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Ruggedness Evaluation of ASTM International Standard Test Methods for Shape Memory Materials: E3097 Standard Test Method for Mechanical Uniaxial Constant Force Thermal Cycling of Shape Memory Alloys

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National Aeronautics and
Space Administration

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- Corrections made: The strain rate value of test run #8 was incorrectly used to calculate the averages values and the half normal plots (Table II). The value was set to 0.01, but the correct value should be 0.001. Calculations were repeated and are reflected in the new figures, but the overall takeaway (TABLE IV) from the paper remained the same.
- Addition: Appendix D.—Calculated Effects, Ranks, and Significance per Factor
- Tables I, II, IV and tables in Appendix D have been modified.

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Level of Review: This material has been technically reviewed by technical management.

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Summary

This paper evaluates the ruggedness testing of the newly released ASTM International E3097 Standard Test Method for Mechanical Uniaxial Constant Force Thermal Cycling of Shape Memory Alloys. The ruggedness experiment was designed with eight runs in two replicates, consisting of seven factors of strain rate ($\dot{e}$), heating and cooling rates ($\dot{T}_{heat}$ and $\dot{T}_{cool}$, respectively), upper and lower cycle temperatures (*UCT* and *LCT*, respectively), hold time (t_{hold}), and minimum load (F_{min}) imparted on the samples. The results indicate that the hold time factor had no effect on any result variable. The minimum load factor, alternatively, had the greatest effect on several result variables, with the greatest influence on the strains at martensite start and finish (strain variation ~0.1 percent), and the strains at the upper and lower cycle temperatures (strain variation of 0.14 percent). The *UCT* was found to have a large effect on the austenite and martensite finish tangent line and data intersect, denoted by A_f* and M_f*, by ~17 and 4 °C, respectively. The testing methodology, analysis techniques, and resulting conclusions on the ruggedness of the test methods are presented.

1.0 Introduction

Shape memory alloy (SMA) actuator properties have been measured and reported for hundreds of alloy systems, yet not in any comprehensive or standardized format. Given their complex behavior and numerous dependent factors, having a standardized and robust method to consistently produce and interpret SMA data can be very beneficial. Initial efforts to address this lack of test methods was spearheaded by the Consortium for the Advancement of Shape Memory Alloy Research and Technology (CASMART) established in 2007 (Ref. 1). Several contributions flourished from this effort and laid the groundwork for several aspects of property measurement, test and analysis methods, and nomenclature, among others. In 2015, a collaborative effort composed of international members from industry and government was formed to build on this prior work and develop the first-ever material specification and test standards for SMA actuators. The team was organized through the Aerospace Vehicle Systems Institute (AVSI) with the purpose of identifying, developing, and disseminating SMA test methods with an established standards development organization (Ref. 2).

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Recently, two newly developed ASTM International test methods for SMA materials and components were released to the public. These standards, listed as E3097 Standard Test Method for Mechanical Uniaxial Constant Force Thermal Cycling of Shape Memory Alloys (UCFTC) (Ref. 3) and E3098 Standard Test Method for Mechanical Uniaxial Pre-strain and Thermal Free Recovery of Shape Memory Alloys (Ref. 4), represent a critical step toward the commercialization and production of SMA actuators. While several other standards exist based primarily on the superelastic response (for the medical industry) (Refs. 5 to 9), these two standards represent the very first universally accepted standards that define procedures for measuring shape memory effect properties, such as transformation temperatures, strains, and stiffness related to SMA thermoelastic actuators.

As with most ASTM standards, it is imperative to evaluate the sensitivity of these methods and ensuing significances. The methods define procedures with method parameters and factors that could influence the test results. These parameters and their suggested values were initially selected based on prior members' experiences to provide guidance and a starting point. Thus, the goal of this work is to perform ruggedness tests on the first test method (E3097) by using controlled experiments in which factors are deliberately varied. Such a test is performed before executing a larger interlaboratory study, mainly to anticipate and/or eliminate potential sources of inaccuracies as well as to determine the level of measured property variation due to the method parameters, aside from material or operator variations (inconsistencies). In conjunction with the AVSI team, a seven-factor ruggedness experiment was designed with eight runs in two replicates. The selected factors were strain rate ($\dot{e}$), heating and cooling rates ($\dot{T}_{heat}$ and $\dot{T}_{cool}$, respectively), upper and lower cycle temperatures (*UCT* and *LCT*, respectively), hold time (t_{hold}), and minimum load (F_{min}) imparted on the samples. Testing is performed at five different organizations on three material forms, including rods, wires, and flat sheets, all of which are critical to SMA actuator applications. Ruggedness test calculations were performed in accordance with established methods (Ref. 10) in addition to other approaches that were used to further examine the SMA behavior. The testing methodology, analysis techniques, and resulting conclusions on the ruggedness of the E3097 test method are presented. The work reported here is limited to tests conducted at the NASA Glenn Research Center that used round dogbone specimens (rod form).

2.0 Experimental Methods

2.1 Material

The material used in this study was a binary NiTi alloy with nominal composition of 55.3Ni-44.7Ti wt% produced by ATI Specialty Alloys and Components (heat #836441). Cylindrical, dogbone specimens, with gage dimensions of 3.81 mm (0.15 in.) in diameter and 19.05 mm (0.75 in.) in length, were machined from a hot-rolled rod and subjected to an annealing heat treatment. Stress-free transformation temperatures were measured by using differential scanning calorimetry (DSC), as shown in Figure 1, and were found to be 77, 96, 67, and 50 °C, for austenite start (A_s), austenite finish (A_f), martensite start (M_s), and martensite finish (M_f), respectively.

2.2 Thermomechanical Testing

Thermomechanical tests were performed on an MTS 810 servohydraulic load frame (MTS Systems Corporation) equipped with an MTS FlexTest® SE digital controller, a Eurotherm® 3504 temperature controller (Schneider Electric), and an Ameritherm NovaStar 7.5-kW induction heater (Ambrell Corporation). A type-K thermocouple was spot welded directly to the midpoint of the sample gage section

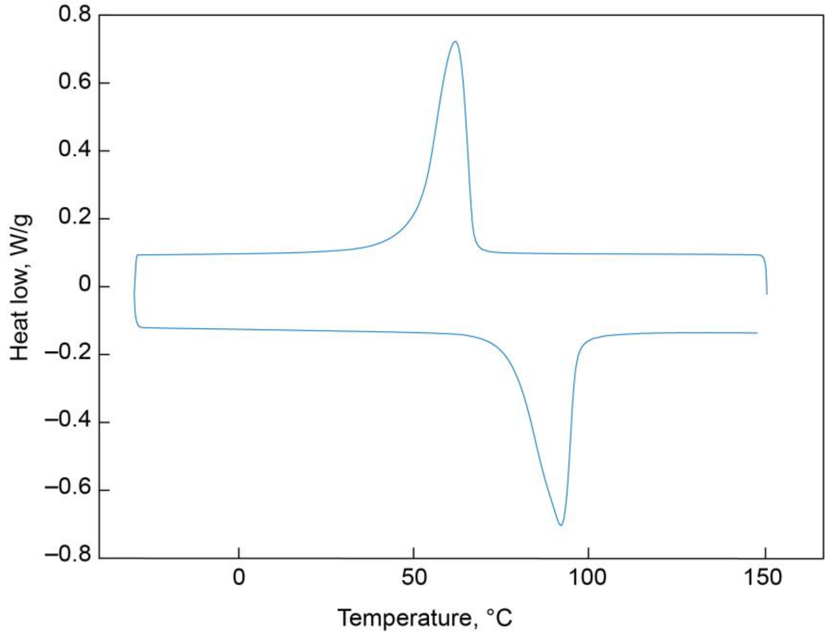

Figure 1.—Differential scanning calorimetry response of 55.3Ni-44.7Ti wt% shape memory alloy tested.

and used to measure temperature. Strain measurements were made by using an MTS 632.53E–14 high-temperature extensometer fitted with alumina rods and having a gage length of 12.7 mm (0.5 in.).

2.3 Test Procedure

Testing was performed in accordance with the test procedures outlined in the ASTM E3097 test methods (Ref. 3) and only a summary is provided here. The UCFTC test consists of thermomechanically cycling an SMA under an applied axial stress to determine transformation temperatures, related transformation strains, and the residual strains. The initial step consists of a normalization phase where the specimen is mounted on the load frame at room temperature and held under a minimum load not to exceed 7 MPa (~1 ksi). The specimen is then heated to the upper cycle temperature (*UCT*), cooled to the lower cycle temperature (*LCT*), and then reheated and held at the *UCT* for a specified time (hold time). This normalization procedure is performed to alleviate any residual stresses that may have arisen from sample handling, such as during machining or mounting operations. After normalization, the specimen is loaded to the selected stress level at *UCT*, followed by cooling and heating between the designated lower and upper cycling temperatures, with holds at both to ensure equilibration of temperature and/or strain. This procedure is schematically illustrated in Figure 2 along with the associated test result variables.

2.4 Experiment Design

The fractional factorial test design and accompanying statistical analysis methods used are performed in accordance with the standard practice for ruggedness tests outlined by ASTM standard E1169 (Ref. 10). The seven factors and their associated level settings are shown in Table I. The selected factors, $\dot{e}$, $\dot{T}_{heat}$, $\dot{T}_{cool}$, *UCT*, *LCT*, t_{hold}, and F_{min}, are believed to have the highest potential to affect the results. For each factor, the level settings, indicated by either (–1) or (+1) for low or high levels, respectively, were chosen to encompass the limits that could be expected to exist between different laboratories with different types of test equipment and control limitations.

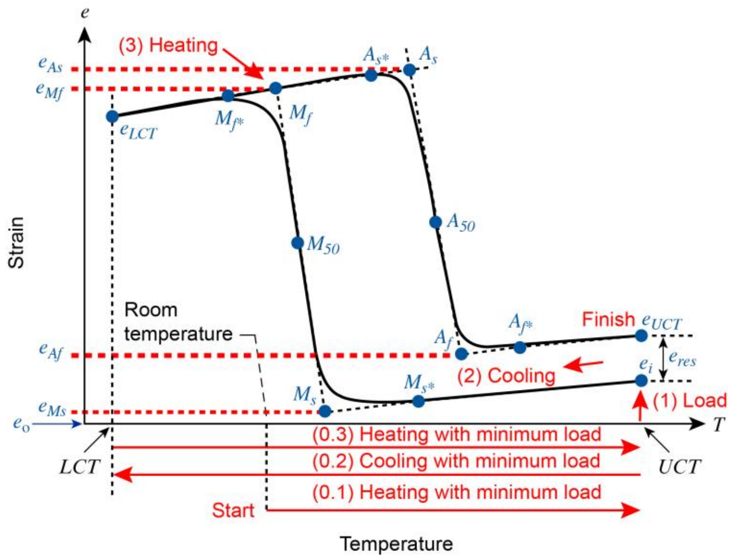

Figure 2.—Constant force thermal cycle and associated test parameters (adopted from Ref. 3). Normalization step is outlined at bottom of sketch labeled as “heating/cooling with minimum load”. Where A_{50} is austenite 50 percent, A_f is austenite finish, A_f* is austenite finish tangent line and data intersect, A_s is austenite start, A_s* is austenite start tangent line and data intersect, e is strain, e_0 is initial strain (at upper cycle temperature (*UCT*) after normalizing), e_{Af} is strain at austenite finish temperature (fit line intersection point), e_{As} is strain at austenite start temperature (fit line intersection point), e_i is initial loading strain (at *UCT*, at load), e_{LCT} is strain at lower cycle temperature (*LCT*) (after cooling under load), e_{Mf} is strain at martensite finish temperature (fit line intersection point), e_{Ms} is strain at martensite start temperature (fit line intersection point), e_{UCT} is strain at upper cycle temperature (after cooling under load), M_{50} is martensite 50 percent, M_f is martensite finish, M_f* is martensite finish tangent line and data intersect, M_s is martensite start, M_s* is martensite start tangent line and data intersect, and T is temperature.

TABLE I.—RUGGEDNESS TEST FACTORS AND LEVEL SETTINGS

Level	A	B	C	D	E	F	G
	Strain rate, $\dot{e}$	Cooling rate, $\dot{T}_{cool}$	Heating rate, $\dot{T}_{heat}$	Upper cycle temperature, *UCT*	Lower cycle temperature, *LCT*	Hold time, t_{hold}	Minimum load, F_{min}
–1	0.001 mm/mm per min	1 °C/min	1 °C/min	150 °C	25 °C	30 s	1 MPa
+1	0.01 mm/mm per min	4 °C/min	4 °C/min	180 °C	37 °C	600 s	7 MPa
Run no.	Level setting						
1, 9	+1	+1	+1	–1	+1	–1	–1
2, 10	–1	+1	+1	+1	–1	+1	–1
3, 11	–1	–1	+1	+1	+1	–1	+1
4, 12	+1	–1	–1	+1	+1	+1	–1
5, 13	–1	+1	–1	–1	+1	+1	+1
6, 14	+1	–1	+1	–1	–1	+1	+1
7, 15	+1	+1	–1	+1	–1	–1	+1
8, 16	–1	–1	–1	–1	–1	–1	–1

3.0 Analysis Methods

All raw data files were reduced and tabulated on a standardized format as defined by the AVSI team per ASTM E3097 (see Appendix B). These data were reduced by a single analyst using Glenn's SMA analyses tools based on tangent line fits, as partially outlined in References 8 and 11. Analysis of the statistical significance and relative importance of the seven different factors was performed by using both half-normal plots and a student's two-tailed *t*-test (Ref. 10). The half-normal plot allows for approximate grouping of factors as important or unimportant for influencing a chosen result in addition to ranking factors by their relative importance. These plots also provide a visual metric of whether a factor's effect falls within the normal scatter of data or provides a real influence. Referring back to Reference 10, the half-normal plots were constructed based on two main quantities: the main effect of each factor on the selected result variable and the standard error of effects from all trials. The main effect of each factor is determined from the average results of all the high (+1) and the low (–1) levels by using Equation (1) as follows:

$$effect = \left(Ave+\right) - \left(Ave-\right) \tag{1}$$

The estimate of the standard error of an effect, denoted by S_{effect}, is given by

$$S_{effect} = \sqrt{\frac{4s_{rep}^2}{N \cdot reps}} \tag{2}$$

where N is the number of runs (i.e., $N = 8$) in the experiment design, *reps* is the number of replicates (i.e., $reps = 2$), and s_{rep} is the estimated standard deviation (STDEV) of the test results given by

$$s_{rep} = \frac{s_d}{\sqrt{2}} \tag{3}$$

where s_d is the STDEV of the differences between replicates 1 and 2, with each difference calculated as rep. 2 – rep. 1. An example calculation used to construct a half-normal plot is shown in Table II for the SMA property, A_f. In this example, the STDEV of the differences s_d is calculated as STDEV (–0.657, 0.482, –0.555, –0.593, 0.475, –2.25, –0.068, –1.668) = 0.962.

