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EXTENSION OF THE M-D MODEL FOR TREATING STRESS DROPS IN SALT*

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ABSTRACT

The multimechanism deformation model for the creep deformation of salt is extended to treat the response of salt to imposed stress drops. Stress drop tests produce a very distinctive behavior where both reversible elastic strain and reversible time dependent strain occur. These transient strains are negative compared to the positive transient strains produced by the normal creep workhardening and recovery processes. A simple micromechanical evolutionary process is defined to account for the accumulation of these reversible strains, and their subsequent release with decreases in stress. A number of experimental stress drop tests for various stress drop magnitudes and temperatures are adequately simulated with the model.

INTRODUCTION

The mechanical response of salt is known to be complex, especially that behavior associated with time dependent deformation or creep. Much of the complexity arises upon any sudden reduction of stress from an initial loading state. In laboratory "stress drop" tests, the sudden drop in stress apparently produces not only an adjustment of elastic strain, but also a reverse time dependent strain, both of which oppose the direction of the continuing forward creep strain and the applied stress. The continuing forward creep strain occurs initially at a diminished rate, but recovers through a transient response to again establish a steady state rate at the new stress conditions. This behavior is commonly found in pure metals [1], as well as salt [2]. As reviewed by Krempl [3], various models have been advanced to treat stress drops from steady state creep. Micromechanical models are those based on internal stresses [1,4] resulting from force fields of dislocation net works and pile ups. A feature of these models is that the internal stress is a constant fraction of the applied stress, which produces a distinctive unloading behavior for stress drops to the predicted internal stress level. Kinematic and isotropic hardening, unified creep plasticity models based on competing workhardening and recovery processes and a continuous evolution in terms of the development of a "back stress" have also treated the stress drop experiment in metals [5]. Krieg [6] and Aubertin *et al.* [7] have applied forms of the unified creep plasticity model to the creep of salt.

Development of the multimechanism deformation (M-D) constitutive model for steady state creep, which incorporates irreversible workhardening and recovery transient strains, was originally motivated by the need to predict very long term closures in underground rooms for radioactive waste repositories in salt [8]. Although the two reversible processes were

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known to exist, Munson and Dawson [9,10] argued at the time that reverse creep behavior and even the recovery process, for that matter, were relatively unimportant in applications to underground mining because stress unloading is gradual and therefore the material response remains essentially in equilibrium. This model, as later modified to more accurately describe the strain response [11], seems to simulate mining situations quite adequately [12]. However, in some applications that result in rapid changes of stress, such as rapid pressure swings in underground storage caverns where potentially large volumes of salt can be involved, reverse strains may become a factor in operational performance.

In this work, the modified M-D creep model [11] is extended to treat the stress drop test. After presenting the mathematical and micromechanical aspects of the original model, the extended model is developed. Then the extended model is used to simulate laboratory stress drop test results.

MODIFIED M-D MODEL

Any constitutive description of creep must at least reproduce the creep curve from a conventional creep test, as shown in Figure 1. The creep strain is often decomposed into steady state and transient creep, which are then added to obtain the total strain. Development of the modified M-D model [11] initially treats the two components separately; but in contrast to typical practice, they are then incorporated into the model through a multiplication process on the strain rate, rather than through addition of strains.

The steady state creep component of the model is based on the deformation mechanism map [10,13] shown in Figure 2. For the application of the model to laboratory stress drop experiments, as well as potential repositories in salt, the range of stresses and temperatures encompass just three regimes of the map, each controlled by dominant mechanisms based on dislocations. As noted, these are (regime 1) a high temperature, low stress regime controlled by dislocation climb, (regime 2) a low temperature, low stress regime controlled by an undefined dislocation mechanism; and (regime 3) a high stress regime controlled by various possible dislocation slip mechanisms. Dislocation climb is a thermally activated mechanism which has a power law stress dependence. The undefined mechanism is undefined only in the sense that it has no associated micromechanical model, but rather is empirically defined on the basis of laboratory characterization. It appears to have the same functional form as the dislocation climb model. The dislocation slip controlled regime actually reflects the general mathematical form of a number of potential micromechanical models of slip, all of which are thermally activated and exhibit an exponential stress dependence.

