{0\epsilon s} = 1 \times 10^7 \text{ s}^{-1}$

$$\bullet \Delta T = \frac{\Psi}{\rho C_p} \sigma(\epsilon) d\epsilon; \text{ when } \dot{\epsilon} \geq 500 \text{ s}^{-1}$$

Where: $\Psi = 0.95, \quad \rho = 7.86 \text{ Mg/m}^3$
 $C_p = 0.0928 + 7.45 \times 10^{-4} T + \frac{12404}{T^2}; \text{ MPa m}^3/\text{Mg/K}$

2% Axial Prestrain MTS Fit

8% Axial Prestrain MTS Fit

2x0% Plane Prestrain MTS Fit

8x0% Plane Prestrain MTS Fit

2x2% Biaxial Prestrain MTS Fit

4x4% Biaxial Prestrain MTS Fit

HSLA 1682 MTS Fit

Dual Phase MTS Fit

Equations and Parameters for AKDQ 2% Axial, MTS Model

$$\bullet \frac{\sigma}{\mu} = \frac{\sigma_a}{\mu} + S_i(\dot{\epsilon}, T) \frac{\hat{\sigma}_i}{\mu_0} + S_\epsilon(\dot{\epsilon}, T) \frac{\hat{\sigma}_\epsilon}{\mu_0}$$

Where: $\frac{\sigma_a}{\mu} = 0.002$

$$\bullet \mu = \mu_0 - \frac{2910 \text{ MPa}}{\exp \frac{-204 \text{ K}}{T}} - 1$$

Where: $\mu_0 = 7.146 \times 10^4 \text{ MPa}$

$$\bullet S_i(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0i}} \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{0i}} \quad \forall q_i \quad \forall p_i$$

Where: $\frac{k}{b^3} = 0.90474 \text{ MPa / K}, \quad k = 1.38 \times 10^{-23} \text{ Joule/K}, \quad b = 2.48 \times 10^{-10} \text{ m}$
 $\dot{\epsilon}_{0i} = 1 \times 10^7 \text{ s}^{-1}, \quad g_{0i} = 0.2076,$
 $q_i = 1.75, \quad p_i = 0.5, \quad \frac{\hat{\sigma}_i}{\mu_0} = 0.0135 \text{ (or } \hat{\sigma}_i = 945 \text{ MPa)}$

$$\bullet S_\epsilon(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0\epsilon}} \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{0\epsilon}} \quad \forall q_\epsilon \quad \forall p_\epsilon$$

Where: $\dot{\epsilon}_{0\epsilon} = 1 \times 10^7 \text{ s}^{-1},$
 $g_{0\epsilon} = 1.6, \quad q_\epsilon = 1, \quad p_\epsilon = 2/3$

$$\bullet \frac{d\hat{\sigma}_\epsilon}{d\epsilon} = \theta_0(\dot{\epsilon}, T) - 1 - \frac{\tanh \alpha \frac{\hat{\sigma}_\epsilon}{\hat{\sigma}_{\epsilon s}(\dot{\epsilon}, T)}}{\tanh(\alpha)}$$

Where: $\alpha = 2.0$
 $\theta_0 = 3500; \text{ MPa}$

$$\bullet \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{0\epsilon s}} = \frac{\mu b^3 g_{0\epsilon s}}{kT} \ln \frac{\hat{\sigma}_{\epsilon s}}{\hat{\sigma}_{\epsilon s 0}}$$

Where: $g_{0\epsilon s} = 1.25, \quad \hat{\sigma}_{\epsilon s 0} = 320 \text{ MPa}, \quad \dot{\epsilon}_{0\epsilon s} = 1 \times 10^7 \text{ s}^{-1}$

$$\bullet \Delta T = \frac{\Psi}{\rho C_p} \sigma(\epsilon) d\epsilon; \text{ when } \dot{\epsilon} \geq 500 \text{ s}^{-1}$$

Where: $\Psi = 0.95, \quad \rho = 7.86 \text{ Mg/m}^3$
 $C_p = 0.0928 + 7.45 \times 10^{-4} T + \frac{12404}{T^2}; \text{ MPa m}^3/\text{Mg/K}$

Equations and Parameters for DQSK 8% Axial, MTS Model

$$\bullet \quad \frac{\sigma}{\mu} = \frac{\sigma_a}{\mu} + S_i(\dot{\epsilon}, T) \frac{\hat{\sigma}_i}{\mu_0} + S_\epsilon(\dot{\epsilon}, T) \frac{\hat{\sigma}_\epsilon}{\mu_0}$$