From these values, the effects of all factors can be ranked and assigned half-normal distribution plotting values, which are predetermined from a half-normal distribution for the seven factors (Ref. 10). This ranking, along with the half-normal plotting values obtained from Table A2.1 in Reference 10, are shown in Table III. These plotting values will comprise the y-coordinates for each factor in the half-normal plot.

TABLE II.—RUGGEDNESS EXAMPLE CALCULATIONS FOR AUSTENITE FINISH, A_f, RESULTS

Run no.	Strain rate, $\dot{e}$	Cooling rate, $\dot{T}_{cool}$	Heating rate, $\dot{T}_{heat}$	Upper cycle temperature, UCT	Lower cycle temperature, LCT	Hold time, t_{hold}	Minimum load, F_{min}	*Rep. 1*	*Rep. 2*	Replicates (*Reps.*) *1* and *2*	
	A	B	C	D	E	F	G	Result	Result	Average	Difference
1	+1	+1	+1	–1	+1	–1	–1	122.876	122.219	122.547	-0.657
2	–1	+1	+1	+1	–1	+1	–1	121.800	122.282	122.041	0.482
3	–1	–1	+1	+1	+1	–1	+1	123.753	123.198	123.476	-0.555
4	+1	–1	–1	+1	+1	+1	–1	127.098	126.505	126.802	-0.593
5	–1	+1	–1	–1	+1	+1	+1	122.374	122.849	122.612	0.475
6	+1	–1	+1	–1	–1	+1	+1	124.048	121.798	122.923	-2.250
7	+1	+1	–1	+1	–1	–1	+1	123.267	123.199	123.233	-0.068
8	–1	–1	–1	–1	–1	–1	–1	125.214	123.546	124.380	-1.668
+1 average	123.876	122.608	122.747	123.888	123.859	123.594	123.061	STDEV[a] of differences between replicates 1 and 2, s_d			0.962
–1 average	123.127	124.395	124.257	123.115	123.144	123.409	123.942	Estimated STDEV of test results, s_{rep}			0.680
Effect	0.749	-1.787	-1.510	0.772	0.715	0.185	-0.882	Standard error of an effect, S_{effect}			0.340

[a]Standard deviation.

TABLE III.—FACTOR RANKINGS AND CALCULATED VALUES FOR EFFECTS ON AUSTENITE FINISH, A_f

Factor ranking	Factor	Effect	Student's *t*-value[a]	*p-value*,[b] percent	Half-normal plotting values (Ref. 10)
1	B	-1.7868	-5.2537	0.1181	1.803
2	C	-1.5098	-4.4392	0.3011	1.242
3	G	-0.8817	-2.5924	3.5818	0.921
4	D	0.7723	2.2708	5.7413	0.674
5	A	0.7492	2.2028	6.3464	0.464
6	E	0.7147	2.1014	7.3718	0.272
7	F	0.1853	0.5448	60.2787	0.090

[a]See Reference 10.
[b]Probability.

Also reported in Table III are the Student's *t*-value (see Ref. 10) and the associated *p-values*. These are used to judge the probability of a null hypothesis being valid. In other words, based on the assumption that a factor has no effect, the probability of a given *t*-score occurring is determined. If this probability, or *p-value*, is less than 5 percent, then the factor can be said to have some effect within a 95 percent confidence interval. The *p-value* for each factor is a function of both the *t*-score for the given factor and the degrees of freedom, ν, for the entire experiment. These two values are given by the expressions

$$t = {effect}/{S_{effect}} \tag{4}$$

and

$$\nu = \left(N - 1\right)\left(reps - 1\right) \tag{5}$$

The *p-value* is then calculated by using conventional expressions such as the incomplete beta function $I_x(z,w)$ given by

$$p = I_{\left(\nu/_{\nu+t^2}\right)}\left(\frac{\nu}{2},\frac{1}{2}\right) \tag{6}$$

The final aspect used in the half-normal plots of this work is the replicate error line, intended to provide a visual metric of the repelicate error present in the experiment. Following ASTM E1169, the replicate error line was calculated by using

$$y = \frac{x}{S_{effect}} \tag{7}$$

An example half-normal plot for the result variable A_f is shown in Figure 3. On the *x*-axis, the absolute value of each factor's effect is plotted, and on the *y*-axis, the half-normal distribution plotting values previously shown in Table III are plotted. Half-normal plots allow for an understanding of what factors may be considered significant or relevant as well as providing a relative ranking of how factors affect a given result variable. The greater the effect of a factor, the farther right it will fall, and the greater the effect relative to other factors observed, the higher it will be placed, meaning that the farther a factor falls from the origin, the more likely it is to have an effect on the result variable. Additionally, the replicate error line provides a quick visual metric for how the effects of a factor compare to the random variation observed across replicates. Anywhere to the left of the line and any effects a factor may have likely fall within the noise observed in the experiment, whereas the farther right of the line a factor falls, the more likely its effect is to be relevant (Figure 3).

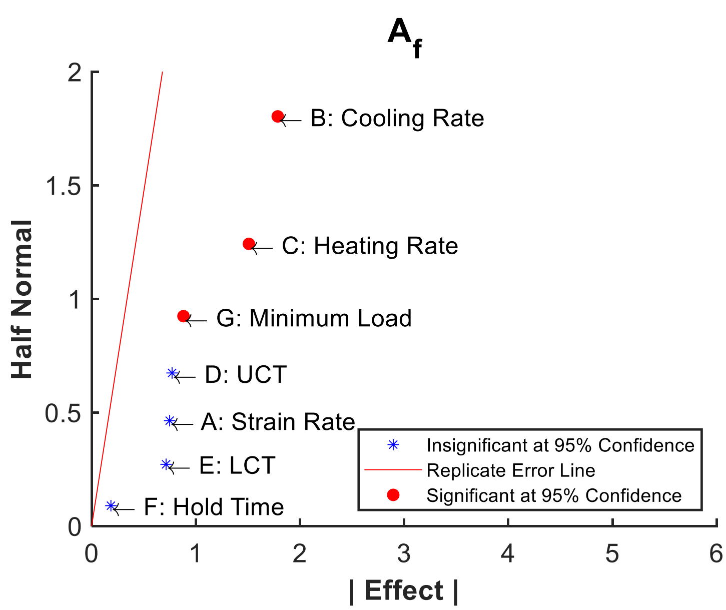

Figure 3.—Example half-normal plot with *t*-test results corresponding to result variable A_f (austenite finish), for factors of A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (*UCT*); E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.

4.0 Results

4.1 Experiment Factor Verification

As an evaluation of ruggedness is contingent on selected experimental factors varying only between the two settings selected, several runs were analyzed to ensure that the seven factors used were properly maintained at their specific levels. Test equipment and test control methods can play a significant role when evaluating ruggedness. All seven factors were verified in multiple tests and the results of run 3 are presented in this section. Figure 4 shows the strain versus time during the loading and unloading periods where the strain rates are verified. Average slopes of these regions show that strain rate control roughly corresponded to the required value of 0.001 mm/mm/min. Though some fluctuations are present in the initial loading, these are unlikely to affect ruggedness results to any significant degree, and strain rate data for all runs otherwise match the required values closely.

Figure 5 shows the cooling and heating rates. Both cooling and heating rates for run 3 match the required factor values closely, matching the –1 °C/min cooling and +4 °C/min heating rates. This same consistency was found to be true for all runs.

UCT, *LCT*, and hold times followed the required factor values relatively well, as is evident by Figure 6. Despite variation of ~1 °C from *UCT* and *LCT* as well as hold times that are not precisely observed in test data, for all runs, *UCT* and *LCT* were observed to match the required values, and temperature uniformity was maintained during the hold times, to within a reasonable tolerance of ±2 °C.

4.2 Baseline Characterization and Normalization Test

Before conducting the ruggedness tests, preliminary alloy evaluation was conducted on this material lot to observe the nature of the strain-temperature response. Although this is not part of the referred standard, gaining familiarity through these initial baseline tests can better guide the experimental design. Figure 7 illustrates three hysteresis curves obtained at stresses of 100, 200, and 300 MPa. It is apparent that an applied stress of 300 MPa results in very high residual strains while a lower stress of 100 MPa results in a more classical response, which was expected in this untrained material. Thus, a stress of 100 MPa was adopted for the ruggedness evaluation presented in this work.

The normalization test, which is conducted while holding a minimum load not to exceed 7 MPa, is shown in Figure 8. Although the stress is kept at zero, small yet discernable hysteresis curves are developed. This may be due to small internal stresses that could have developed during the material processing or due to the volume change from B2 ⇔ B19′ monoclinic, with the high-temperature B2 phase having a smaller crystallographic volume (Ref. 12).

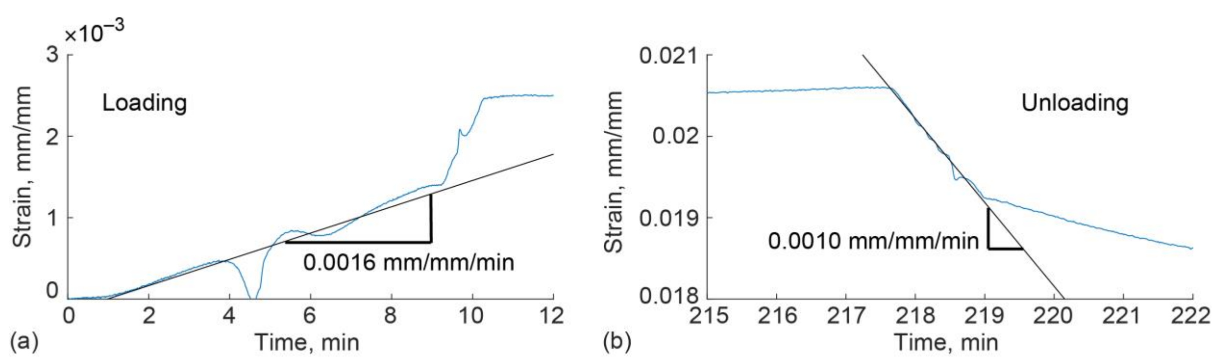

Figure 4.—Strain rate verification: strain versus time corresponding to run 3. (a) Loading. (b) Unloading.

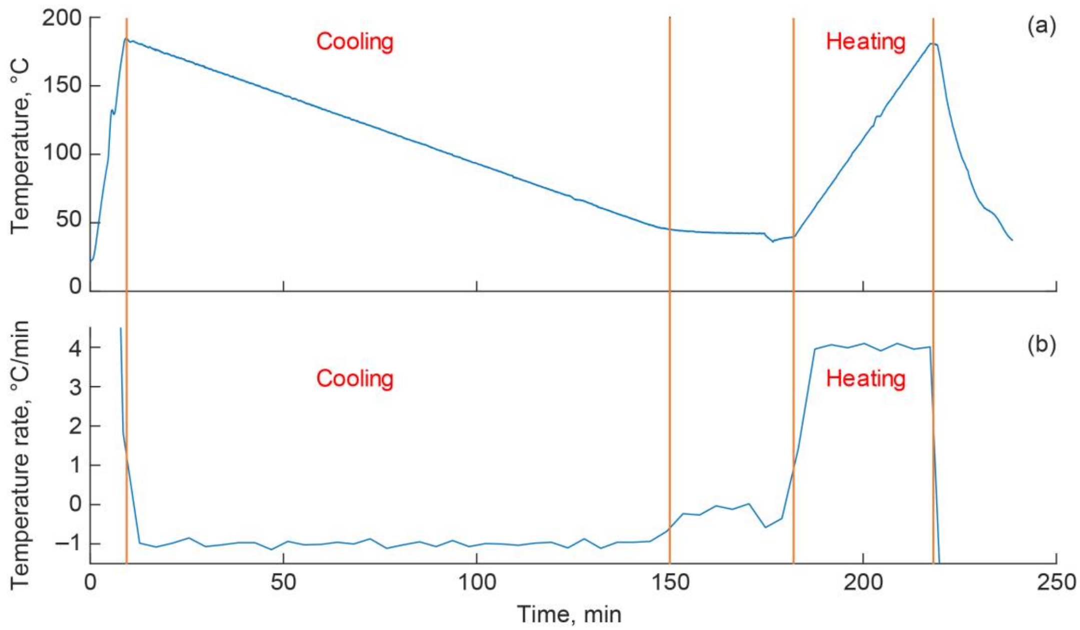

Figure 5.—Cooling and heating rate verification. (a) Temperature versus time. (b) Temperature rate versus time corresponding to run 3.

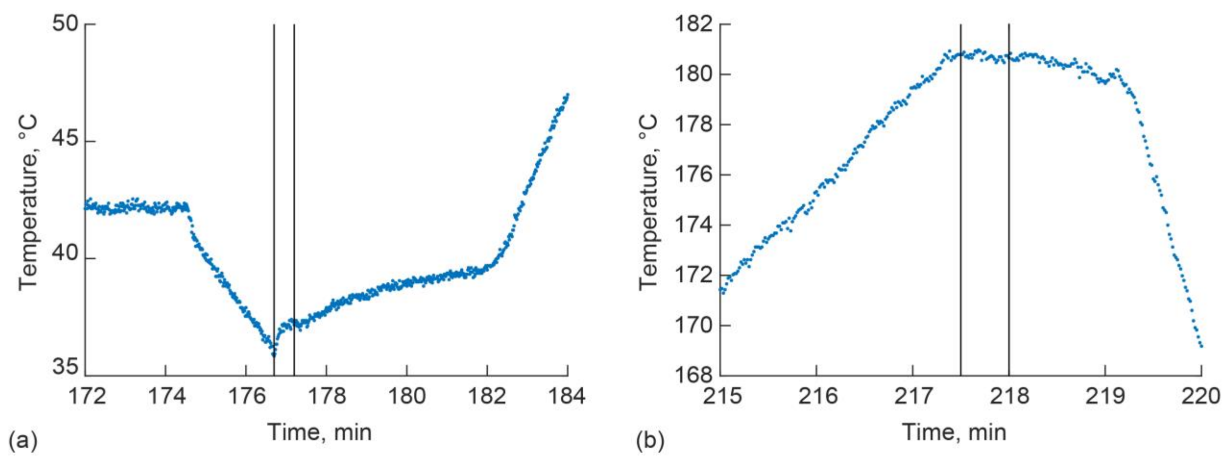

Figure 6.—Sample temperature versus hold time verification. Vertical bars indicate 30-s hold periods. (a) Lower cycle temperature. (b) Upper cycle temperature.