These mechanisms act concurrently; and therefore, their creep rates are additive. Thus, the total steady state creep rate is just the sum of the steady state rates of the individual micromechanical mechanisms [11], which results in

$$\dot{\epsilon}_s = \sum_{i=1}^3 \dot{\epsilon}_{s_i} \quad 1$$

Steady state creep rates of the three relevant mechanisms are of the following form

$$\dot{\epsilon}_{s_i} = A_i e^{\frac{-Q_i}{RT}} \left(\frac{\sigma}{\mu} \right)^{n_i} \quad (\text{Climb}) \quad 2a$$

Figure 1 - Schematic of the conventional creep curve, with elastic strain added.

$$\dot{\epsilon}_{s_2} = A_2 e^{\frac{-Q_2}{RT}} \left(\frac{\sigma}{\mu} \right)^{n_2} \quad (\text{Undefined}) \quad 2b$$

$$\dot{\epsilon}_{s_3} = |H(\sigma - \sigma_0)| \left[B_1 e^{\frac{-Q_1}{RT}} + B_2 e^{\frac{-Q_2}{RT}} \right] \sinh \left[\frac{q(\sigma - \sigma_0)}{\mu} \right] \quad (\text{Slip}) \quad 2c$$

where the A's and B's are constants, the Q's are activation energies, T is the absolute temperature, R the universal gas constant, μ the shear modulus, σ the generalized stress (the generalized stress is based on the Tresca maximum shear stress criterion), n 's the stress exponents, q the stress constant, and σ_0 the stress limit of the dislocation slip mechanism. $|H|$ is a Heaviside step function with argument $(\sigma - \sigma_0)$.

The total irreversible creep rate, which is that component that is always forward creep, is accommodated through a multiplier on the steady state creep rate, essentially in the same form as in the original model

$$\dot{\epsilon}_c = F \dot{\epsilon}_s \quad 3$$

but subscripted differently to reflect that it no longer represents quite the same quantity. As a result of Eq. 3, the mechanism for both the transient and steady state components are the same within a regime, with identical thermal activation and stress dependence.

The transient response, F , is defined by the function

$$F = \begin{cases} e^{+\Delta \left(1 - \frac{\zeta}{\epsilon_c^*}\right)^2}; & \zeta \leq \epsilon_c^* \\ 1 & \\ e^{-\delta \left(1 - \frac{\zeta}{\epsilon_c^*}\right)^2}; & \zeta \geq \epsilon_c^* \end{cases} \quad 4$$

Clearly, the transient function consists of three branches: a workhardening branch, a steady state (trivial) branch, and a recovery branch, respectively, in the order of their appearance. The steady state branch is trivial because the creep processes are in equilibrium. Here, Δ and δ are the workhardening and recovery parameters, respectively, and ϵ_c^* is now the irreversible transient strain limit, replacing the original transient strain limit.

The evolutionary equation describing the rate of change of the internal state variable, ζ , is given by

$$\dot{\zeta} = (F - 1) \dot{\epsilon}_s \quad 5$$

The workhardening and recovery parameters, which can never be less than zero, are functions of stress, as given by

$$\Delta = \alpha_w + \beta_w \log \left(\frac{\sigma}{\mu} \right) \quad 6a$$

$$\delta = \alpha_r + \beta_r \log\left(\frac{\sigma}{\mu}\right) \quad 6b$$

where the α 's and β 's are constants and the subscripts denote workhardening and recovery, respectively.

To complete the constitutive description, the irreversible transient strain limit is described as a function of both stress and temperature, as follows

$$\epsilon_c^* = K_0 e^{cT} \left(\frac{\sigma}{\mu}\right)^m \quad 7$$

where K_0 , c , and m are constants. The constant m is related to the development of subgrains from the strain generated dislocations and should have a value near three [9]. The temperature dependence was determined empirically.

The microstructural framework of the M-D model is reasonably clear. It is based on the principle that the internal defect structure is in equilibrium when the material is in steady state creep. In steady state creep, for those micromechanisms based on dislocations, the generation and annihilation of dislocations is balanced. Thus, in equilibrium, the internal structure remains constant with time, even though deformation continues to occur. For internal structures that are not in equilibrium, the defect structure changes. This change is driven by a potential. Although the form of the potential function cannot be determined from first principles, it can be approximated as the change in strain rate with strain. A schematic of the strain based equivalent is shown in Figure 3, as a nondimensional ratio of strain rate to steady state creep rate as a function of the ratio of the state parameter to the transient strain limit. In workhardening, the internal defect structure continues to become more dense with further strain. For primary creep, the workhardening potential function is determined readily from the experimental creep curve [9]. The recovery potential, while identical in principle, is more difficult to determine because it represents a decrease in defect content as the material approaches equilibrium from an overhardened condition. However, even this function, based on the strain rates, can also be determined experimentally. Mathematically, the higher order kinetic functions of Eq. 4 represent the experimentally measured functions quite well [11].

