JMEPEG (2009) 18:985–989
DOI: 10.1007/s11665-008-9328-z
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1059-9495/$19.00

Rapid Flow Stress Characterization of Steel

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(Submitted August 15, 2008)

This rapid flow stress characterization concept involves rapid heating to an initial test temperature, T_1, followed by loading and short-time stress relaxation measurement, followed by heating to a higher temperature, T_2, followed by loading and short-time stress relaxation measurement, followed by heating to T_3, and so on. This test sequence can generate stress-strain rate-temperature data over a wide spectrum, with a single specimen. The principal advantage of this method of flow stress characterization is its short-time format. The cost of specimen preparation is modest, as well. Beyond this, the test methodology provides very accurate temperature control. It also tests a given metallurgical structure, with minimal complications from structural evolution due to plastic deformation. This study has demonstrated the feasibility of this method on plain carbon and austenitic stainless steels, using a Gleeble testing machine. This includes demonstrated consistency between single-test-per-specimen data and data derived from sequential testing on a single specimen, as well as consistency with conventionally developed flow stress data.

Keywords advanced characterization, carbon/alloy steels, forging, mechanical testing, stainless steels

1. Introduction

Software systems for deformation processing design, automation and control developed rapidly in the last quarter of the twentieth century, and it is now generally acknowledged that physical data base development did not keep pace. This resulted in imprecise and/or premature application of a number of process analysis systems, or to their restriction to certain limited process scenarios or heavily researched conditions.

Major efforts are now underway to characterize flow stresses, friction indices, heat transfer coefficients, and so on, so as to allow broad use of the available software systems. Even so, the generation of data and physical understanding can be tedious, especially if subtle metallurgical variations and wide ranges of deformation and deformation rate are to be considered.

For the development of flow stress databases, there is great potential for truly rapid, but sophisticated measurements by way of sequential stress relaxation characterization with closed-loop thermo-mechanical testing machines. Stress relaxation testing allows flow stress to be set forth over an essentially continuous range of strain rates, in a single test. Flow stress-strain rate relationships can be readily developed from stress relaxation data, and the usefulness of closed-loop thermo-mechanical testing machines for such purposes has been demonstrated for ASTM 1016, 1017, and 8620 steels in the 1000-1200 °C range (Ref 1). The test format was of approximately 2 min duration, with strain rates over a range from 10^{-3} to 6×10^{-2} s^{-1}.

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While such previous flow stress projection work was relatively efficient, it can be developed into a much more powerful tool, if a sequence of stress relaxation tests is undertaken on a single specimen. Such a rapid flow stress characterization concept involves rapid heating to an initial test temperature, T_1, followed by loading and short-time stress relaxation measurement, followed by heating to a higher temperature, T_2, followed by loading and short-time stress relaxation measurement, followed by heating to T_3, and so on, until the temperature range of interest has been covered or the specimen has been "exhausted" in one manner or another. In principle, this test sequence, on a single specimen, will generate stress-strain rate-temperature data over a wide spectrum in, say, 15 min of testing machine time.

The principal value of this *rapid*, multi-temperature, single-specimen test concept lies in its applicability to near "real time" manufacturing support evaluations. Applications to substituted, unfamiliar alloys, variations in billets from different sources, different process histories, contingent processing requirements and process troubleshooting are envisioned.

2. Testing Theory and Method of Data Analysis

Stress relaxation measurements have been undertaken for many years in order to develop engineering data bases for stress relaxation, per se, and in order to monitor metallurgical phenomena that perturb the relaxation response. For example, the decline in stresses in mechanical fasteners may be assessed, or the progress of phase changes may be monitored.

Basically, a stress is applied, corresponding elongation develops, and then the overall elongation is arrested, and held constant. The arrested elongation is directly related to the stress that initially exists. With time, this stress causes plastic strain (creep), the stress relaxes, and elastic elongation is progressively exchanged for plastic strain.