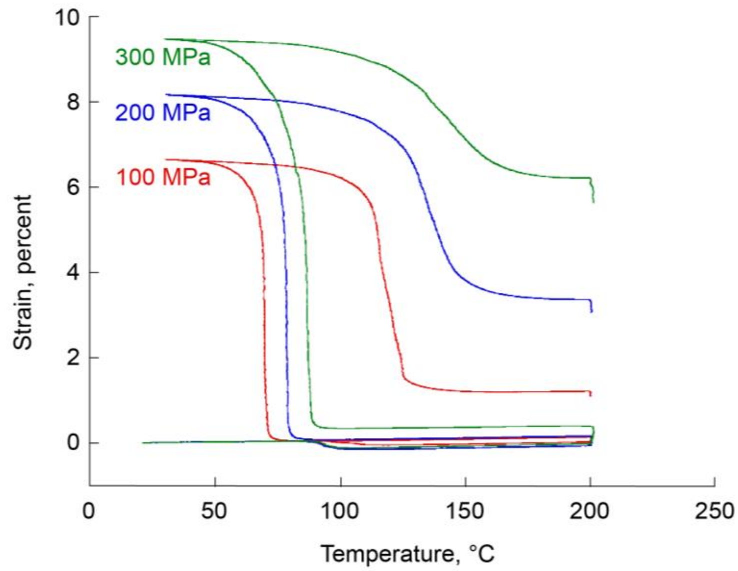

Figure 7.—Strain-temperature responses at different applied stresses.

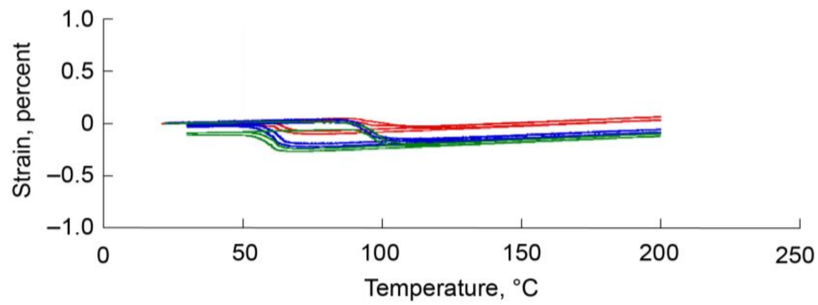

Figure 8.—Example normalization test for three different runs while holding stress at ~0 MPa.

4.3 Ruggedness Test Results

In addition to the half-normal plots, data were also presented in two other formats to observe trends and other potentially useful correlations. Each result variable related to this standard (23 in total, Figure 9 to Figure 31) was plotted as a function of run number including both replicates, and as a function of the low- and high-level settings corresponding to each factor listed in Table I.

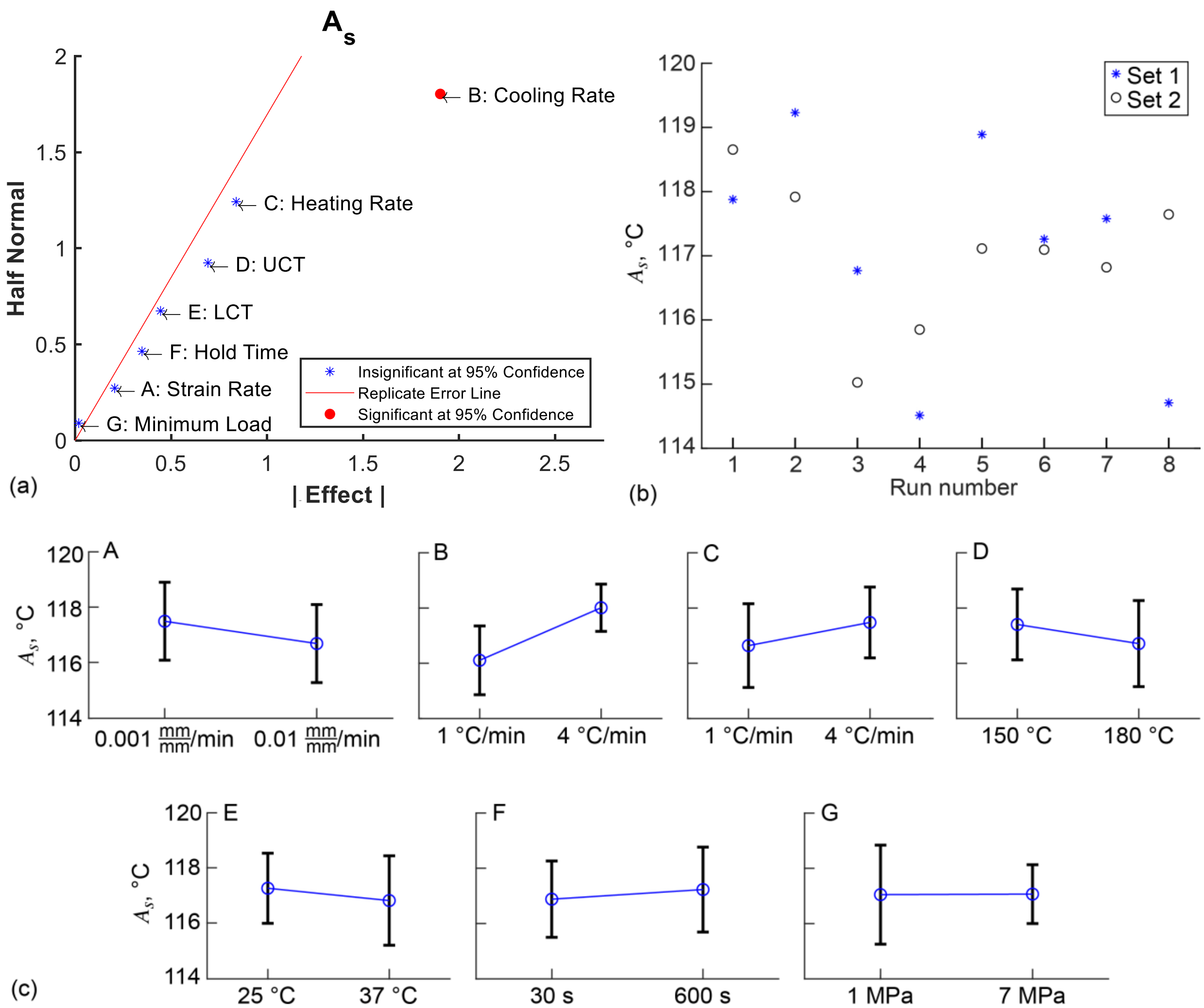

Figure 9.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for austenite start, A_s. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (*UCT*); E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.

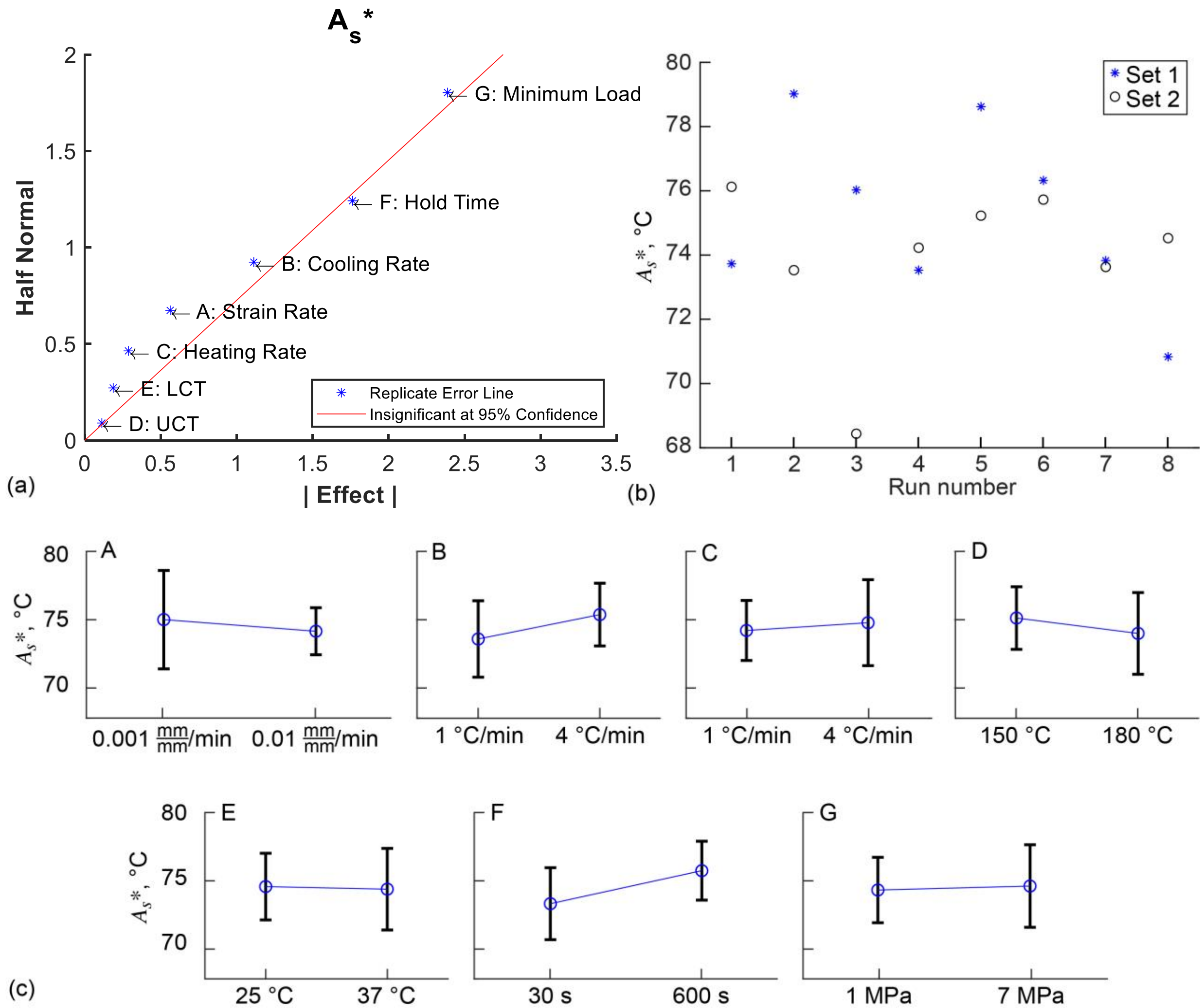

Figure 10.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for austenite start tangent line and data intersect, A_s*. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (*UCT*); E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.

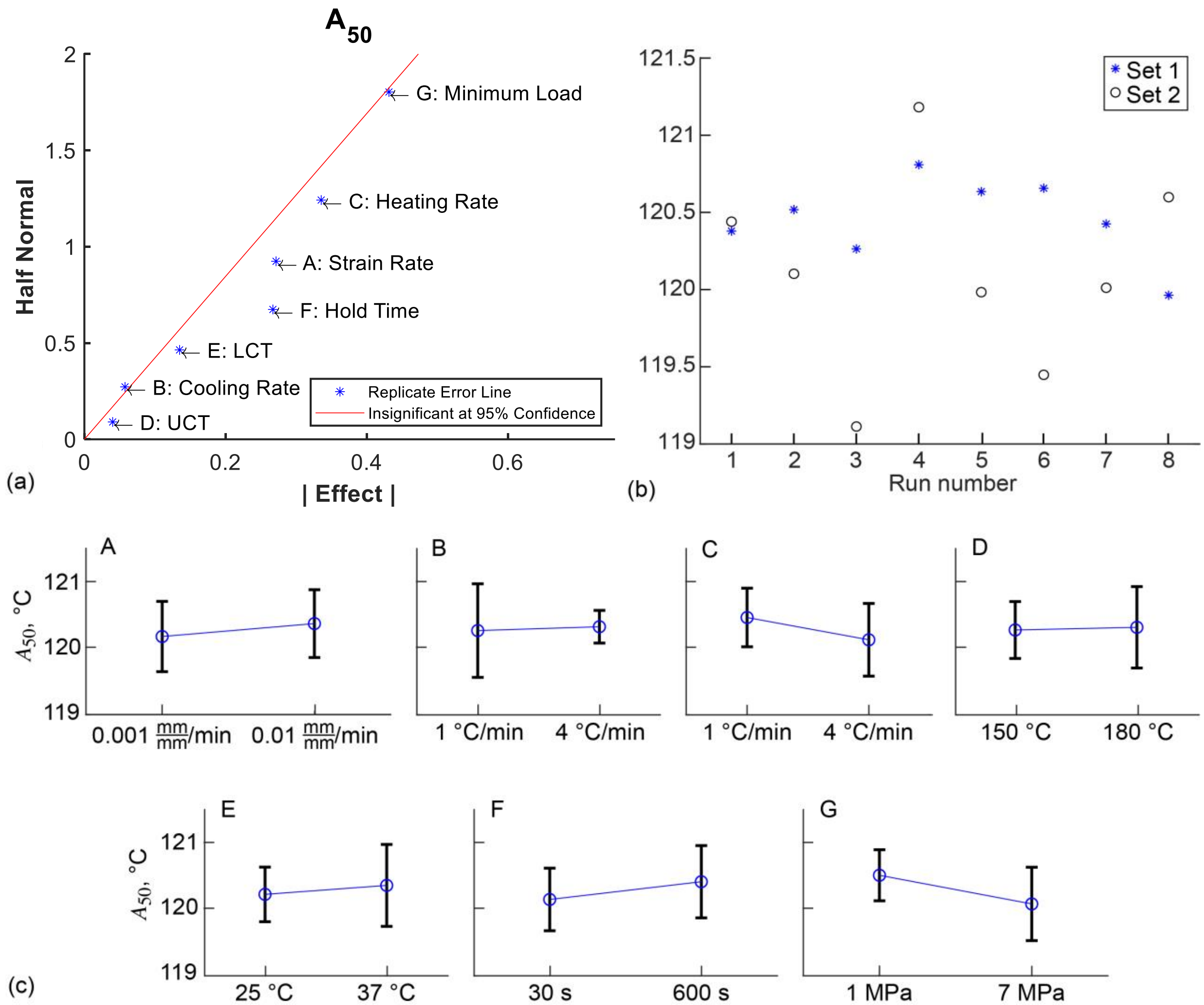

Figure 11.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for austenite 50 percent, A_{50}. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (*UCT*); E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.