The strategy for handling changes, either increases or decreases, in applied stress and temperature [9] is based on translating between workhardening and recovery irreversible transient response curves at a constant structure. This is equivalent to constant values of the internal state parameter, ζ . In Figure 4a, a creep test initially under conditions of σ_1 and T_1 undergoes some primary (workhardening) transient strain along its applicable strain rate vs. irreversible strain curve, until it responds to an increase in stress and temperature to the new conditions of σ_2 and T_2 . This is a simple translation at constant ζ from the transient curve representing the initial conditions to the transient response curve at the new conditions. In this case, the material remains less strained than the equilibrium value of ϵ_c^* (2) and will continue to workharden. The creep curve generated for this history appears in Figure 4b, where the creep rate accelerates at the time of the change in stress and temperature in a typical workhardening response. If after some additional strain, the stress is decreased to new conditions of σ_3 and T_3 in Figure 4a, the translation at constant ζ is from a material still undergoing workhardening to a material that is now overhardened. The value of the state parameter after the stress decrease exceeds the applicable ϵ_c^* (3) for the new conditions of stress and temperature. In this case, the creep curve as shown in Figure 4b exhibits the recognizable recovery response.

Figure 2 - Deformation mechanism map for salt (after Munson [13]).

Figure 3 - Transient creep curves for workhardening and recovery.

Figure 4 - Schematic of strategy for treating successive changes in stress (after [9]).

At this point, all of the equations and processes described are identical to those for the original modified M-D model, except that some quantities now pertain only to irreversible creep strains as indicated by the subscript, c.

EXTENDED M-D MODEL DEVELOPMENT

In high resolution, carefully performed stress drop experiments, observed behavior differs from that modeled by the modified M-D model which incorporates only workhardening under stress loading and recovery under stress unloading conditions. Although not usually specifically stated, the elastic component is included in the model and provides instantaneous elastic strain adjustment with loading changes. However, experimental results of Hunsche [2] in Figure 5, suggest an additional, time dependent reversible strain component, as well as the elastic component, is contained within the observed behavior. Both the instantaneous elastic and the time dependent reversible strain directions depend upon the sign of the stress change, rather than always continuing in the forward strain direction. As shown schematically in Figure 6, the creep strain at the time of the stress drop can be separated into (1) irreversible recovery, (2) reversible elastic, and (3) reversible time dependent components. The two reversible strain components and recovery appear only upon unloading. The total strain, as indicated in the figure, is the sum of the three components.

Interestingly, even though the workhardening transient response appears simplistic, the processes occurring in this part of the creep test must set the stage for the unloading response. The implication is that during the primary creep reversible strains are generated and stored within the structure, and these strains can be released. For loading, the transient strain accumulates as the dislocation substructure forms. It is reasonable to postulate that the latent reversible strains evolve together with the development of the internal defect structure. In fact, we might assume that the magnitude of the reversible strain is directly related to the strain required to develop the internal structure. In steady state creep, the internal dislocation structure becomes stable and does not change even though the material continues to strain. However, it appears that even in steady state the latent reversible strains must remain available. Although the exact nature of the generation of the time dependent reversible strain is unknown, it may be the result of the interaction forces between dislocations as they are forced against networks, subgrain boundaries, or pile ups by the applied stress, as proposed by Eshelby et al. [14] for dislocation pile ups. As the applied stress is changed, the spacing of the dislocations must adjust. In regimes other than those involving dislocation mechanisms addressed by the M-D model, one would not expect to see reversible strains generated.

As the internal structure evolves during workhardening, the reversible strain accumulates concurrently with the irreversible strains. As shown in Figure 1, the total accumulated creep strain can be written as the sum of the irreversible creep strain and the reversible creep strain

$$\epsilon_t = \epsilon_c + \epsilon_r \quad 8$$

In steady state creep, the internal defect structure is in equilibrium and constant, and no further accumulation of transient strain occurs. All of the components have then reached their maximum or limit values. Thus, the total transient strain at steady state is now the sum of the transient strain limits of the individual components

$$\epsilon_t^* = \epsilon_c^* + \epsilon_r^* \quad [\text{accumulation}] \quad 9$$

At this time, the manner of the accumulation of the reversible time dependent strain is unknown. As a consequence, a fundamental assumption will be made that this strain

Figure 5 - Experimental stress drop test (data of Hunsche [2]) and simulation.