When using a closed-loop thermo-mechanical testing machine, a test rod is held between two grips, and a current is passed through the test rod, so as to produce and maintain a programmed temperature near the (longitudinal) mid-point of the bar. The temperature program system involves a thermocouple connected to the mid-point of the bar, in conjunction with a closed-loop control system. The specimen is loaded in tension to the desired stress, and the stoke is arrested and held, so as to allow the desired stress relaxation response. While the overall rod elongation and strain is held constant, the development of *plastic* elongation, $\Delta\ell$, may be expressed as follows:

$$\Delta\ell = -[(\Delta P)/(AE)]\ell_{\text{gage}} - [(\Delta P)/(AE)](\ell_{\text{spec}} - \ell_{\text{gage}}) - (\Delta P)/(K), \quad \text{(Eq 1)}$$

where ΔP is the related change (of negative sign, or a decrease) in force, A is the rod cross-sectional area, E is Young's modulus, K is the elastic or "spring" constant of the testing machine, and ℓ_{spec} and ℓ_{gage}, respectively, are the total length of the specimen (between grips), and the length of the plastically deforming part ("hot zone") of the specimen. The three segments of the right side of Eq 1 represent the decreases in elastic elongation that must be "replaced" by plastic elongation, in order for the overall rod elongation to remain constant. That is, $[(\Delta P)/(AE)]\ell_{\text{gage}}$ is the decrease in elastic elongation of the plastically deforming portion of the gage section, $[(\Delta P)/(AE)](\ell_{\text{spec}} - \ell_{\text{gage}})$ is the decrease in elastic elongation of the remaining portion of the specimen (between grips), and $(\Delta P)/(K)$ is the decrease in elastic extension of the testing machine elements. Now dividing through by ℓ_{gage} and combining terms, one obtains the plastic strain, $(\Delta\ell)/(\ell_{\text{gage}})$, or ε_p:

$$(\Delta\ell)/(\ell_{\text{gage}}) = \varepsilon_p = -[(\Delta P)/A](\ell_{\text{spec}}/\ell_{\text{gage}})\left[1/E + A/(K\ell_{\text{spec}})\right], \quad \text{(Eq 2)}$$

or

$$\varepsilon_p = -(\Delta\sigma)(\ell_{\text{spec}}/\ell_{\text{gage}})\left[1/E + A/(K\ell_{\text{spec}})\right], \quad \text{(Eq 3)}$$

where the stress change, $\Delta\sigma$, has been substituted for $(\Delta P)/A$. Finally, the plastic strain rate, $d\varepsilon_p/dt$, can be related to the rate of stress change, $d\sigma/dt$, by way of:

$$d\varepsilon_p/dt = -(d\sigma/dt)(\ell_{\text{spec}}/\ell_{\text{gage}})\left[1/E + A/(K\ell_{\text{spec}})\right] \quad \text{(Eq 4)}$$

This plastic strain rate may be related to the simultaneously occurring stress, leading to familiar high temperature constitutive equations, such as $\sigma = C\,(d\varepsilon/dt)^m$, where C and m are empirical constants.

Assessing the effective value of ℓ_{gage} is a problem intrinsic to such thermo-mechanical testing, since a longitudinal temperature gradient exists on either side of a "hot zone" that occurs midway between the grips. In most analyses a somewhat arbitrary "effective" value is used, enabling calculations of strain and strain rate, consistent with other test observations and with data developed by test techniques involving a well-defined gage length. In the present work, the effective value of ℓ_{gage} has been set equal to the test rod diameter.

It is also important to realize that some plastic extension of the rod may occur on loading to the peak stress, prior to the relaxation process. This plastic extension, $\ell_{\text{loading}} - \ell_{\text{gage}}$, increases the hot zone rod length, and decreases the cross-sectional area within the hot zone. This loading strain can be approximated as $(\ell_{\text{loading}} - \ell_{\text{gage}})/\ell_{\text{gage}}$, or $\varepsilon_{\text{loading}}$. The impact on the gage length cross-sectional area can be addressed by using A_{loading} for A, where $A_{\text{loading}} = (\ell_{\text{gage}}/\ell_{\text{loading}})A_{\text{gage}}$, where A_{gage} is the initial cross-sectional area. This cross-sectional area correction is particularly necessary when $\Delta\ell_{\text{loading}}$ reflects plastic strain not only with the "current" test, but also from loading during previous testing on the same specimen, such as at previous, lower temperatures. Corrections of this type have been employed in the work reported below.

It may also be argued that the value of ℓ_{gage}, itself, should be revised since it has been assigned the value of the rod diameter, or $(4A/\pi)^{1/2}$. However, given the rod-long heat transfer issues, and the somewhat arbitrary use of the rod diameter for ℓ_{gage}, this further adjustment has not been addressed in the work reported below.

3. Materials, Testing, and Results

Testing was undertaken on 10 mm diameter rod stock of AISI-SAE 1018 plain carbon steel (UNS Designation G10180) and Type 304 stainless steel (UNS Designation S30400). The value of ℓ_{spec} was 124.6 mm.