Where: $\frac{\sigma_a}{\mu} = 0.002$

$$\bullet \quad \mu = \mu_0 - \frac{2910 \text{ MPa}}{\exp \frac{-204 \text{ K}}{T}} - 1$$

Where: $\mu_0 = 7.146 \times 10^4 \text{ MPa}$

$$\bullet \quad S_i(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0i}} \ln \frac{\dot{\epsilon}_{0i}}{\dot{\epsilon}} \quad \begin{matrix} \psi q_i & \psi p_i \\ - & - \end{matrix}$$

Where: $\frac{k}{b^3} = 0.90474 \text{ MPa / K}, \quad k = 1.38 \times 10^{-23} \text{ Joule/K}, \quad b = 2.48 \times 10^{-10} \text{ m}$
 $\dot{\epsilon}_{0i} = 1 \times 10^7 \text{ s}^{-1}, \quad g_{0i} = 0.2076,$
 $q_i = 1.75, \quad p_i = 0.5, \quad \frac{\hat{\sigma}_i}{\mu_0} = 0.017 \text{ (or } \hat{\sigma}_i = 1215 \text{ MPa)}$

$$\bullet \quad S_\epsilon(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0\epsilon}} \ln \frac{\dot{\epsilon}_{0\epsilon}}{\dot{\epsilon}} \quad \begin{matrix} \psi q_\epsilon & \psi p_\epsilon \\ - & - \end{matrix}$$

Where: $\dot{\epsilon}_{0\epsilon} = 1 \times 10^7 \text{ s}^{-1},$
 $g_{0\epsilon} = 1.6, \quad q_\epsilon = 1, \quad p_\epsilon = 2/3$

$$\bullet \quad \frac{d\hat{\sigma}_\epsilon}{d\epsilon} = \theta_0(\dot{\epsilon}, T) - 1 - \frac{\tanh \alpha \frac{\hat{\sigma}_\epsilon}{\hat{\sigma}_{\epsilon s}(\dot{\epsilon}, T)}}{\tanh(\alpha)}$$

Where: $\alpha = 2.0$
 $\theta_0 = 3500; \text{ MPa}$

$$\bullet \quad \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{0\epsilon s}} = \frac{\mu b^3 g_{0\epsilon s}}{kT} \ln \frac{\hat{\sigma}_{\epsilon s}}{\hat{\sigma}_{\epsilon s0}}$$

Where: $g_{0\epsilon s} = 1.25, \quad \hat{\sigma}_{\epsilon s0} = 260 \text{ MPa}, \quad \dot{\epsilon}_{0\epsilon s} = 1 \times 10^7 \text{ s}^{-1}$

$$\bullet \quad \Delta T = \frac{\Psi}{\rho C_p} \sigma(\epsilon) d\epsilon; \text{ when } \dot{\epsilon} \leq 500 \text{ s}^{-1}$$

Where: $\Psi = 0.95, \quad \rho = 7.86 \text{ Mg/m}^3$
 $C_p = 0.0928 + 7.45 \times 10^{-4} T + \frac{12404}{T^2}; \text{ MPa m}^3/\text{Mg/K}$

Equations and Parameters for DQSK 2% Plane, MTS Model

$$\bullet \frac{\sigma}{\mu} = \frac{\sigma_a}{\mu} + S_i(\dot{\epsilon}, T) \frac{\hat{\sigma}_i}{\mu_0} + S_\epsilon(\dot{\epsilon}, T) \frac{\hat{\sigma}_\epsilon}{\mu_0}$$

Where: $\frac{\sigma_a}{\mu} = 0.002$

$$\bullet \mu = \mu_0 - \frac{2910 \text{ MPa}}{\exp \frac{-204 \text{ K}}{T}} - 1$$

Where: $\mu_0 = 7.146 \times 10^4 \text{ MPa}$

$$\bullet S_i(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0i}} \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{0i}} \quad \psi q_i \quad \psi p_i$$

Where: $\frac{k}{b^3} = 0.90474 \text{ MPa / K}, \quad k = 1.38 \times 10^{-23} \text{ Joule/K}, \quad b = 2.48 \times 10^{-10} \text{ m}$