Figure 6 - Decomposition of the irreversible and reversible strains of a stress drop test.

accumulates in direct proportion to the irreversible strain during workhardening. As will become evident this is perhaps the simplest assumption; but it is too restrictive and currently precludes the description of reversible strain transients in workhardening branches of the creep response, if these occur. Accumulation of the reversible time dependent strain component is specified through the use of the new state parameter, ξ . This reversible state parameter is directly proportional to the internal state parameter, ζ , and accumulates according to

$$\xi = \zeta \frac{\epsilon_r^*}{\epsilon_c^*} \quad 10$$

This defines the amount of reversible strain available anywhere along the workhardening curve.

At this time, the reversible strain limit, ϵ_r^* , cannot be determined directly from experiment, and is effectively unknown. However, with the assumption of the direct relationship to the irreversible creep, the form of the function may be taken the same as Eq. 7, as follows

$$\epsilon_r^* = k_0 e^{c\tau} \left(\frac{\sigma}{\mu} \right)^r \quad 11$$

The only difference is the magnitude of the constant, where k_0 is a constant that now can be determined from experiment and is the only new parameter introduced in the extended M-D model. In addition, r is a constant with a value of 3. The value of 3 reflects the same volume relationship as Eq. 7.

We now address the influence of stress changes on the reversible components. This can be visualized as imposing another higher order transient kinetic process onto the transient process of workhardening and recovery. When a stress change takes place, the transient reversible strain responses must adjust to the new conditions. The elastic component responds by coming instantaneously to its proper value of ϵ_e^* at the new conditions. In the case of the workhardening and recovery processes, the instantaneous imposition of a new set of conditions occurs at a constant value of the internal state parameter, ζ . Similarly, the value of ξ remains unchanged by the instantaneous stress change.

The time dependent reversible strain component response depends upon whether the stress change is an increase or a decrease, and exactly how the current value of ξ relates to the new value of ϵ_r^* . This transient response is illustrated in Figure 7. The reversible strain potential functions are parabolic equations that relate the initial state to the final state, similar to the potential functions for workhardening and recovery. In the figure, the ratio of the logarithm of the reversible strain rate divided by the strain rate in the unloaded condition is shown with respect to the value of the ξ parameter. Just before the stress change, the value of ξ is denoted as ξ_b and this value is the one that must adjust to the new value of the reversible strain limit, ϵ_r^* , which in turn is on a path related to the creep process at the new conditions of stress. Initial and new rates are related by

$$\dot{\epsilon}_r = (f - 1) \dot{\epsilon}_u \quad 12$$

Figure 7 - Potential functions for the reversible time dependent strain transient .

where $\dot{\epsilon}_u$ is the creep rate at the new (after) condition and the function, f , is given by the equation

$$f = \begin{cases} e^{D \left(1 - \left(\frac{\xi_b - \xi}{\xi_b - \xi_u} \right)^2 \right)} ; \xi \leq \xi_u \leq \epsilon_r^* \\ 1 \\ e^{d \left(1 - \left(\frac{\xi_b - \xi}{\xi_b - \epsilon_r^*} \right)^2 \right)} ; \xi \geq \epsilon_r^* \end{cases} \quad 13$$

Here, ξ_b denotes the initial (before) conditions and ξ_u the final (after) values. The parameters D and d are constants which define the driving potential for the transient process.

The three branches of Eq. 13 interact with the forward creep process in a complex manner, which is further complicated by the restrictive nature of the fundamental assumption of direct proportionality between reversible and irreversible strains. In Figure 8, which shows the workhardening and recovery transients, the trivial branch of Eq. 13 is attained only for a stress drop (C in the figure) where the value of ξ_b is exactly equal to ϵ_r^* (also ξ is exactly equivalent to ϵ_c^*) for the new conditions. This condition is called the critical condition.