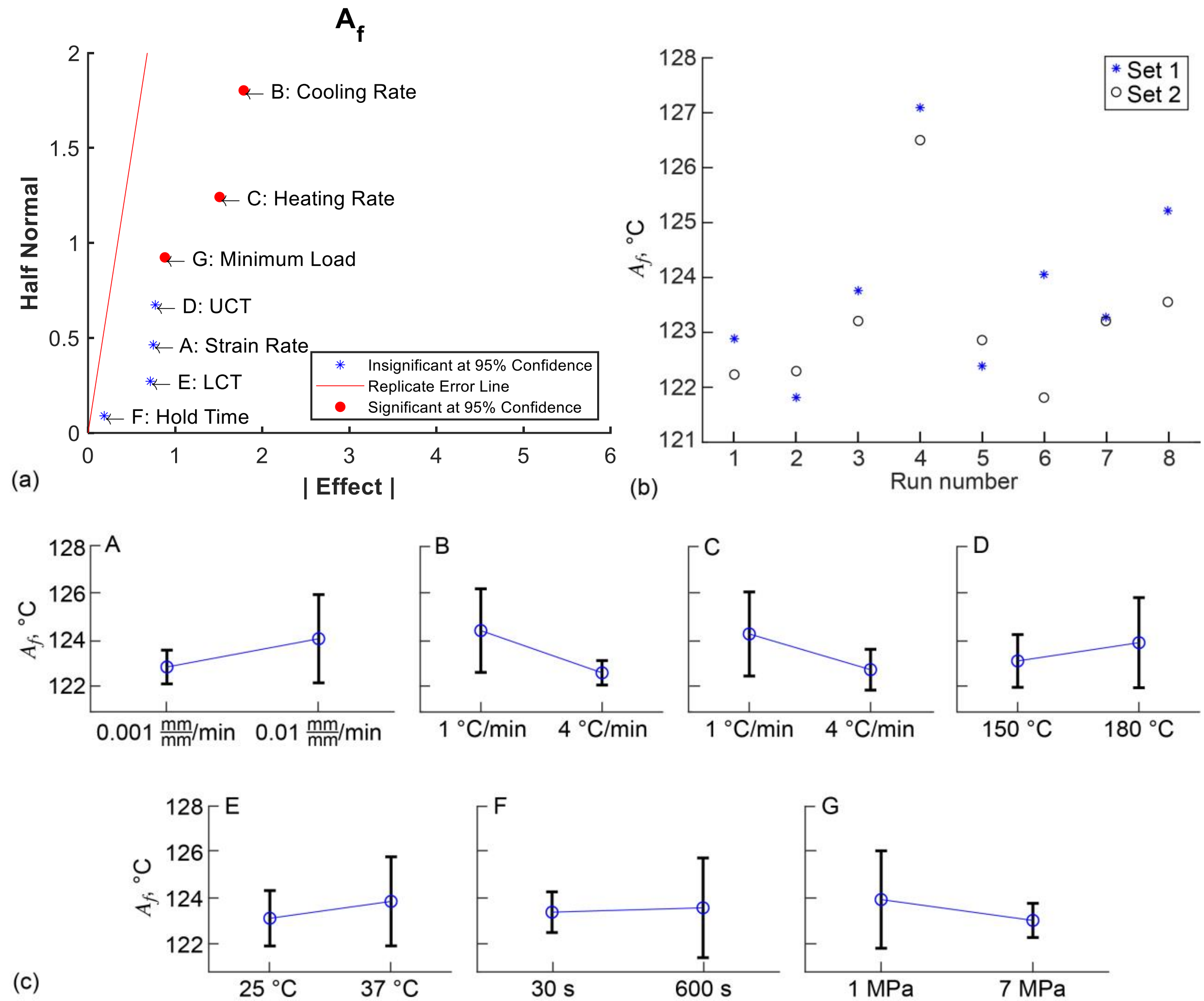

Figure 12.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for austenite finish, A_f. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (*UCT*); E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.

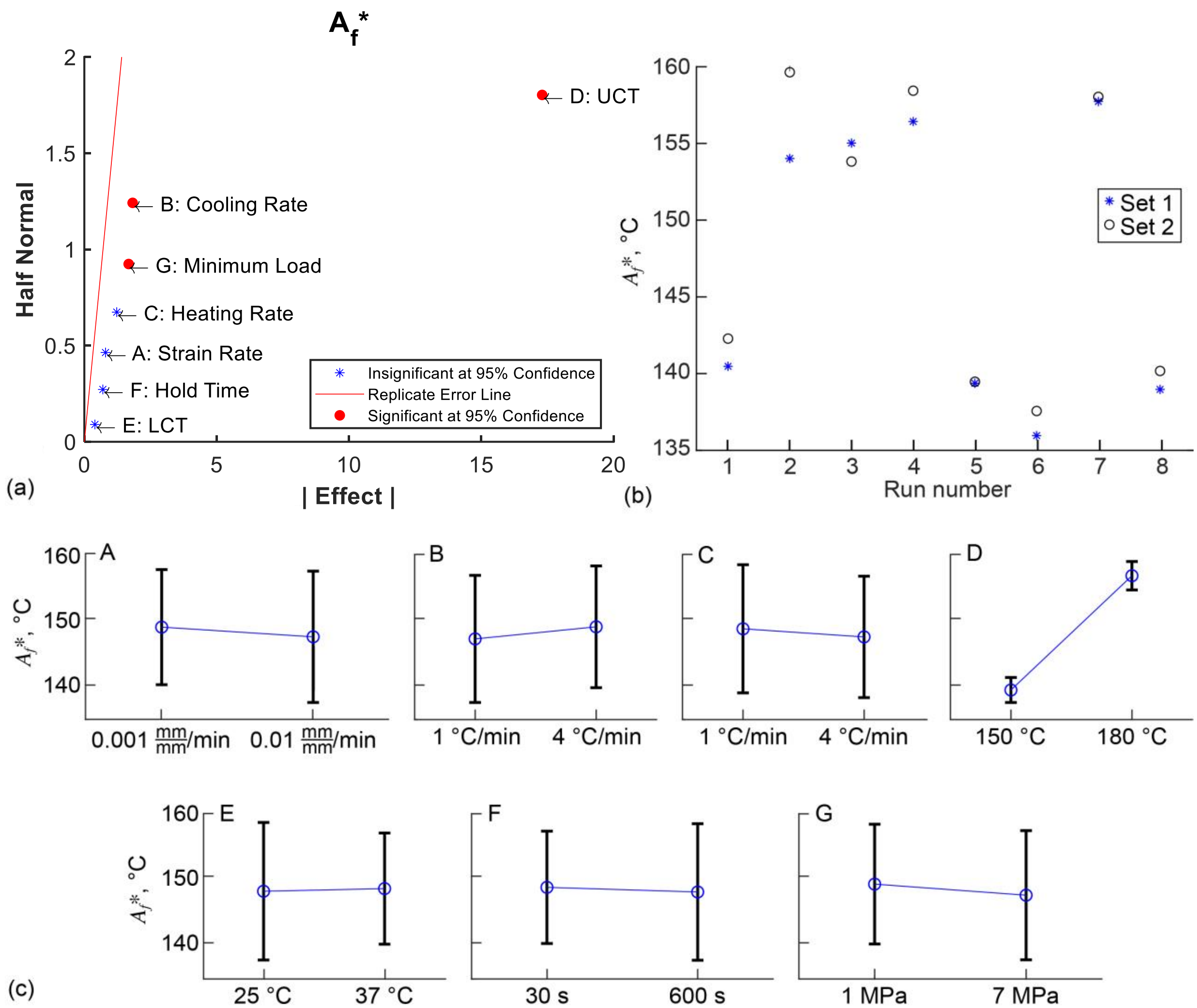

Figure 13.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for austenite finish tangent line and data intersect, A_f*. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and standard deviation for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (*UCT*); E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.

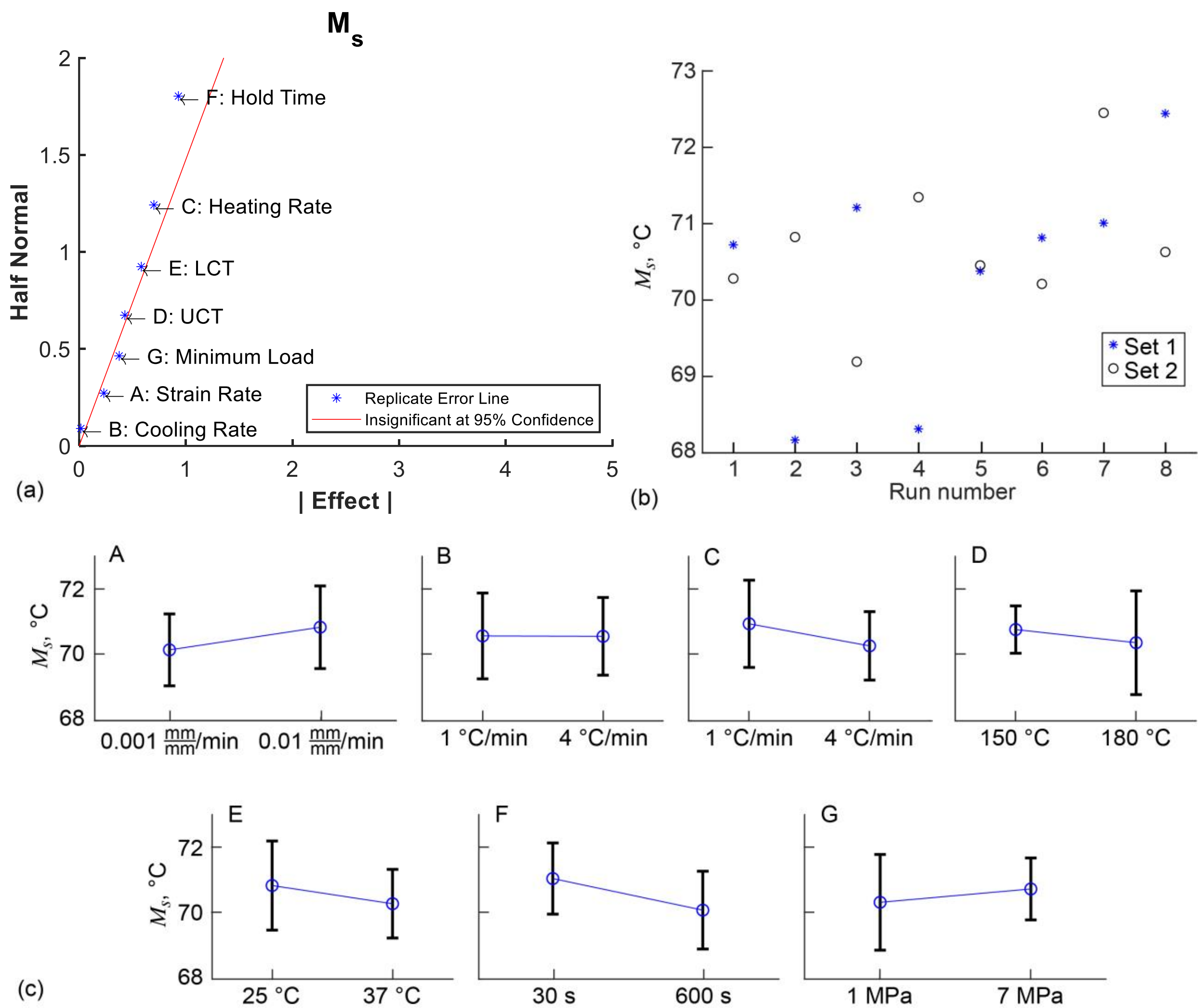

Figure 14.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for martensite start, M_s. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (*UCT*); E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.

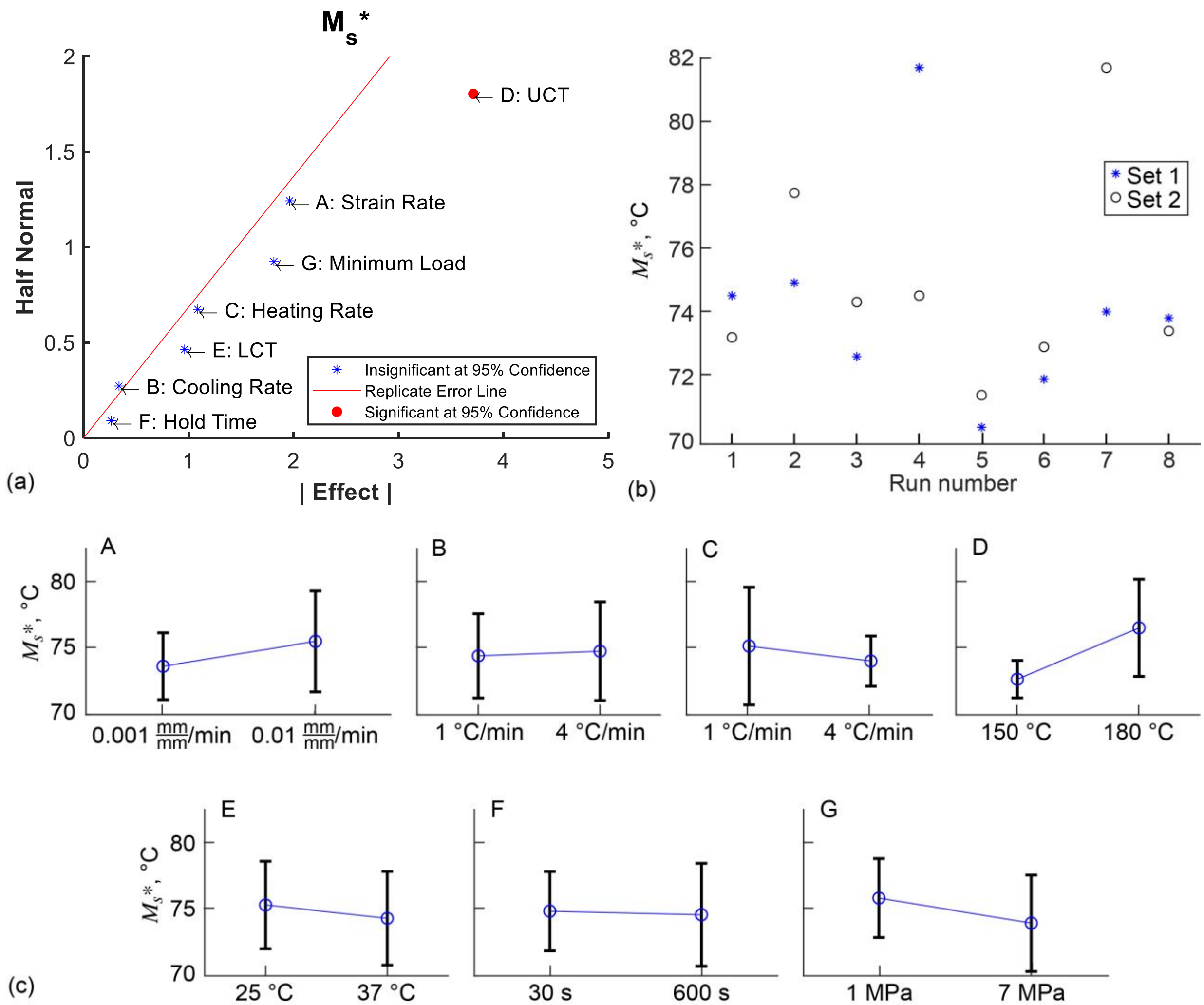

Figure 15.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for martensite start tangent line and data intersect, M_s*. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (*UCT*); E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.