$\dot{\epsilon}_{0i} = 1 \times 10^7 \text{ s}^{-1}, \quad g_{0i} = 0.2076,$

$q_i = 1.75, \quad p_i = 0.5, \quad \frac{\hat{\sigma}_i}{\mu_0} = 0.0135 \text{ (or } \hat{\sigma}_i = 945 \text{ MPa)}$

$$\bullet S_\epsilon(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0\epsilon}} \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{0\epsilon}} \quad \psi q_\epsilon \quad \psi p_\epsilon$$

Where: $\dot{\epsilon}_{0\epsilon} = 1 \times 10^7 \text{ s}^{-1},$

$g_{0\epsilon} = 1.6, \quad q_\epsilon = 1, \quad p_\epsilon = 2/3$

$$\bullet \frac{d\hat{\sigma}_\epsilon}{d\epsilon} = \theta_0(\dot{\epsilon}, T) - 1 - \frac{\tanh \alpha \frac{\hat{\sigma}_\epsilon}{\hat{\sigma}_{\epsilon 0}(\dot{\epsilon}, T)}}{\tanh(\alpha)}$$

Where: $\alpha = 2.0$

$\theta_0 = 3500; \text{ MPa}$

$$\bullet \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{0\epsilon s}} = \frac{\mu b^3 g_{0\epsilon s}}{kT} \ln \frac{\hat{\sigma}_{\epsilon s}}{\hat{\sigma}_{\epsilon s 0}}$$

Where: $g_{0\epsilon s} = 1.25, \quad \hat{\sigma}_{\epsilon s 0} = 320 \text{ MPa}, \quad \dot{\epsilon}_{0\epsilon s} = 1 \times 10^7 \text{ s}^{-1}$

$$\bullet \Delta T = \frac{\Psi}{\rho C_p} \sigma(\epsilon) d\epsilon; \text{ when } \dot{\epsilon} \sim 500 \text{ s}^{-1}$$

Where: $\Psi = 0.95, \quad \rho = 7.86 \text{ Mg/m}^3$

$C_p = 0.0928 + 7.45 \times 10^{-4} T + \frac{12404}{T^2}; \text{ MPa m}^3/\text{Mg/K}$

Equations and Parameters for DQSK 8% Plane, MTS Model

$$\frac{\sigma}{\mu} = \frac{\sigma_a}{\mu} + S_i(\dot{\epsilon}, T) \frac{\hat{\sigma}_i}{\mu_0} + S_\epsilon(\dot{\epsilon}, T) \frac{\hat{\sigma}_\epsilon}{\mu_0}$$

Where: $\frac{\sigma_a}{\mu} = 0.002$

$$\mu = \mu_0 - \frac{2910 \text{ MPa}}{\exp \frac{-204 \text{ K}}{T}} - 1$$

Where: $\mu_0 = 7.146 \times 10^4 \text{ MPa}$

$$S_i(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0i}} \ln \frac{\dot{\epsilon}_{0i}}{\dot{\epsilon}} \quad \begin{matrix} q_i & p_i \\ - & - \end{matrix}$$

Where: $\frac{k}{b^3} = 0.90474 \text{ MPa / K}, \quad k = 1.38 \times 10^{-23} \text{ Joule/K}, \quad b = 2.48 \times 10^{-10} \text{ m}$

$\dot{\epsilon}_{0i} = 1 \times 10^7 \text{ s}^{-1}, \quad g_{0i} = 0.2076,$

$q_i = 1.75, \quad p_i = 0.5, \quad \frac{\hat{\sigma}_i}{\mu_0} = 0.018 \text{ (or } \hat{\sigma}_i = 1286 \text{ MPa)}$

$$S_\epsilon(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0\epsilon}} \ln \frac{\dot{\epsilon}_{0\epsilon}}{\dot{\epsilon}} \quad \begin{matrix} q_\epsilon & p_\epsilon \\ - & - \end{matrix}$$

Where: $\dot{\epsilon}_{0\epsilon} = 1 \times 10^7 \text{ s}^{-1},$

$g_{0\epsilon} = 1.6, \quad q_\epsilon = 1, \quad p_\epsilon = 2/3$

$$\frac{d\hat{\sigma}_\epsilon}{d\epsilon} = \theta_0(\dot{\epsilon}, T) - 1 - \frac{\tanh \alpha \frac{\hat{\sigma}_\epsilon}{\hat{\sigma}_{\epsilon s}(\dot{\epsilon}, T)}}{\tanh(\alpha)}$$