In general, the first or accumulation branch should apply whenever accumulation of reversible strain continues to occur after the stress change, as illustrated by potential curve to the left in Figure 7. For accumulation, as indicated in Figure 7, the end state need not be the total reversible strain limit. In fact it is the appropriate value of ξ after the stress change, as denoted by ξ_u . Interestingly, ξ_u is itself in transition. However, under the current restrictions, stress changes to the left of the critical condition in Figure 8 always occur with just the correct proportionality between reversible and irreversible strains as given by Eq. 10, rather than Eq. 13. As a consequence, the model does not produce a transient in reversible strain to the right of the critical condition in Figure 8. All that happens is a change in the rate of reversible strain accumulation at the time of the stress change. This restriction, although similar to other theories limiting the stress drops to those from steady state creep, is probably unrealistic. Results of Blum and Fleischmann [15] on cubic specimens of salt for stress changes in this region of Figure 8 indicate possible transients that Eq. 10 cannot model. Until this restriction is removed, application of the extended model is currently limited to transitions from the recovery to the workhardening transient curves to the right of the critical condition. This presents no immediate problem in interpretation of the stress drop data of Hunsche [2], where the initial creep conditions are typically to the right of the critical condition.

The third or release branch of Eq. 13 applies for those stress changes which produce deaccumulation of reversible strain and becomes active only for stress drops that involve the potential function to the right or deaccumulation side of ϵ_r^* , as shown in Figure 7. Under these conditions, the stress drop always translates the material from a workhardening curve to a recovery curve. Typically, stress drop experiments are conducted from steady state, as shown. In Figure 8, these conditions are to the right of the critical condition. In this area of response, the constant d is given by the following

$$d = \ln \left(\frac{\dot{\epsilon}_{i_u}}{\dot{\epsilon}_b} \right) = \Delta_b + \ln \left(\frac{\dot{\epsilon}_{s_b}}{\dot{\epsilon}_u} \right) \quad 14$$

Figure 8 - Driving potentials for reversible strains related to the transient strain curves.

Under the restrictions of the current model formulation, a stress increase from a recovery curve to a workhardening curve in the region to the right of the critical condition gives a driving potential, D , which is identical to the potential d defined by Eq. 14. If the restriction is removed, additional driving potentials will have to be defined, as appropriate.

The driving potential is based on the principle that the change in the force supporting the current dislocation configuration will always produce an instantaneous response of the dislocations as though they were moving into a small volume of an unhardened material. In effect, the supposition is that, at the time of the stress change, the defect configuration supports a local equilibrium where the force within the defect structure just matches that force against the outside of the defect structure. In the instance of the stress change, these defect configuration forces are out of balance. The initial strain rate into this unhardened material is essentially at the virgin creep rate for the largest value of stress the system has experienced. As is evident, this stress could be either the initial (before) condition or new (after) conditions. Thus, for a stress drop, the ratio of the initial rate to the new rate can be very large. A large driving potential causes the reversible strain corrections to occur quite rapidly. However, because the volume is small, the dislocation movement is restricted and the response soon becomes again representative of the new surrounding defect structure and local equilibrium.

COMPARISON TO EXPERIMENTAL RESULTS

We now make use of the extended model to simulate experimental stress drop results. Hunsche [2] has been able to use very precise, specially designed apparatus to obtain excellent results through the transition. These results involved staged tests with several magnitudes of stress drop at several temperatures, where the initial condition was near steady state creep. Specimen materials were obtained from two sources, the Gorleben salt stock which is the proposed location of the German repository and the Asse Mine, which has been a traditional source for the German laboratory specimens. One of the principal problems in the analyses is that the exact specimen internal structure along the curves of Figure 8 cannot be calculated because the entire history of the tests are not given. As a consequence, the simulations require assumptions on history, as well as, the proper creep parameters for the different materials.

The Gorleben test results will be treated first, because the time (but not strain) history is complete and apparently the test utilized a single specimen. Moreover, the value of k_0 can be estimated from the experimental data. Data from the experiment are reproduced in Figure 5. The initial condition of the specimen was probably essentially unstrained because the Gorleben specimens were cored from deep holes drilled from the ground surface. The laboratory test was loaded to the initial stress of 5.71 MPa at a constant temperature of 105 °C and allowed to creep at this condition for about 40 days. The time was apparently insufficient for the specimen to actually achieve steady state. At 40 days the stress was dropped to 0.571 MPa (10% of the original) for an additional 6 days before returning the stress to the initial level. At the time of the stress drop, a marked reversible strain occurs, with a time dependent response that eventually produces a slightly negative creep rate. The reversible strain components can be evaluated from the test. If the elastic modulus is taken for WIPP salt, as given in Table I, the reversible elastic strain for this stress drop is estimated to be 1.84×10^{-4} . When the elastic strain is subtracted from the measured total negative strain, the reversible time dependent strain, as extrapolated to its asymptotic value, is 5.60×10^{-5} . This value actually represents the magnitude of the state parameter, ξ , because the material is still in the primary transient. Based on this value, ϵ^*_T is estimated to be 6.73×10^{-5} , which gives (from Eq. 11) a k_0 value of 21300.