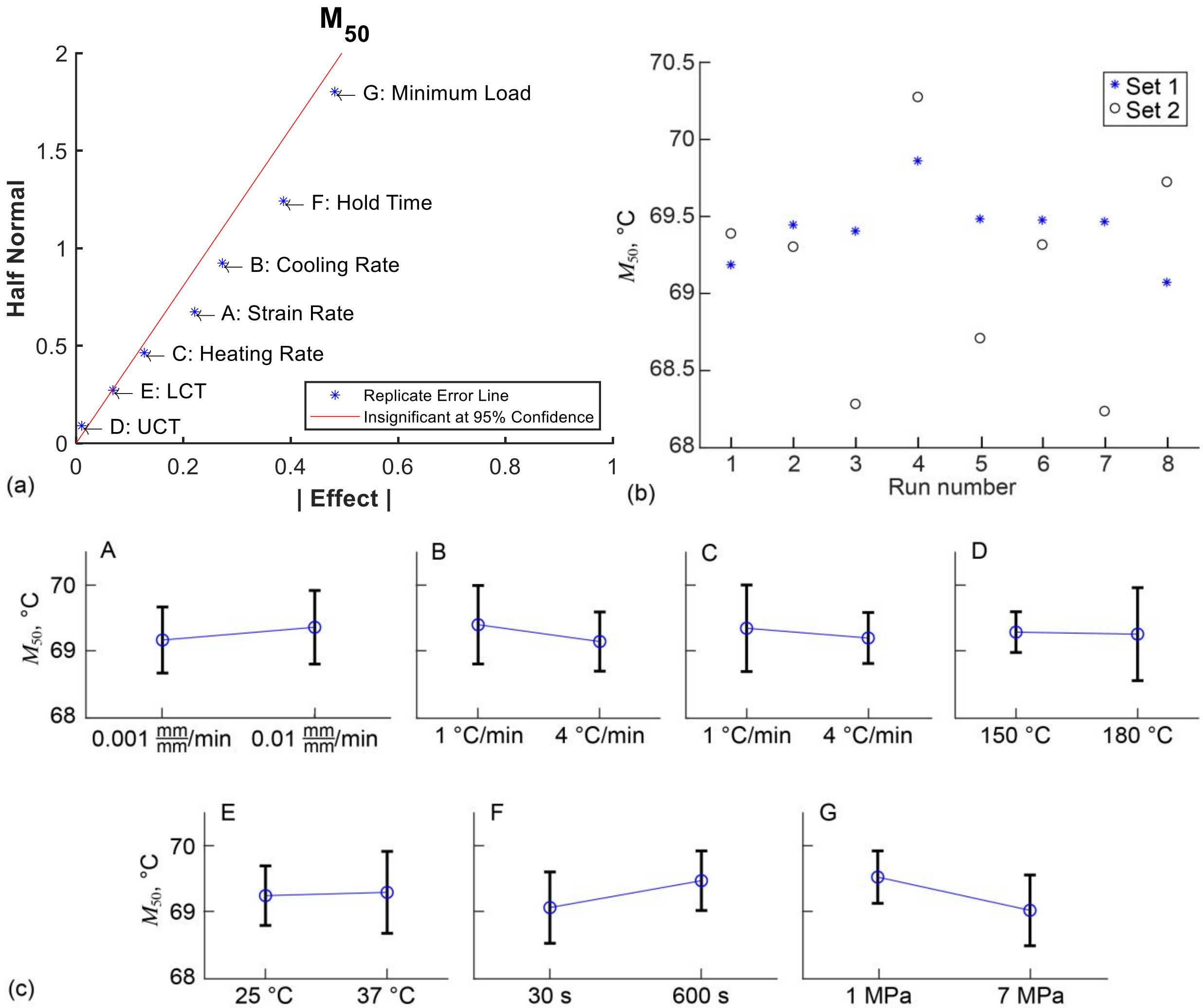

Figure 16.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for martensite 50 percent, M_{50}. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (*UCT*); E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.

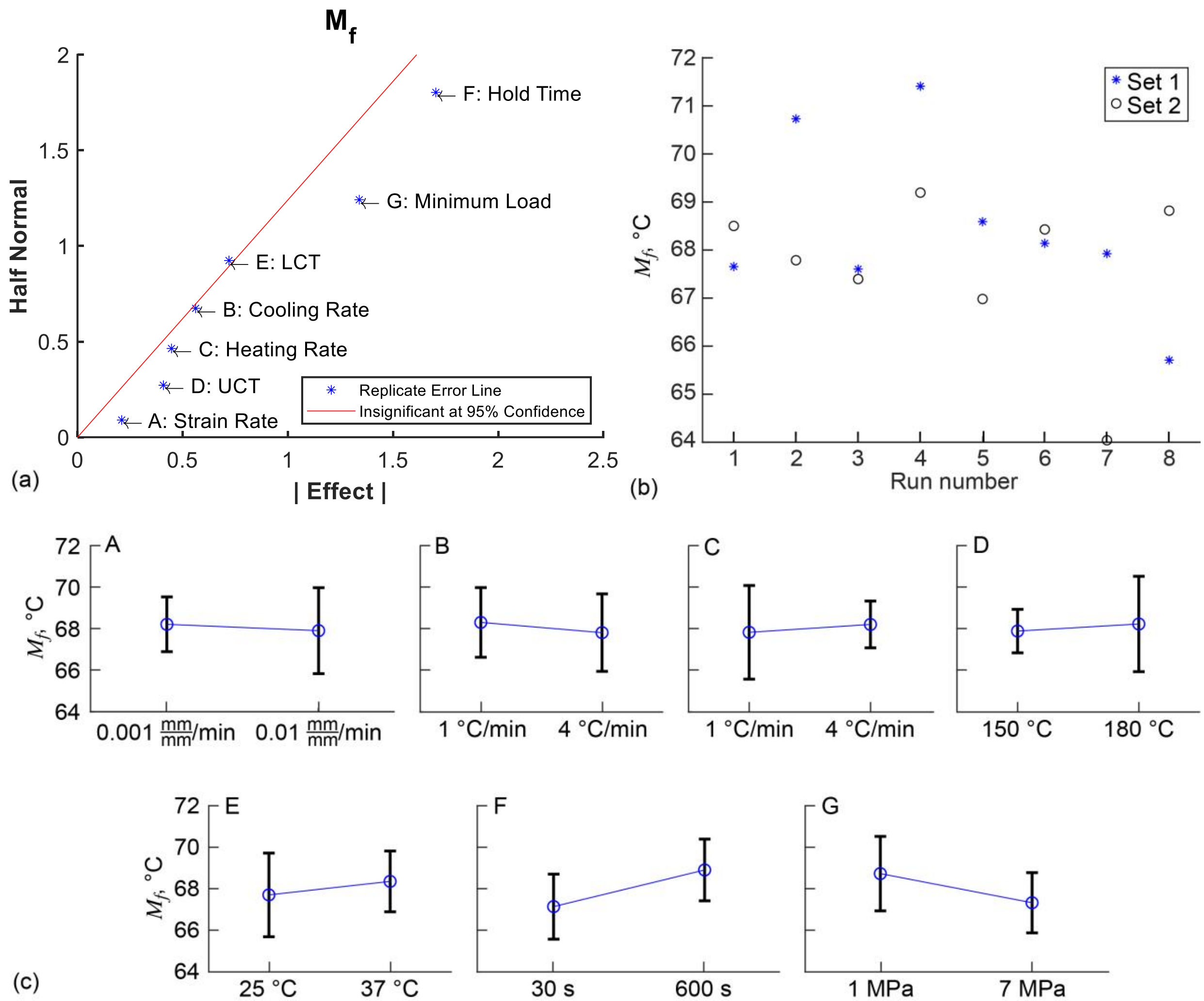

Figure 17.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for martensite finish, M_f. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (*UCT*); E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.

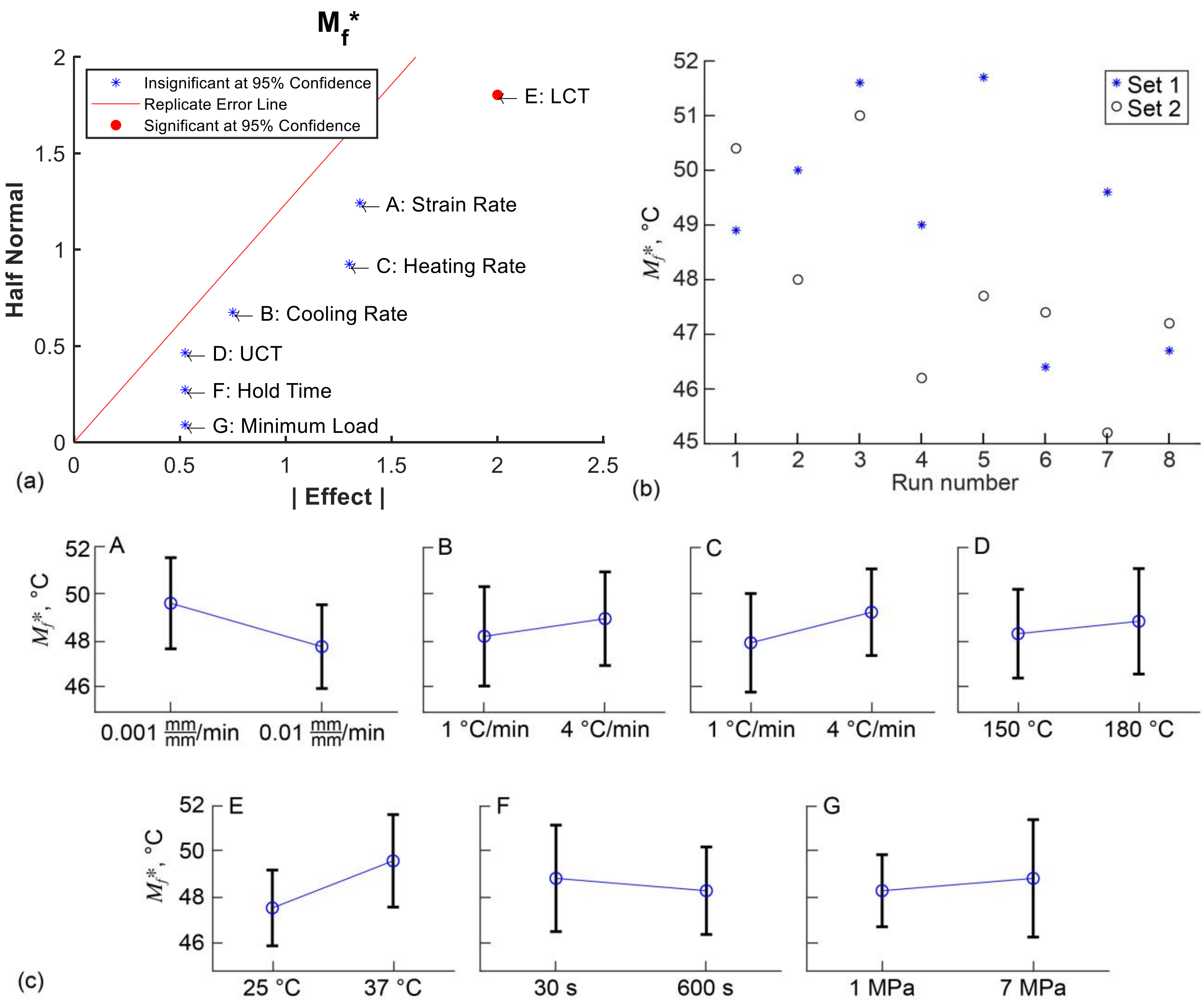

Figure 18.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for martensite finish tangent line and data intersect, M_f*. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (*UCT*); E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.

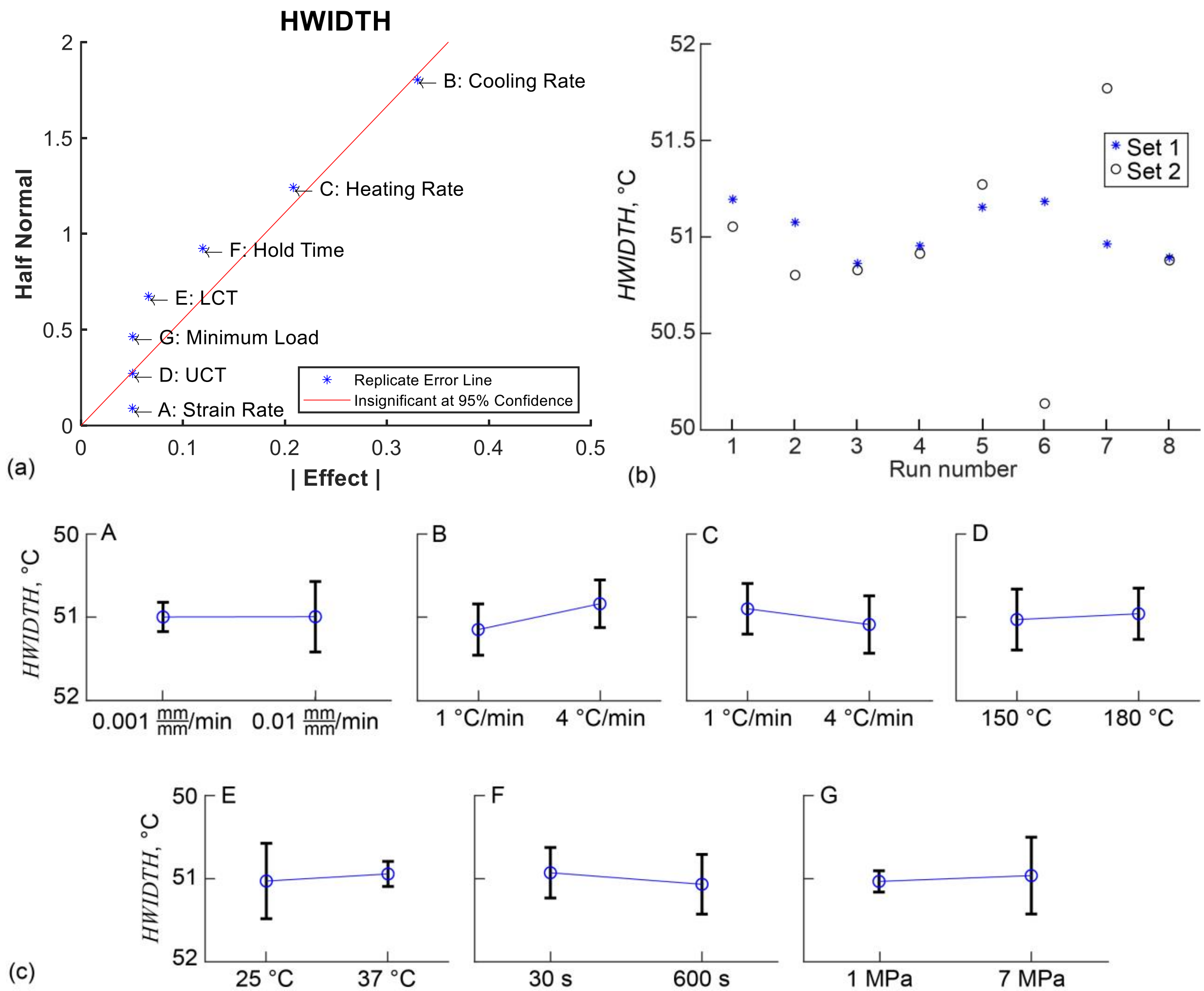

Figure 19.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for hysteresis width, *HWIDTH*. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (*UCT*); E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.