Where: $\alpha = 2.0$

$\theta_0 = 3500; \text{ MPa}$

$$\ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{0\epsilon s}} = \frac{\mu b^3 g_{0\epsilon s}}{kT} \ln \frac{\hat{\sigma}_{\epsilon s}}{\hat{\sigma}_{\epsilon s 0}}$$

Where: $g_{0\epsilon s} = 1.25, \quad \hat{\sigma}_{\epsilon s 0} = 320 \text{ MPa}, \quad \dot{\epsilon}_{0\epsilon s} = 1 \times 10^7 \text{ s}^{-1}$

$$\Delta T = \frac{\Psi}{\rho C_p} \sigma(\epsilon) d\epsilon; \text{ when } \dot{\epsilon} \leq 500 \text{ s}^{-1}$$

Where: $\Psi = 0.95, \quad \rho = 7.86 \text{ Mg/m}^3$

$C_p = 0.0928 + 7.45 \times 10^{-4} T + \frac{12404}{T^2}; \text{ MPa m}^3/\text{Mg/K}$

Equations and Parameters for DQSK 2x2% Biaxial, MTS Model

$$\bullet \quad \frac{\sigma}{\mu} = \frac{\sigma_a}{\mu} + S_i(\dot{\epsilon}, T) \frac{\hat{\sigma}_i}{\mu_0} + S_\epsilon(\dot{\epsilon}, T) \frac{\hat{\sigma}_\epsilon}{\mu_0}$$

Where: $\frac{\sigma_a}{\mu} = 0.002$

$$\bullet \quad \mu = \mu_0 - \frac{2910 \text{ MPa}}{\exp \left(\frac{-204 \text{ K}}{T} \right) - 1}$$

Where: $\mu_0 = 7.146 \times 10^4 \text{ MPa}$

$$\bullet \quad S_i(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0i}} \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{0i}} \quad \begin{matrix} \psi_{q_i} & \psi_{p_i} \\ - & - \end{matrix}$$

Where: $\frac{k}{b^3} = 0.90474 \text{ MPa / K}, \quad k = 1.38 \times 10^{-23} \text{ Joule/K}, \quad b = 2.48 \times 10^{-10} \text{ m}$

$\dot{\epsilon}_{0i} = 1 \times 10^7 \text{ s}^{-1}, \quad g_{0i} = 0.2076,$

$q_i = 1.75, \quad p_i = 0.5, \quad \frac{\hat{\sigma}_i}{\mu_0} = 0.0145 \text{ (or } \hat{\sigma}_i = 1036 \text{ MPa)}$

$$\bullet \quad S_\epsilon(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0\epsilon}} \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{0\epsilon}} \quad \begin{matrix} \psi_{q_\epsilon} & \psi_{p_\epsilon} \\ - & - \end{matrix}$$

Where: $\dot{\epsilon}_{0\epsilon} = 1 \times 10^7 \text{ s}^{-1},$

$g_{0\epsilon} = 1.6, \quad q_\epsilon = 1, \quad p_\epsilon = 2/3$

$$\bullet \quad \frac{d\hat{\sigma}_\epsilon}{d\epsilon} = \theta_0(\dot{\epsilon}, T) - 1 - \frac{\tanh \alpha \frac{\hat{\sigma}_\epsilon}{\hat{\sigma}_{\epsilon s}(\dot{\epsilon}, T)}}{\tanh(\alpha)}$$

Where: $\alpha = 2.0$

$\theta_0 = 3500; \text{ MPa}$

$$\bullet \quad \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{0\epsilon s}} = \frac{\mu b^3 g_{0\epsilon s}}{kT} \ln \frac{\hat{\sigma}_{\epsilon s}}{\hat{\sigma}_{\epsilon s 0}}$$

Where: $g_{0\epsilon s} = 1.25, \quad \hat{\sigma}_{\epsilon s 0} = 320 \text{ MPa}, \quad \dot{\epsilon}_{0\epsilon s} = 1 \times 10^7 \text{ s}^{-1}$

$$\bullet \quad \Delta T = \frac{\Psi}{\rho C_p} \sigma(\epsilon) d\epsilon; \quad \text{when } \dot{\epsilon} \leq 500 \text{ s}^{-1}$$