Young's modulus, E, was assigned a nominal value of 200 GPa. It is true, of course, that Young's modulus, in this analysis, represents behavior over a wide range of temperatures, and that Young's moduli are affected to a limited degree by alloying. However, the contributions of the elastic strains of the specimens, in these tests and analyses, are dominated by the elastic response of the testing machine. Hence, little error is introduced by modest uncertainties and variations in the value of E.

Testing was carried out at Dynamic Systems Inc., Poestenkill, NY, on a Gleeble 3500 system equipped with a 100 GPM servovalve (the Gleeble 3500 thermo-mechanical testing machine is made by Dynamic Systems Inc.). In the case of specimens tested at only one temperature, heating was undertaken at a rate of 50 °C/s, with the avoidance of tensile stress from thermal expansion. The temperature was then held for 10 s, followed by loading with a stroke rate of 50 mm/s to a stroke position of 1.0 mm in the case of 1018 steel, and a stroke position of 0.5 mm in the case of 304 stainless steel. Careful tuning was undertaken to avoid stroke overshoot. The value of $(\ell_{\text{loading}} - \ell_{\text{gage}})/\ell_{\text{gage}}$ for the case of 1018 steel was 0.08, and the value of $(\ell_{\text{loading}} - \ell_{\text{gage}})/\ell_{\text{gage}}$ for 304 stainless steel was 0.00. In any event, final stroke position was maintained, and load relaxation monitored for approximately 10 s. Temperature was held constant during relaxation.

Subsequent testing on a single specimen, involved discontinuation of heating, and unloading, promptly followed by reheating, stroke application, and relaxation consistent with conditions outlined in the previous paragraph. For each subsequent test, the value of A was adjusted, where necessary, for the contribution of $(\ell_{\text{loading}} - \ell_{\text{gage}})/\ell_{\text{gage}}$.

Regarding the elastic response of the testing machine, testing of unheated specimens allowed calculation of a K-value of 4.0×10^4 N/mm, utilizing the relationship:

$$\text{stroke/force} = (\ell_{\text{spec}})/(AE) + 1/K. \quad \text{(Eq 5)}$$

Stress relaxation testing was undertaken at 1000, 1100, and 1200 °C. For the cases of both steels, single temperature tests were undertaken for each of the test temperatures. Sequential tests were also performed on single specimens with the

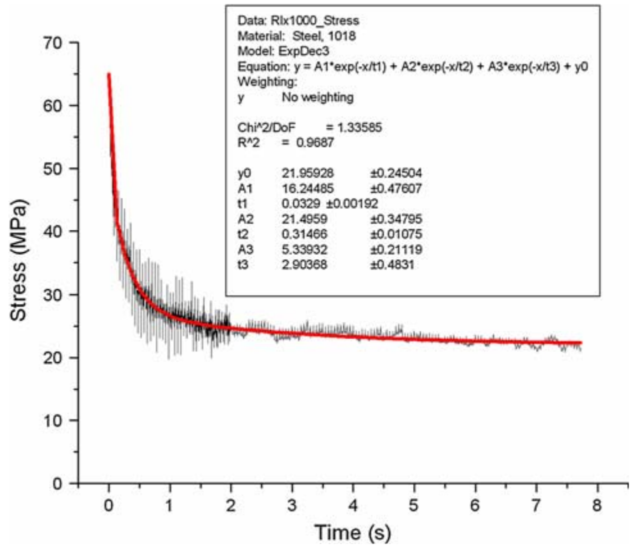

Fig. 1 Curve fit for stress relaxation data from AISI-SAE 1018 steel tested at 1000 °C

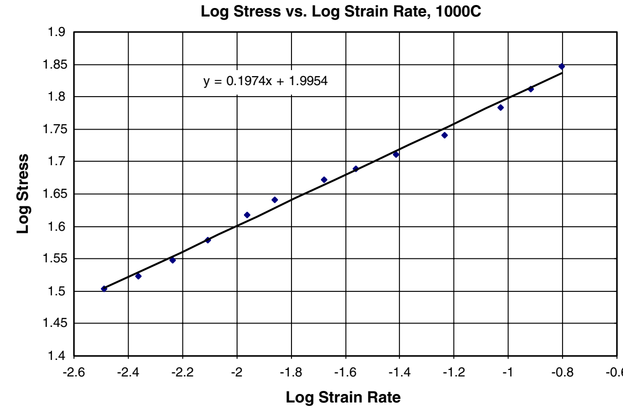

Fig. 2 Linear regression analysis of data from stress relaxation testing of AISI-SAE 1018 steel at 1000 °C, as used to identify constants C and m from Eq 7