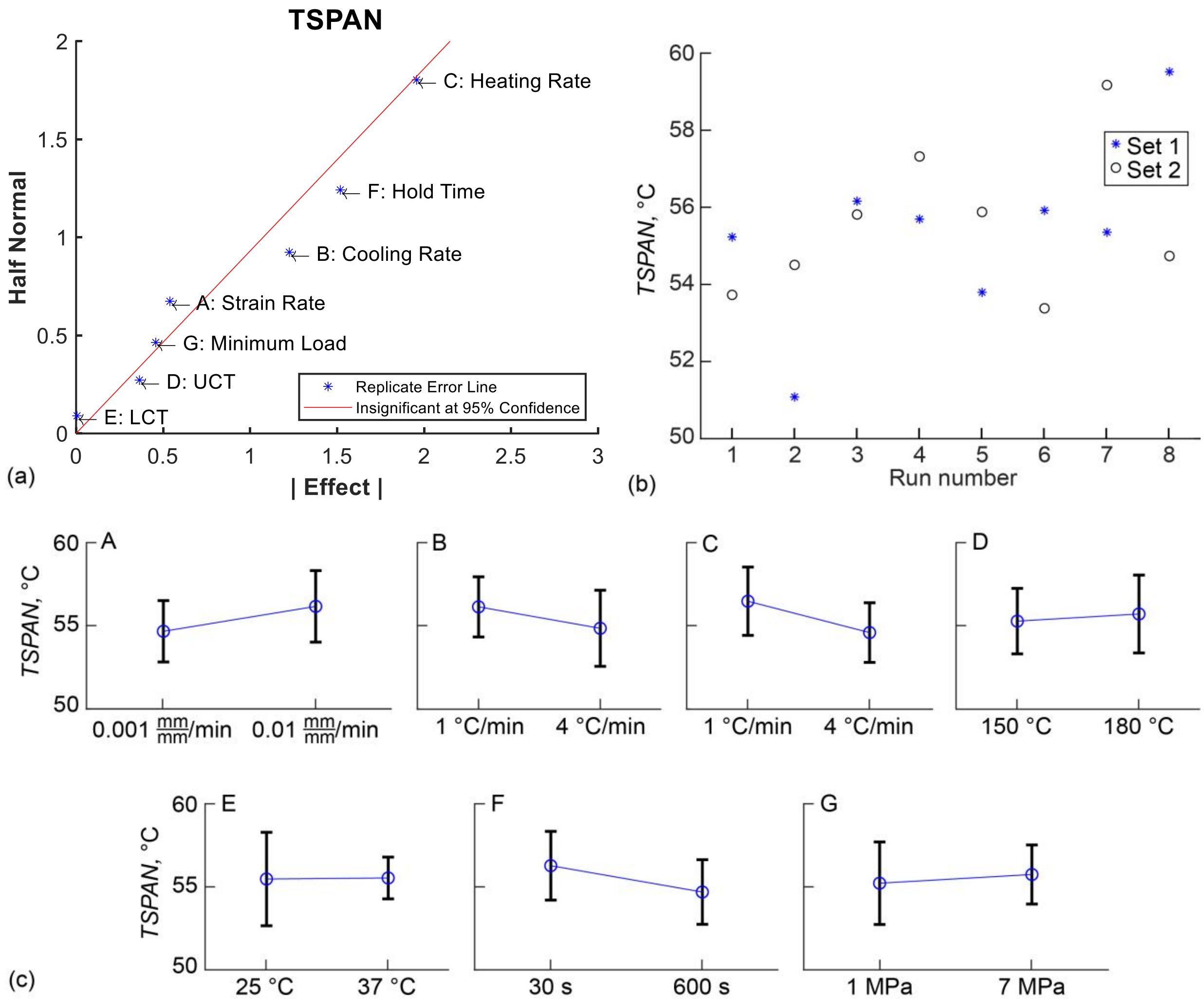

Figure 20.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for thermal transformation span, *TSPAN*. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (*UCT*); E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.

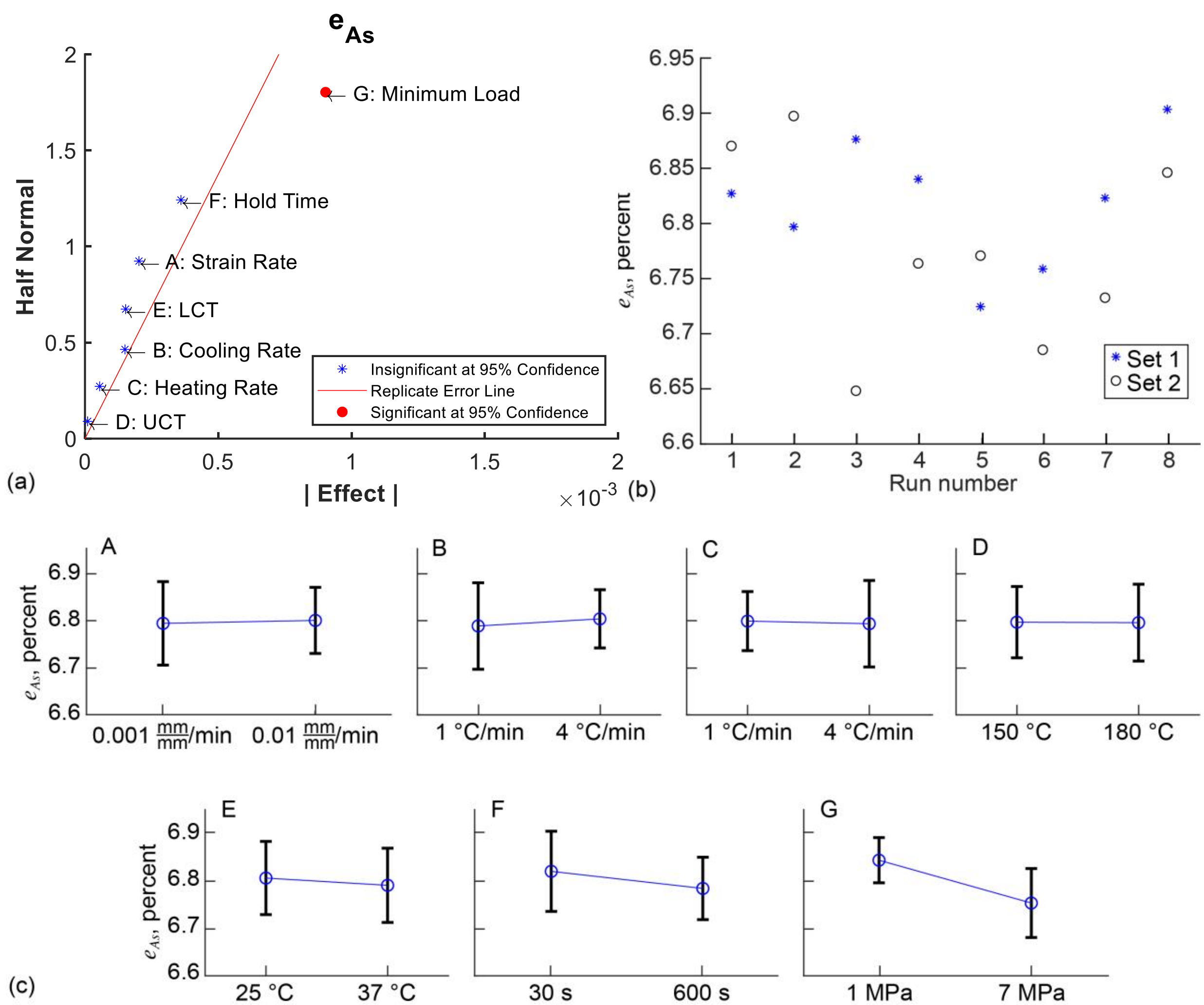

Figure 21.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for strain at austenite start temperature (fit line intersection point), e_{As}. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (*UCT*); E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.

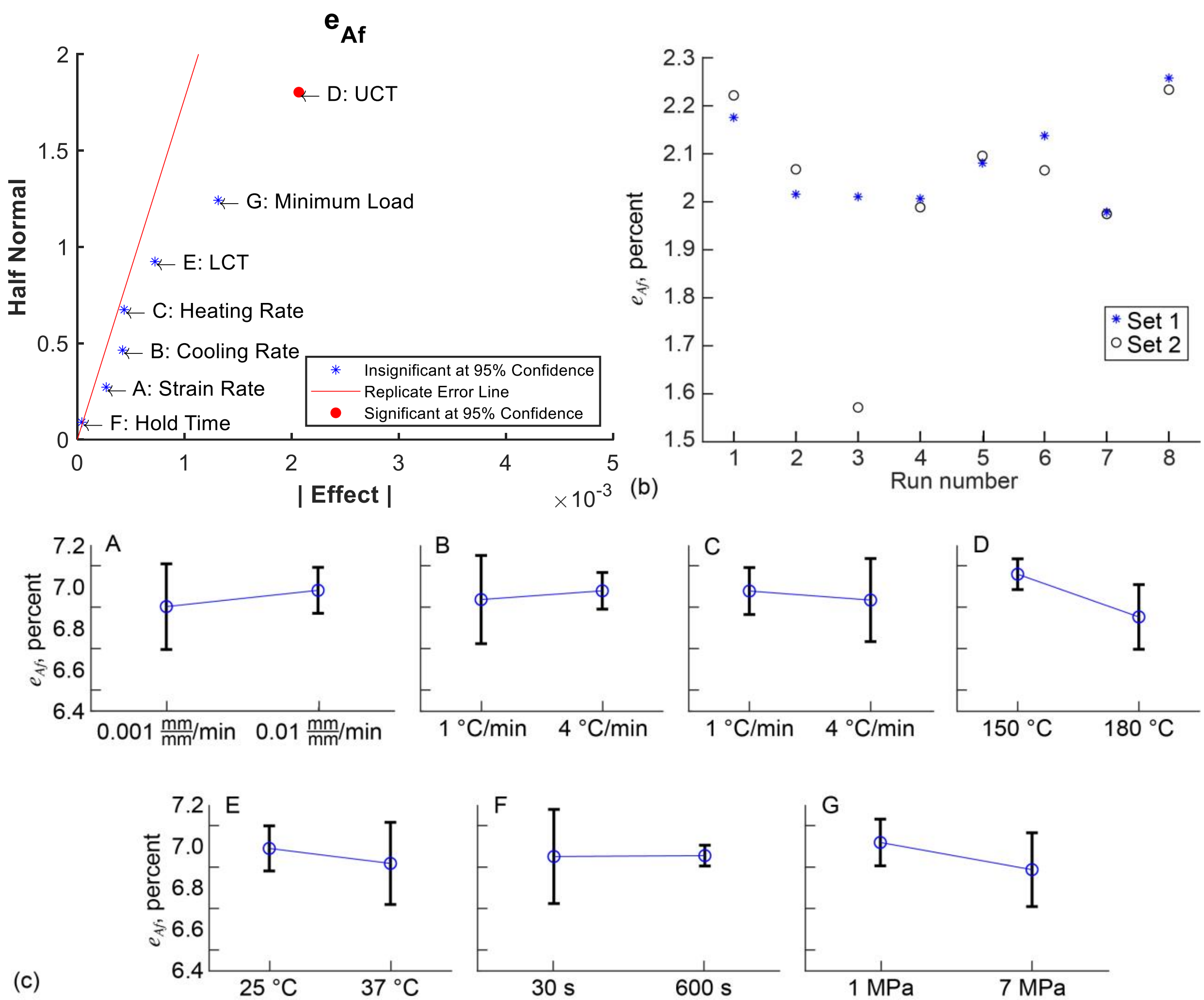

Figure 22.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for strain at austenite finish temperature (fit line intersection point), e_{Af}. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (*UCT*); E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.