Where: $\Psi = 0.95, \quad \rho = 7.86 \text{ Mg/m}^3$

$C_p = 0.0928 + 7.45 \times 10^{-4} T + \frac{12404}{T^2}; \text{ MPa m}^3/\text{Mg/K}$

Equations and Parameters for DQSK 2x2% Biaxial, MTS Model

$$\bullet \frac{\sigma}{\mu} = \frac{\sigma_a}{\mu} + S_i(\dot{\epsilon}, T) \frac{\hat{\sigma}_i}{\mu_0} + S_\epsilon(\dot{\epsilon}, T) \frac{\hat{\sigma}_\epsilon}{\mu_0}$$

Where: $\frac{\sigma_a}{\mu} = 0.002$

$$\bullet \mu = \mu_0 - \frac{2910 \text{ MPa}}{\exp \frac{-204 \text{ K}}{T}} - 1$$

Where: $\mu_0 = 7.146 \times 10^4 \text{ MPa}$

$$\bullet S_i(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0i}} \ln \frac{\dot{\epsilon}_{0i}}{\dot{\epsilon}} \quad \forall q_i \quad \forall p_i$$

Where: $\frac{k}{b^3} = 0.90474 \text{ MPa / K}$, $k = 1.38 \times 10^{-23} \text{ Joule/K}$, $b = 2.48 \times 10^{-10} \text{ m}$

$\dot{\epsilon}_{0i} = 1 \times 10^7 \text{ s}^{-1}$, $g_{0i} = 0.2076$,

$q_i = 1.75$, $p_i = 0.5$, $\frac{\hat{\sigma}_i}{\mu_0} = 0.0165$ (or $\hat{\sigma}_i = 1179 \text{ MPa}$)

$$\bullet S_\epsilon(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0\epsilon}} \ln \frac{\dot{\epsilon}_{0\epsilon}}{\dot{\epsilon}} \quad \forall q_\epsilon \quad \forall p_\epsilon$$

Where: $\dot{\epsilon}_{0\epsilon} = 1 \times 10^7 \text{ s}^{-1}$,

$g_{0\epsilon} = 1.6$, $q_\epsilon = 1$, $p_\epsilon = 2/3$

$$\bullet \frac{d\hat{\sigma}_\epsilon}{d\epsilon} = \theta_0(\dot{\epsilon}, T) - 1 - \frac{\tanh \alpha \frac{\hat{\sigma}_\epsilon}{\hat{\sigma}_{\epsilon s}(\dot{\epsilon}, T)}}{\tanh(\alpha)}$$

Where: $\alpha = 2.0$

$\theta_0 = 3500$; MPa

$$\bullet \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{0\epsilon s}} = \frac{\mu b^3 g_{0\epsilon s}}{kT} \ln \frac{\hat{\sigma}_{\epsilon s}}{\hat{\sigma}_{\epsilon s 0}}$$

Where: $g_{0\epsilon s} = 1.25$, $\hat{\sigma}_{\epsilon s 0} = 320 \text{ MPa}$, $\dot{\epsilon}_{0\epsilon s} = 1 \times 10^7 \text{ s}^{-1}$

$$\bullet \Delta T = \frac{\Psi}{\rho C_p} \sigma(\epsilon) d\epsilon; \text{ when } \dot{\epsilon} \leq 500 \text{ s}^{-1}$$

Where: $\Psi = 0.95$, $\rho = 7.86 \text{ Mg/m}^3$

$C_p = 0.0928 + 7.45 \times 10^{-4} T + \frac{12404}{T^2}$; MPa m³/Mg/K

Equations and Parameters for HSLA 1682, MTS Model

$$\bullet \quad \frac{\sigma}{\mu} = \frac{\sigma_a}{\mu} + S_i(\dot{\epsilon}, T) \frac{\hat{\sigma}_i}{\mu_0} + S_\epsilon(\dot{\epsilon}, T) \frac{\hat{\sigma}_\epsilon}{\mu_0}$$

$$\text{Where: } \frac{\sigma_a}{\mu} = 0.002$$

$$\bullet \quad \mu = \mu_0 - \frac{2910 \text{ MPa}}{\exp\left(\frac{-204 \text{ K}}{T}\right) - 1}$$

$$\text{Where: } \mu_0 = 7.146 \times 10^4 \text{ MPa}$$

$$\bullet \quad S_i(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0i}} \ln \frac{\dot{\epsilon}_{0i}}{\dot{\epsilon}} \quad \psi_{q_i} \quad \psi_{p_i}$$