When the Gorleben salt test was initially simulated using the complete set of the WIPP salt parameters, it became apparent the Gorleben material strain rates were considerably lower

than the WIPP parameters could possibly produce. The reason for this becomes clear from the experimental values of steady state creep ([16] Figure 2). These data for Gorleben salt suggest that it indeed has a lower steady state rate than either Asse or WIPP salt. Hunsche's creep results are shown in Figure 9, together with a fit for Asse salt, our evaluation of the best fit to the Gorleben salt, and representation of the WIPP salt according to the Table I values. Our evaluation of Gorleben salt gives an A_2 of roughly 2.660 E12/s. We have found such differences in other salt materials could be adequately "scaled" from the WIPP steady state structure factors, A's, and the transient strain limit constant, K_0 . Using this approach, the scale for A_2 between the WIPP and Gorleben materials is 0.275. This scale applied to A_1 gives a value of 2.306 E22 for the first mechanism. The Gorleben salt is a little harder than the WIPP salt which suggests a slightly smaller value of the transient strain limit, K_0 . The

Table I. Parameters for the extended M-D model simulations

Elastic Properties						
μ	12.4 GPa					
E	31.0 GPa					
ν	0.25					
Creep Properties						
Parameters	Clean WIPP Salt	Gorleben	Asse	Notes	Units	
A_1	8.386 E22	2.306 E22	3.941 E22	(%)	/s	
Q_1	25000	25000	25000	WIPP	cal/mol	
n_1	5.5	5.5	5.5	WIPP		
B_1	6.086 E6	None	None	Not used		
A_2	9.672 E12	<u>2.660 E12</u>	<u>4.530 E12</u>	Expt. [16]	/s	
Q_2	10000	<u>10000</u>	<u>10000</u>	WIPP	cal/mol	
n_2	5.0	5.0	5.0	WIPP		
B_2	3.034 E-2	None	None	Not used		
σ_0	20.57	None	None	Not used		
q	5.335 E3	None	None	Not used		
m	3.0	3.0	3.0	WIPP		
K_0	6.275 E5	4.000 E5	<u>4.450 E5</u>	Expt. [16-18]		
c	0.009198	0.009198	0.009198	WIPP	/T	
α_w	-17.37	-17.37	-17.37	WIPP		
β_w	-7.738	-7.738	-7.738	WIPP		
α_r	-3.0	-3.0	-3.0	WIPP		
β_r	-1.1	-1.1	-1.1	WIPP		
k_0		<u>21300</u>	23700	Expt. [2]

Figure 9- Steady state creep for WIPP, Gorleben, and Asse salt.

value to give agreement with the measured creep rate just prior to the stress drop is $4.00 \text{ E}5$. The activation energies for the three mechanisms were taken as the WIPP parameters. When Hunsche [2,16] analyzed the temperature dependence of creep, a single creep function was used. Typically, because the tests are in a transition region of the mechanism map, the single function analysis causes the activation energy to appear to increase with test temperature. This is handled correctly by the multiple mechanism approach using the WIPP activation energies.

Use of these reevaluated A and K_0 parameters, with the remaining unchanged WIPP parameters and the value of k_0 noted above, produced the simulation shown in Figure 5. The lowest permitted calculated strain rate was $1 \text{ E-}12/\text{s}$, to match the lowest experimentally detectable rate as limited by the apparatus [2]. Although some discrepancies exist, the agreement between the simulation and data could be considered quite reasonable. The fact that some adjustments were necessary in the WIPP parameters to accommodate the different Gorleben material is probably reasonable and not detrimental to the simulation.