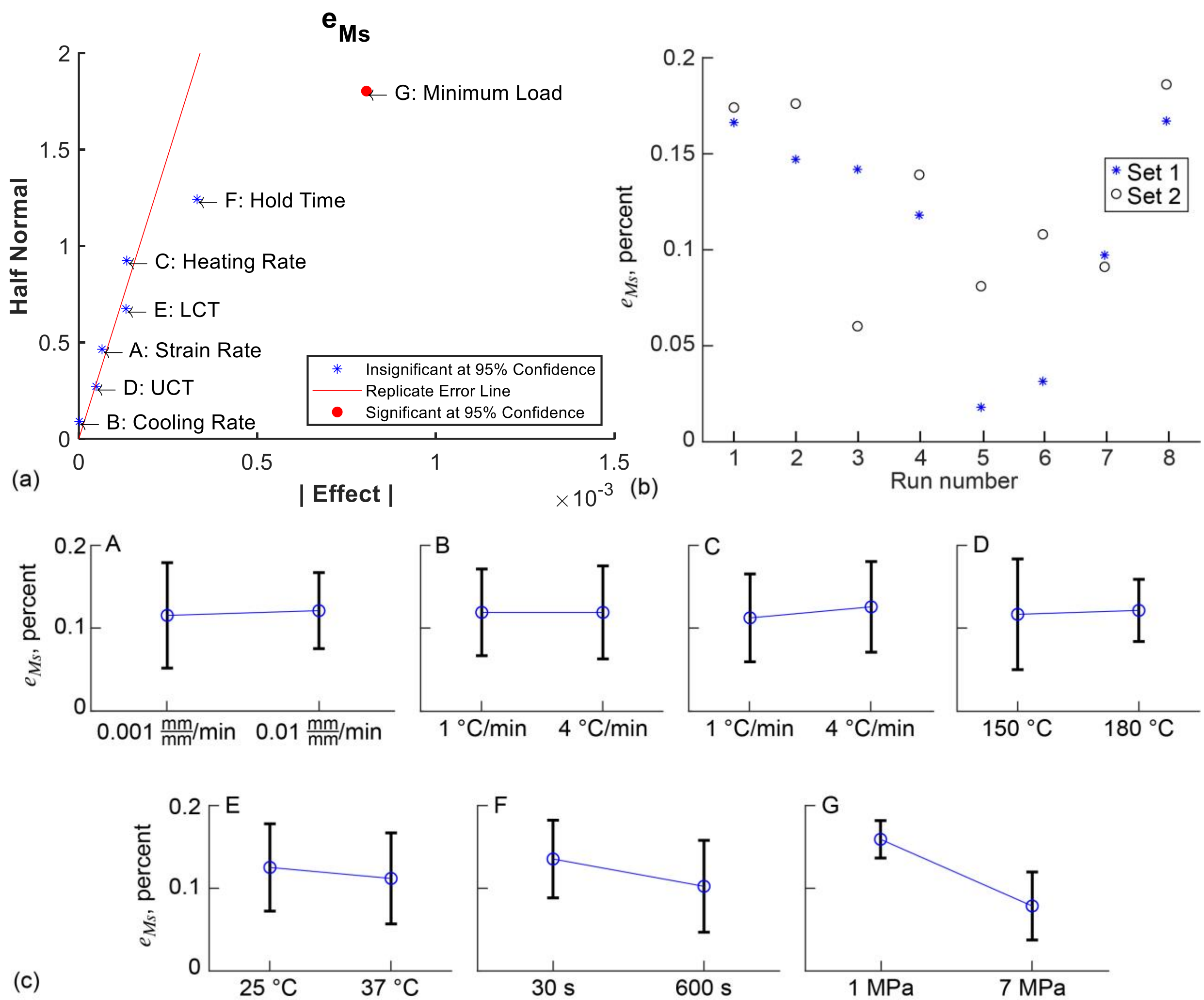

Figure 23.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for strain at martensite start temperature (fit line intersection point), e_{Ms}. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (UCT); E, lower cycle temperature (LCT); F, hold time; and G, minimum load.

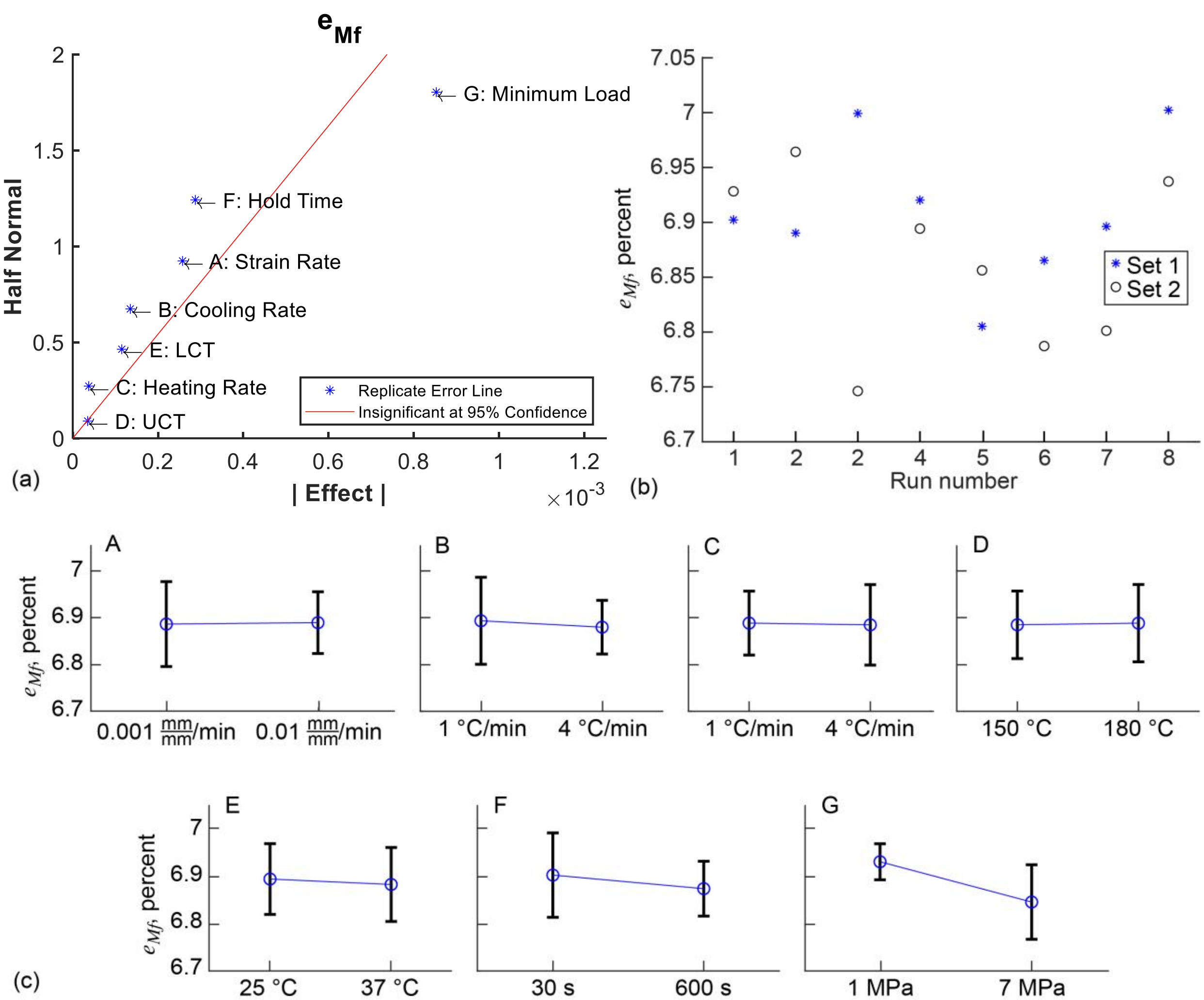

Figure 24.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for strain at martensite finish temperature (fit line intersection point), e_{Mf}. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (*UCT*); E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.

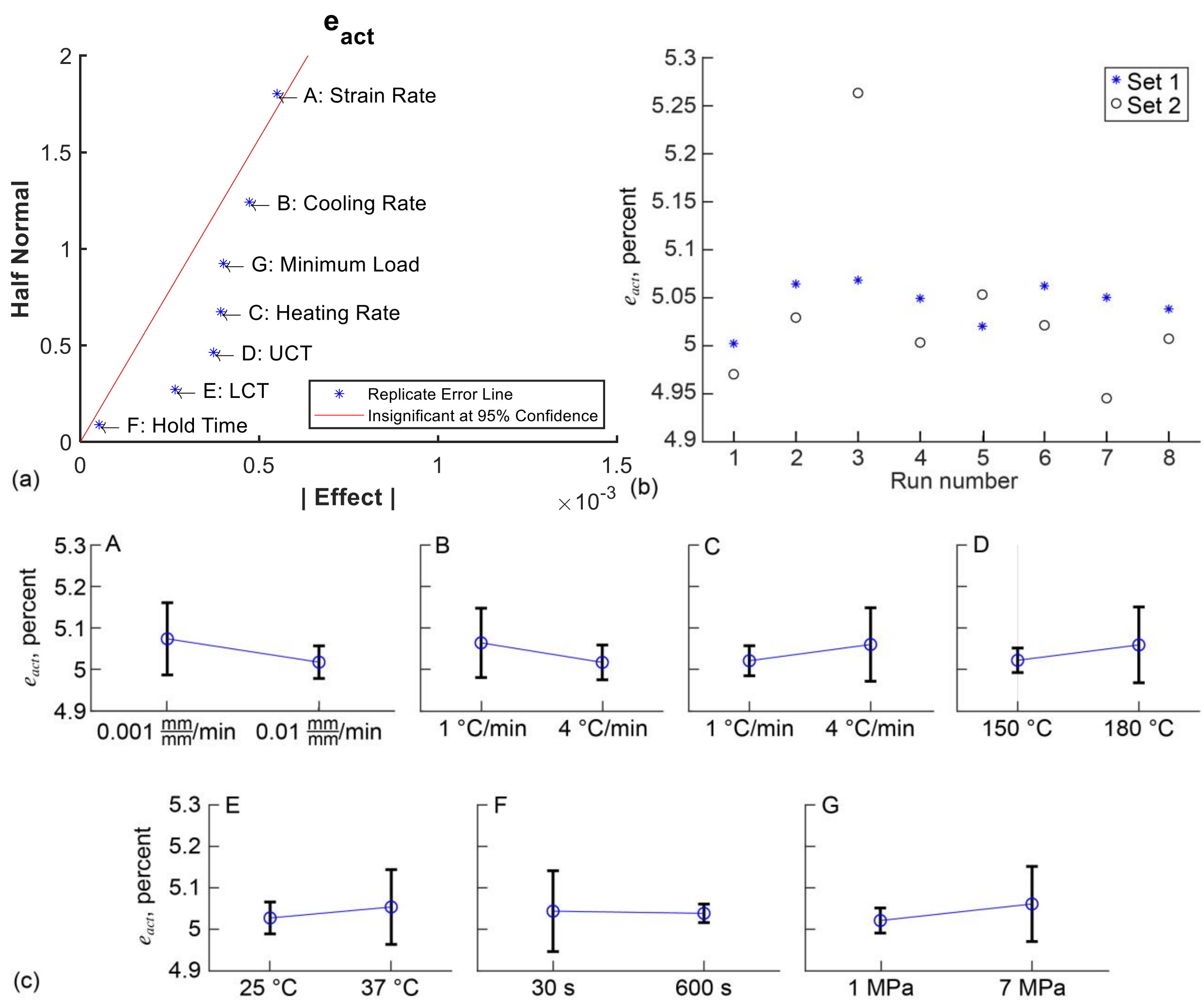

Figure 25.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for actuation strain, e_{act}. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (*UCT*); E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.

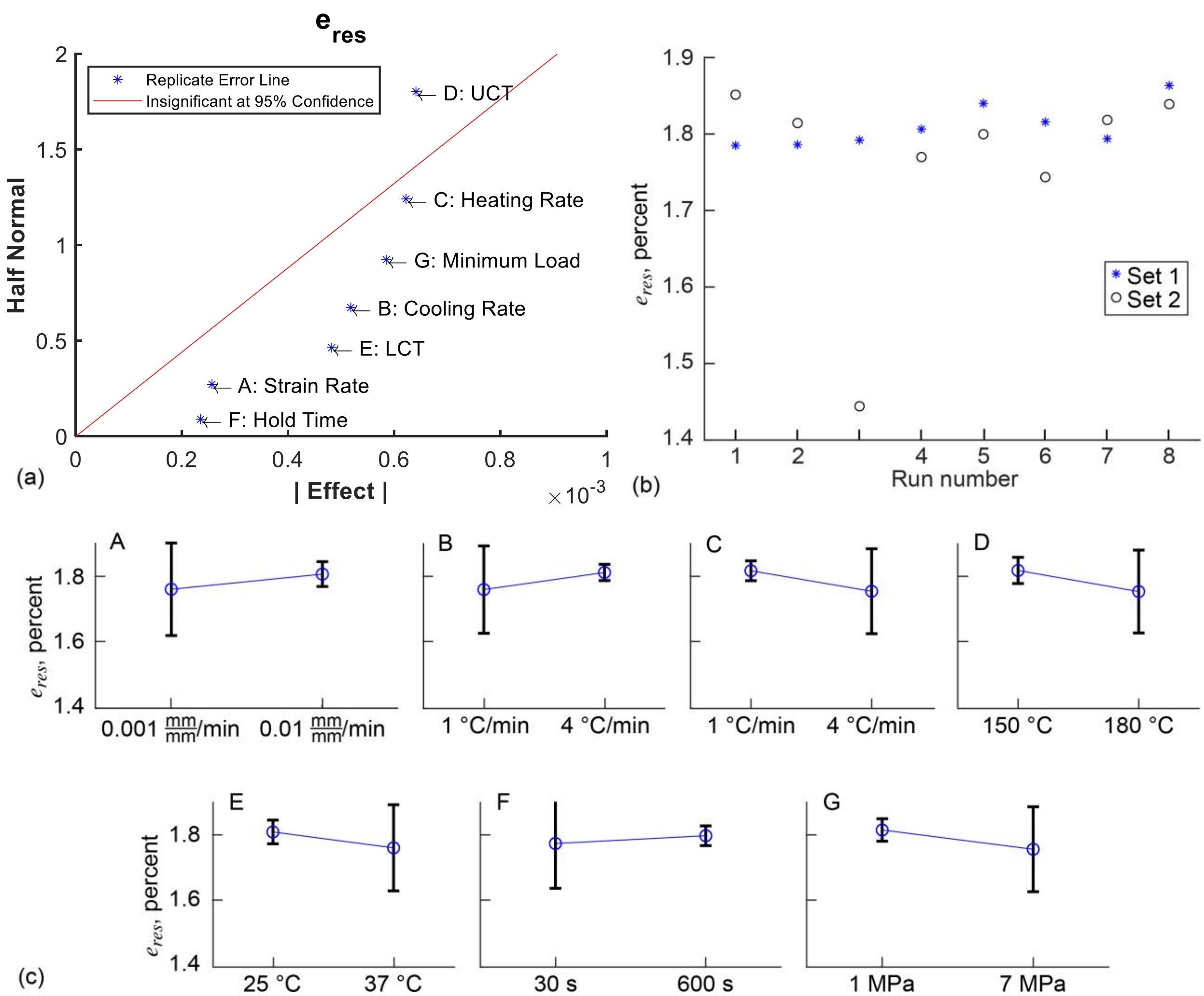

Figure 26.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for residual strain, e_{res}. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (*UCT*); E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.