$$\text{Where: } \frac{k}{b^3} = 0.90474 \text{ MPa / K}, \quad k = 1.38 \times 10^{-23} \text{ Joule/K}, \quad b = 2.48 \times 10^{-10} \text{ m}$$

$$\dot{\epsilon}_{0i} = 1 \times 10^6 \text{ s}^{-1}, \quad g_{0i} = 0.42,$$

$$q_i = 1.75, \quad p_i = 0.5, \quad \frac{\hat{\sigma}_i}{\mu_0} = 0.0102 \text{ (or } \hat{\sigma}_i = 729 \text{ MPa)}$$

$$\bullet \quad S_\epsilon(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0\epsilon}} \ln \frac{\dot{\epsilon}_{0\epsilon}}{\dot{\epsilon}} \quad \psi_{q_\epsilon} \quad \psi_{p_\epsilon}$$

$$\text{Where: } \dot{\epsilon}_{0\epsilon} = 1 \times 10^7 \text{ s}^{-1},$$

$$g_{0\epsilon} = 1.6, \quad q_\epsilon = 1, \quad p_\epsilon = 2/3$$

$$\bullet \quad \frac{d\hat{\sigma}_\epsilon}{d\epsilon} = \theta_0(\dot{\epsilon}, T) \left[1 - \frac{\tanh\left(\alpha \frac{\hat{\sigma}_\epsilon}{\hat{\sigma}_{\epsilon s}(\dot{\epsilon}, T)}\right)}{\tanh(\alpha)} \right]$$

$$\text{Where: } \alpha = 2.0$$

$$\theta_0 = 2800; \text{ MPa}$$

$$\bullet \quad \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{0\epsilon s}} = \frac{\mu b^3 g_{0\epsilon s}}{kT} \ln \frac{\hat{\sigma}_{\epsilon s}}{\hat{\sigma}_{\epsilon s0}}$$

$$\text{Where: } g_{0\epsilon s} = 1.25, \quad \hat{\sigma}_{\epsilon s0} = 560 \text{ MPa}, \quad \dot{\epsilon}_{0\epsilon s} = 1 \times 10^7 \text{ s}^{-1}$$

$$\bullet \quad \Delta T = \frac{\Psi}{\rho C_p} \sigma(\epsilon) d\epsilon; \text{ when } \dot{\epsilon} \leq 500 \text{ s}^{-1}$$

$$\text{Where: } \Psi = 0.95, \quad \rho = 7.86 \text{ Mg/m}^3$$

$$C_p = 0.0928 + 7.45 \times 10^{-4} T + \frac{12404}{T^2}; \text{ MPa m}^3/\text{Mg/K}$$

Equations and Parameters for Dual Phase, MTS Model

$$\frac{\sigma}{\mu} = \frac{\sigma_a}{\mu} + S_i(\dot{\epsilon}, T) \frac{\hat{\sigma}_i}{\mu_0} + S_\epsilon(\dot{\epsilon}, T) \frac{\hat{\sigma}_\epsilon}{\mu_0}$$

Where: $\frac{\sigma_a}{\mu} = 0.002$

$$\mu = \mu_0 - \frac{2910 \text{ MPa}}{\exp\left(\frac{-204 \text{ K}}{T}\right) - 1}$$

Where: $\mu_0 = 7.146 \times 10^4 \text{ MPa}$

$$S_i(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0i}} \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{0i}} \quad \forall q_i \quad \forall p_i$$

Where: $\frac{k}{b^3} = 0.90474 \text{ MPa / K}$, $k = 1.38 \times 10^{-23} \text{ Joule/K}$, $b = 2.48 \times 10^{-10} \text{ m}$
 $\dot{\epsilon}_{0i} = 1 \times 10^7 \text{ s}^{-1}$, $g_{0i} = 1.2$,
 $q_i = 1.5$, $p_i = 0.5$, $\frac{\hat{\sigma}_i}{\mu_0} = 0.0165$ (or $\hat{\sigma}_i = 1179 \text{ MPa}$)

$$S_\epsilon(\dot{\epsilon}, T) = 1 - \frac{kT}{\mu b^3 g_{0\epsilon}} \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{0\epsilon}} \quad \forall q_\epsilon \quad \forall p_\epsilon$$