temperatures undertaken in increasing order (1000 °C, then 1100 °C, and then 1200 °C). Stress relaxation responses were fitted by the equation:

$$y = y_o + (A1)\exp(-x/t_1) + (A2)\exp(-x/t_2) + (A3)\exp(-x/t_3), \quad \text{(Eq 6)}$$

where y represents stress in MPa, x represents time in seconds, and where y_o, $A1$, $A2$, $A3$, t_1, t_2, and t_3 are curve fitting constants. An example of such a curve fit is shown in Fig. 1. The noise visible in Fig. 1 is due entirely to electrical interference with the load cell measurements, and not to intrinsic variations in stress relaxation response.

Derivatives were taken of the equations fitting the stress relaxation data, so as to allow strain rate calculation by way of Eq 4. Log_{10} stress was then plotted versus $\log_{10}$ strain rate, and a linear regression analysis was used to identify constants, C and m, in the relationship:

$$\sigma = C(\mathrm{d}\varepsilon/\mathrm{d}t)^m. \quad \text{(Eq 7)}$$

An example of such a plot is shown in Fig. 2. Data analysis was generally limited to the first 2 s of relaxation time, roughly corresponding to a strain rate range of 10^{-3} to 10^{-1} per second.

The results of the tests in terms of C and m values, and calculated flow stresses for combinations of temperature and strain rate are presented in Tables 1 and 2.

Table 1 Flow stress measurements, by way of Eqs 6 and 7, for 1018 plain carbon steel

Temperature, °C	C value, MPa	m value	σ, @ 10^{-3} s^{-1}, MPa	σ, @ 10^{-2} s^{-1}, MPa	σ, @ 10^{-1} s^{-1}, MPa
1000 (a)	98.9	0.1974	25	40	63
1100 (a)	72.2	0.178	22	32	48
1200 (a)	80.6	0.3293	8	18	38
1100 (b)	84.1	0.2303	17	29	50
1200 (b)	60.8	0.2102	14	23	38

(a) One test per specimen, or initial test
(b) Sequential tests

Table 2 Flow stress measurements, by way of Eqs 6 and 7, for Type 304 stainless steel

Temperature, °C	C value, MPa	m value	σ, @ 10^{-3} s^{-1}, MPa	σ, @ 10^{-2} s^{-1}, MPa	σ, @ 10^{-1} s^{-1}, MPa
1000 (a)	139.3	0.1145	63	82	107
1100 (a)	110.8	0.1545	38	54	78
1200 (a)	87.5	0.1855	24	37	57
1100 (b)	111.7	0.1486	40	56	79
1200 (b)	84.3	0.1741	25	38	57

(a) One test per specimen, or initial test
(b) Sequential tests

4. Discussion

The principal advantage of the rapid flow stress characterization by stress relaxation testing with the thermo-mechanical testing machine is that of its short-time format, particularly when multiple test temperatures can be used with the same specimen. Stress-strain rate-temperature spectra can be examined in minutes that would occupy many hours with conventional testing. The cost of specimen preparation is modest, as well. Beyond this, the test methodology provides very accurate temperature control. It also tests a given metallurgical structure, with minimal complications from structural evolution due to plastic deformation.

These advantages mean little, however, unless the data are credible in terms of reproducibility, particularly with sequential testing on a single specimen. The data must also compare reasonably to data bases developed with conventional, albeit more cumbersome testing.

Table 1 allows comparison of carbon steel flow stress data developed for one temperature on one specimen with flow stress data developed for three temperatures on one specimen,

Table 3 Comparisons of carbon steel flow stress for the cases of data developed for one temperature on one specimen, and data developed for three temperatures on one specimen

Test method	Temperature, °C	Strain rate, s^{-1}	Flow stress, MPa
1 T/specimen	1100	10^{-3}	22
3 T/specimen	1100	10^{-3}	17
1 T/specimen	1100	10^{-2}	32
3 T/specimen	1100	10^{-2}	29
1 T/specimen	1100	10^{-1}	48
3 T/specimen	1100	10^{-1}	50
1 T/specimen	1200	10^{-3}	8
3 T/specimen	1200	10^{-3}	14
1 T/specimen	1200	10^{-2}	18
3 T/specimen	1200	10^{-2}	23
1 T/specimen	1200	10^{-1}	38
3 T/specimen	1200	10^{-1}	38