We turn now to the tests on Asse salt. Although there is a large quantity of creep data available for the Asse salt, the reported data are predominantly steady state creep. Few data address the transient creep response, which we will use fully. From steady state data and the A value fit given by Hunsche [16], we find that Asse salt is also somewhat harder than WIPP salt, with structure factors A's, at about 0.468 of the WIPP values, as given in Table I. A transient strain limit was estimated from the data representing just six Asse salt creep curves ([16] Figure 2; [17] Figure 6; [18] Figures 3 and 4). These data are plotted in Figure 10 and do not include the specimen strain accumulated in the mine prior to coring of the specimens. To obtain the virgin material response, the proper analysis is the straight line fit which asymptotes to the experimental data at high stresses [11]. As shown, the transient strain limits give a K_0 of $4.45 \text{ E}5$. Because of the direct relationship of reversible and irreversible strains, we take the ratio of k_0 to K_0 for Asse salt to be the same as found for the Gorleben salt. This gives a k_0 of 23700 for the Asse salt.

Experimental data on Asse salt specimens are given in Figure 11 for three different stress drops at a test temperature of 100°C and in Figure 12 for a constant stress drop at five different temperatures (the test at 170°C was not modeled). It appears the testing involved no more than two individual specimens, with all of the stress drops obtained in cycles of initial load to some strain, a stress drop, and then after some additional strain a return to the original stress condition. When the experimentalist thought the specimen strain rates had recovered from the first stress drop cycle, the second cycle was initiated, to be followed by another cycle. In the case of the temperature changes, essentially the same procedure probably was followed, except the temperature was changed also during the period between cycles. Because the complete test history was not reported, it was not possible to simulate the exact history of individual test specimens through all of the cycles. Consequently, each stress drop was treated as though it was a separate simulation, beginning with the initial loading and ending with the indicated stress drop. The creep test simulation was carried to the point that the calculated strain rate matched the measured strain rate of the test just prior to the stress drop. At that point, the simulation modeled the stress drop and was terminated as appropriate to the reported data.

The simulations seem to duplicate the Asse salt experimental data in reasonable detail, except for the 4.50 to 0.272 MPa stress drop test in Figure 11 which showed a much larger release of strain than the simulation would suggest. Detailed evaluation of the test indicated a measured elastic strain considerably greater than can be explained by the elastic modulus of 31 GPa. Since a sudden reduction of modulus during one cycle of what appears a multiple cycle test of the same specimen seems unlikely, it is possible that some error occurred in the test

Figure 10 - Transient strain limit for Asse salt.

Figure 11- Asse salt tests and simulations for several stress change magnitudes, at 100°C.

Figure 12 - Asse salt tests and simulations for a constant stress drop and various temperatures.

procedure or apparatus. When the apparent error in the elastic reversible strain is corrected, the comparison to the data is improved, but a significant discrepancy remains. Also, the recovery process after the stress drop is not well modeled at the two highest temperatures.

DISCUSSION

As is apparent, the extended M-D model predicts a continuous response with the magnitude of the stress drop, rather than unique behavior as predicted by the internal stress models [1,4] at the theoretical ratio of the internal stress to applied stress. In terms of the back stress theories [5,7], the M-D model evolves to steady state conditions from non-steady conditions in contrast to concurrent workhardening and recovery processes with continuous evolution of a back stress. In fact, we have postulated a very simple mechanism for development of reversible strain. The complexity arises because of the diversity of initial and final structural states that can be accessed experimentally. If for example, the initial state was the critical condition for the stress drop experiment, there would be absolutely no transient reversible strain response predicted by the extended M-D model.

The extended M-D model, as currently developed, applies only to sudden stress drops. Moreover, because of the restriction introduced by direct proportionality between reversible and irreversible time dependent strains, stress changes involving transitions within the accumulation portion of the creep behavior cannot be treated. To obtain a general model, this restriction must eventually be eliminated. Also, in those cases where the material controls the release of stress, it appears additional mechanisms may be required to explain the process. The exact reasons for this are not yet clear; however, additional development will be necessary before general stress decrease paths can be treated.

In a general sense, this proposed concept is quite interesting, because the entire creep behavior appears to be composed of transient responses. The steady state condition is a thermally activated process that depends only on the applied stress and temperature, but transitions take place between mechanism regimes as specified by the mechanism map. Workhardening and recovery are irreversible transient processes that attempt to return the material to the steady state condition. And now, another kind of transient response is introduced to drive the reversible transient strains to whatever condition is dictated by the irreversible transients.

SUMMARY

The use of a simple model for the accumulation of reversible elastic and time dependent strains has been postulated. These accumulated reversible strains may produce negative strains when they are released. This release results in a transient response imposed on the transient response of the forward creep strains of workhardening and recovery. This additional transient is treated in the extended M-D model, and applied to simulate the results of several stress drop experiments, with reasonable agreement.

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