Where: $\dot{\epsilon}_{0\epsilon} = 1 \times 10^7 \text{ s}^{-1}$,
 $g_{0\epsilon} = 1.6$, $q_\epsilon = 1$, $p_\epsilon = 2/3$

$$\frac{d\hat{\sigma}_\epsilon}{d\epsilon} = \theta_0(\dot{\epsilon}, T) - 1 - \frac{\tanh\left(\alpha \frac{\hat{\sigma}_\epsilon}{\hat{\sigma}_{\epsilon s}(\dot{\epsilon}, T)}\right)}{\tanh(\alpha)}$$

Where: $\alpha = 2.0$
 $\theta_0 = 5500$; MPa

$$\ln \frac{\dot{\epsilon}}{\dot{\epsilon}_{0\epsilon s}} = \frac{\mu b^3 g_{0\epsilon s}}{kT} \ln \frac{\hat{\sigma}_{\epsilon s}}{\hat{\sigma}_{\epsilon s 0}}$$

Where: $g_{0\epsilon s} = 1.25$, $\hat{\sigma}_{\epsilon s 0} = 580 \text{ MPa}$, $\dot{\epsilon}_{0\epsilon s} = 1 \times 10^7 \text{ s}^{-1}$

$$\Delta T = \frac{\Psi}{\rho C_p} \sigma(\epsilon) d\epsilon; \text{ when } \dot{\epsilon} \leq 500 \text{ s}^{-1}$$

Where: $\Psi = 0.95$, $\rho = 7.86 \text{ Mg/m}^3$
 $C_p = 0.0928 + 7.45 \times 10^{-4} T + \frac{12404}{T^2}$; MPa m³/Mg/K

Equation and Parameters for MTS Model

MTS model	α	ϵ_{ss}	g_{ss}	$\sigma_{\epsilon s0}$	g_{ϵ}	$\epsilon_{0\epsilon}$	$q\epsilon$	$p\epsilon$
DQSK	2	1.0E+7	1.25	360	1.6	1.0E+7	1.0	0.667
HSLA	2	1.0E+7	1.25	560	1.6	1.0E+7	1.0	0.667
IF	2	1.0E+7	1.55	420	1.6	1.0E+7	1.0	0.667
M190	2	1.0E+7	1.45	580	1.6	1.0E+7	1.0	0.667
AKDQ 2%a	2	1.0E+7	1.25	320	1.6	1.0E+7	1.0	0.667
AKDQ 8%a	2	1.0E+7	1.25	260	1.6	1.0E+7	1.0	0.667
AKDQ 2%p	2	1.0E+7	1.25	320	1.6	1.0E+7	1.0	0.667
AKDQ 8%p	2	1.0E+7	1.25	260	1.6	1.0E+7	1.0	0.667
AKDQ 2%b	2	1.0E+7	1.25	320	1.6	1.0E+7	1.0	0.667
AKDQ 4%b	2	1.0E+7	1.25	320	1.6	1.0E+7	1.0	0.667
HSLA 1682	2	1.0E+7	1.25	560	1.6	1.0E+7	1.0	0.667
Dual Phase	2	1.0E+7	1.25	580	1.6	1.0E+7	1.0	0.667

AKDQ As Received Tensile Data

AKDQ 2% Axial Prestrain Tensile Data

AKDQ 8% Axial Prestrain Tensile Data

AKDQ 2x0% Plane Prestrain Tensile Data

AKDQ 8x0% Plane Prestrain Tensile Data

AKDQ 2x2% Biaxial Prestrain Tensile Data

AKDQ 4x4% Biaxial Prestrain Tensile Data

Dual Phase Tensile Data

HSLA 1682 Tensile Data

R-Value Results

	AK	AK	AK	AK	AK	AK	AK	AK	AK	AK	AK	DP	HS
	AR	2%	8%	2x0	8x0	2x2	4x4						LA
0°		1.82	1.54	1.49	1.32	1.45	1.58	1.40	1.51				
	1.50												
22°													
	1.21												
45°		1.10	1.12	1.06	1.19	1.04	1.07	1.28	1.16				
	1.10												
67°													
	1.33												
90°		1.71	1.48	1.64	1.59	1.67	1.47	1.15	1.11				
	1.57												
Avg. 0+2x45 +90		1.43	1.32	1.31	1.32	1.30	1.30	1.28	1.24				
	1.33