Table 4 Comparisons of stainless steel flow stress for the cases of data developed for one temperature on one specimen and data developed for three temperatures on one specimen

Test method	Temperature, °C	Strain rate, s^{-1}	Flow stress, MPa
1 T/specimen	1100	10^{-3}	38
3 T/specimen	1100	10^{-3}	40
1 T/specimen	1100	10^{-2}	54
3 T/specimen	1100	10^{-2}	56
1 T/specimen	1100	10^{-1}	78
3 T/specimen	1100	10^{-1}	79
1 T/specimen	1200	10^{-3}	24
3 T/specimen	1200	10^{-3}	25
1 T/specimen	1200	10^{-2}	37
3 T/specimen	1200	10^{-2}	38
1 T/specimen	1200	10^{-1}	57
3 T/specimen	1200	10^{-1}	57

as directly set forth in Table 3. While the flow stress data are in reasonable agreement in general, for high temperature testing, it is significant that the agreement is best for the highest strain rates, given that such strain rates are more relevant to commercial deformation processing operations.

Table 2 allows comparison of stainless steel flow stress data developed for one temperature on one specimen with flow stress data developed for three temperatures on one specimen, as directly set forth in Table 4. The flow stress data are in remarkable agreement, perhaps due to the fact that $(\ell_{loading} - \ell_{gage})/\ell_{gage}$ for 304 stainless steel was 0.00.

The carbon steel data seem to be in good agreement with published values in the literature. Donnelly has reviewed a broad array of mild steel flow stress data for the case of strain to 0.05 (Ref 2). This data base is compared with data from this study in Table 5.

Comparisons to Type 304 stainless steel data are somewhat more difficult, owing to the focus, in the literature, on flow stress measurements at high strains and strain rates in the context of dynamic recrystallization. Rapid rises in flow stress are often to be noted at small strains. In any case, the "Tabular

Table 5 Comparison of carbon steel flow stress measurements from this work, with summary data from a review by Donnelly (Ref 2)

Temperature, °C	Data source	σ, @ 10^{-3} s^{-1}, MPa	σ, @ 10^{-2} s^{-1}, MPa	σ, @ 10^{-1} s^{-1}, MPa
1000 (a)	This work	25	40	63
1000	Donnelly	25	35	63
1100 (a)	This work	22	32	48
1100	Donnelly	16	26	44
1200 (a)	This work	8	18	38
1200	Donnelly	10	18	31

(a) One test per specimen

Table 6 Comparison of Type 304/302 stainless steel flow stress measurements from this work, with summary data from the ASMI Handbook of Workability and Process Design (Ref 3)

Temperature, °C	Data source	σ, @ 10^{-1} s^{-1}, MPa
1000 (a)	This work	107
1000	ASMI	97
1100 (a)	This work	78
1100	ASMI	76
1200 (a)	This work	57
1200	ASMI	49

(a) One test per specimen

Summaries of Typical Flow Stress Data" in the ASMI Handbook of Workability and Process Design lists data for Type 302 stainless steel (at a chemical analysis comparable to Type 304) at a strain of 0.05 for strain rates down to 1.5 s^{-1} (Ref 3). Using the C and m values from this ASMI database, one can project comparative data as shown in Table 6.

This limited comparison reveals at least a fair consistency of the current work with conventionally developed stainless steel data. Beyond this, the data of Table 4 show an excellent agreement between single-test-per-specimen data and data derived from sequential testing on a single specimen.

Clearly, though, there is a need for a much broader data base for the case of rapid flow stress characterization by stress relaxation testing with thermo-mechanical testing machines, especially involving industrial samplings, and "round robin" testing at multiple laboratories. Beyond this, the data acquisition and analysis formats need to be consolidated and streamlined to facilitate broad usage.

5. Summary

This study has demonstrated the feasibility of rapid flow stress characterization by stress relaxation testing with a closed loop thermo-mechanical testing machine. This includes demonstrated consistency between single-test-per-specimen data and data derived from sequential testing on a single specimen, particularly in the case of Type 304 stainless steel. It has also been shown that the data are consistent with conventionally developed flow stress data, from the literature, especially for the broad array of comparisons available for the case of carbon steel.

Acknowledgment

This work was supported by a FINKL Graduate Fellowship provided by the Forging Industry Educational & Research Foundation.

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