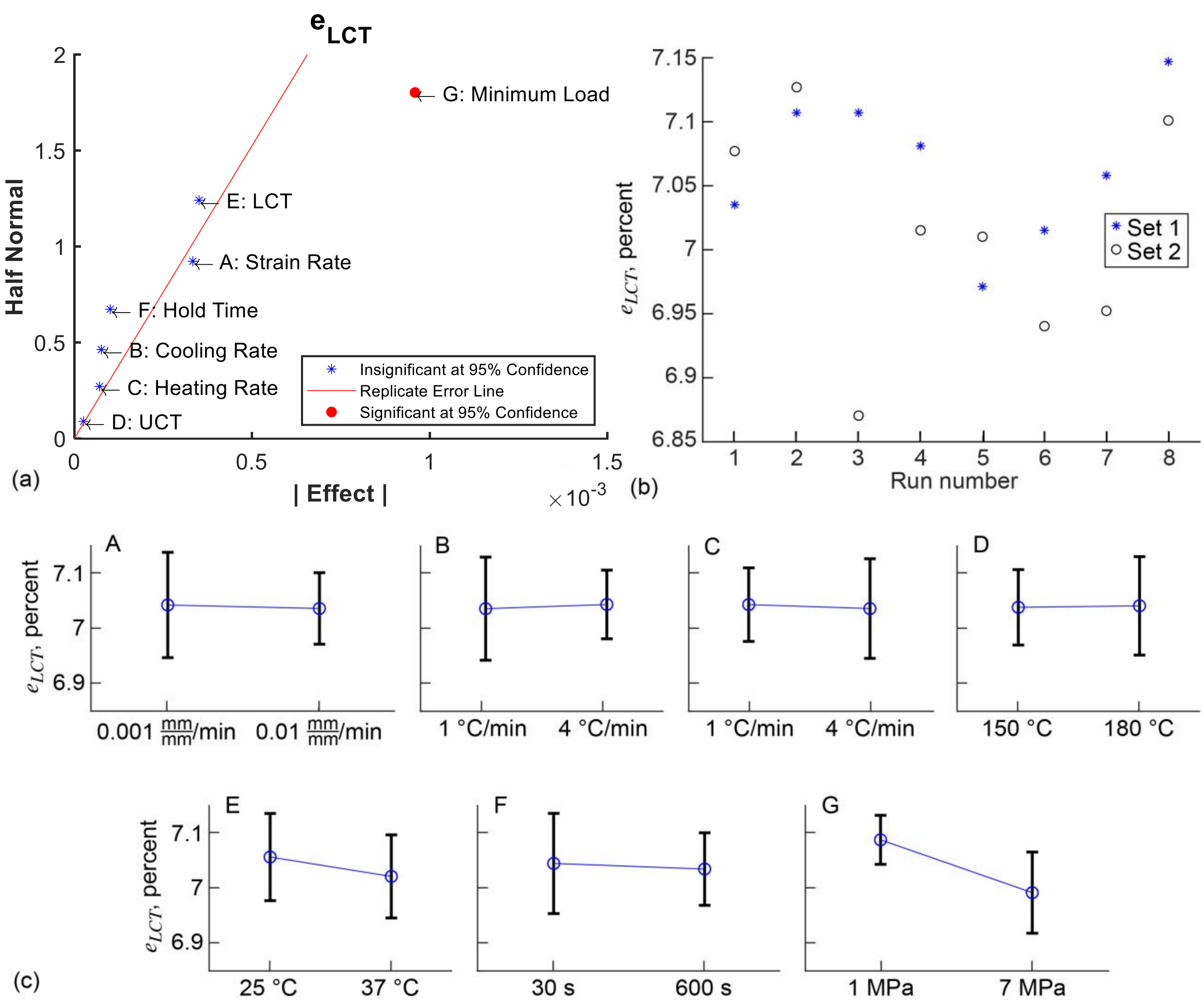

Figure 27.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for strain at lower cycle temperature (after cooling under load), e_{LCT}. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (UCT); E, lower cycle temperature (LCT); F, hold time; and G, minimum load.

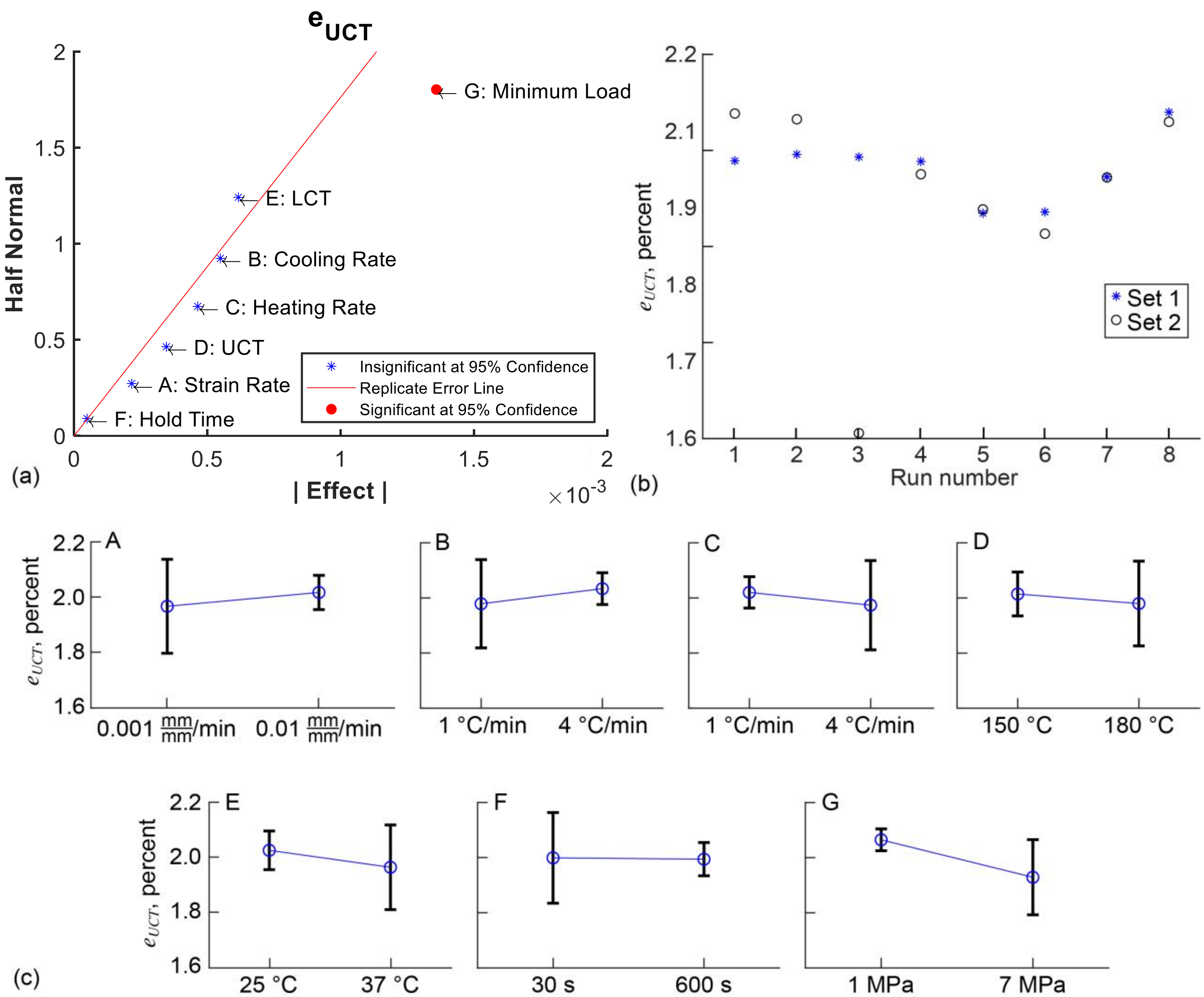

Figure 28.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for strain at upper cycle temperature (after full thermal cycle under load), e_{UCT}. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (UCT); E, lower cycle temperature (LCT); F, hold time; and G, minimum load.

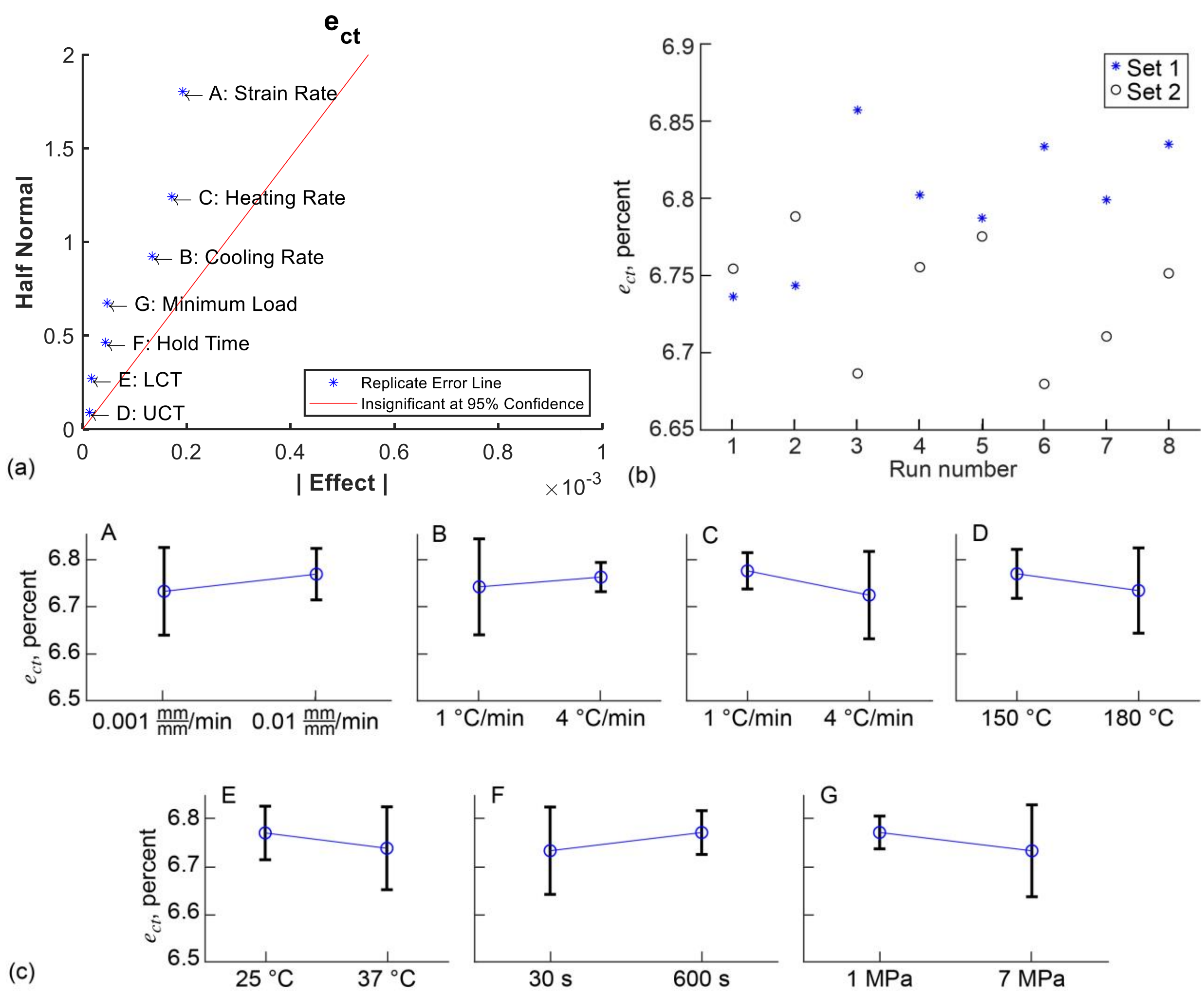

Figure 29.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for cooling transformation strain, e_{ct}. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (UCT); E, lower cycle temperature (LCT); F, hold time; and G, minimum load.

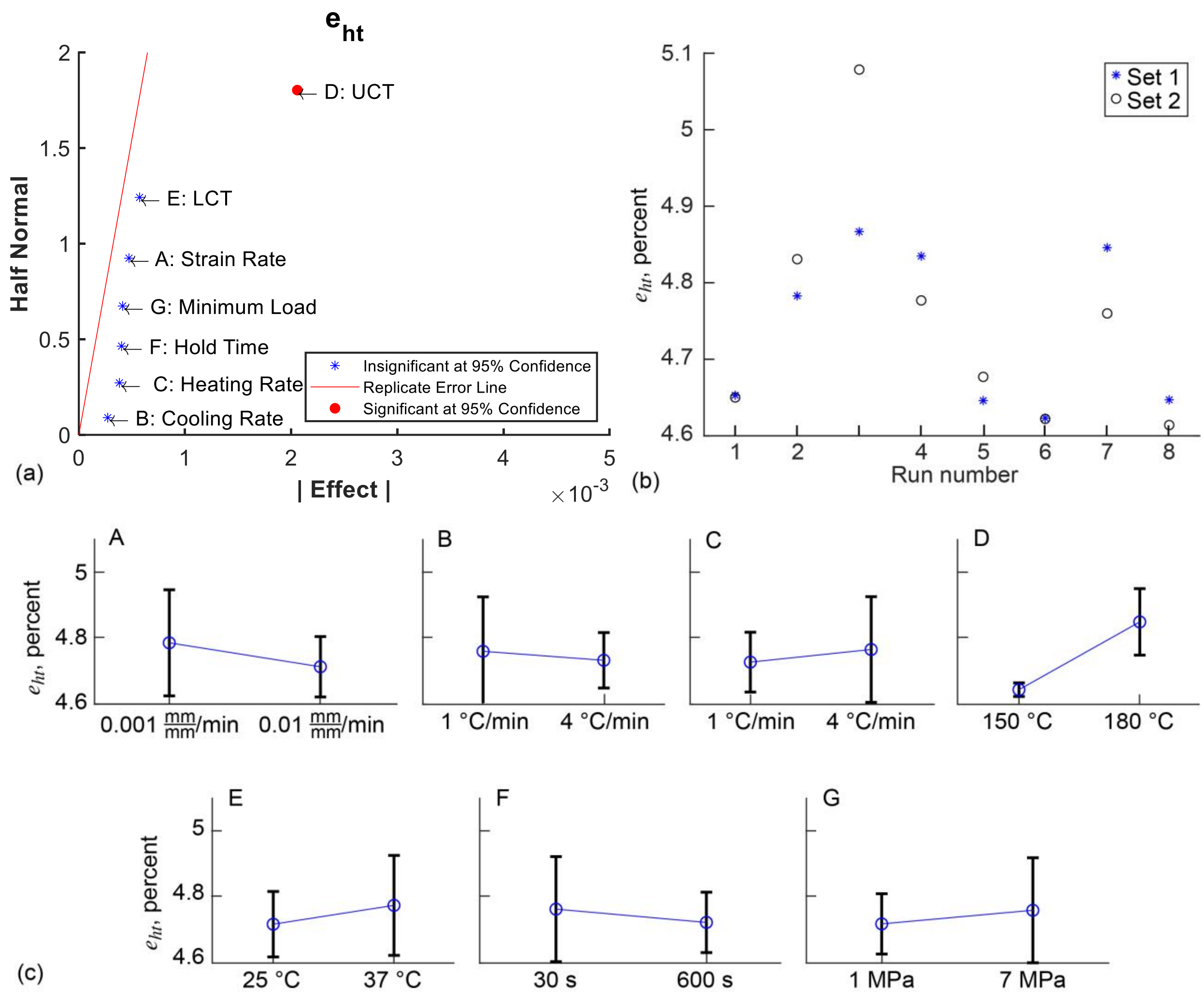

Figure 30.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for heating transformation strain, e_{ht}. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper cycle temperature (*UCT*); E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.

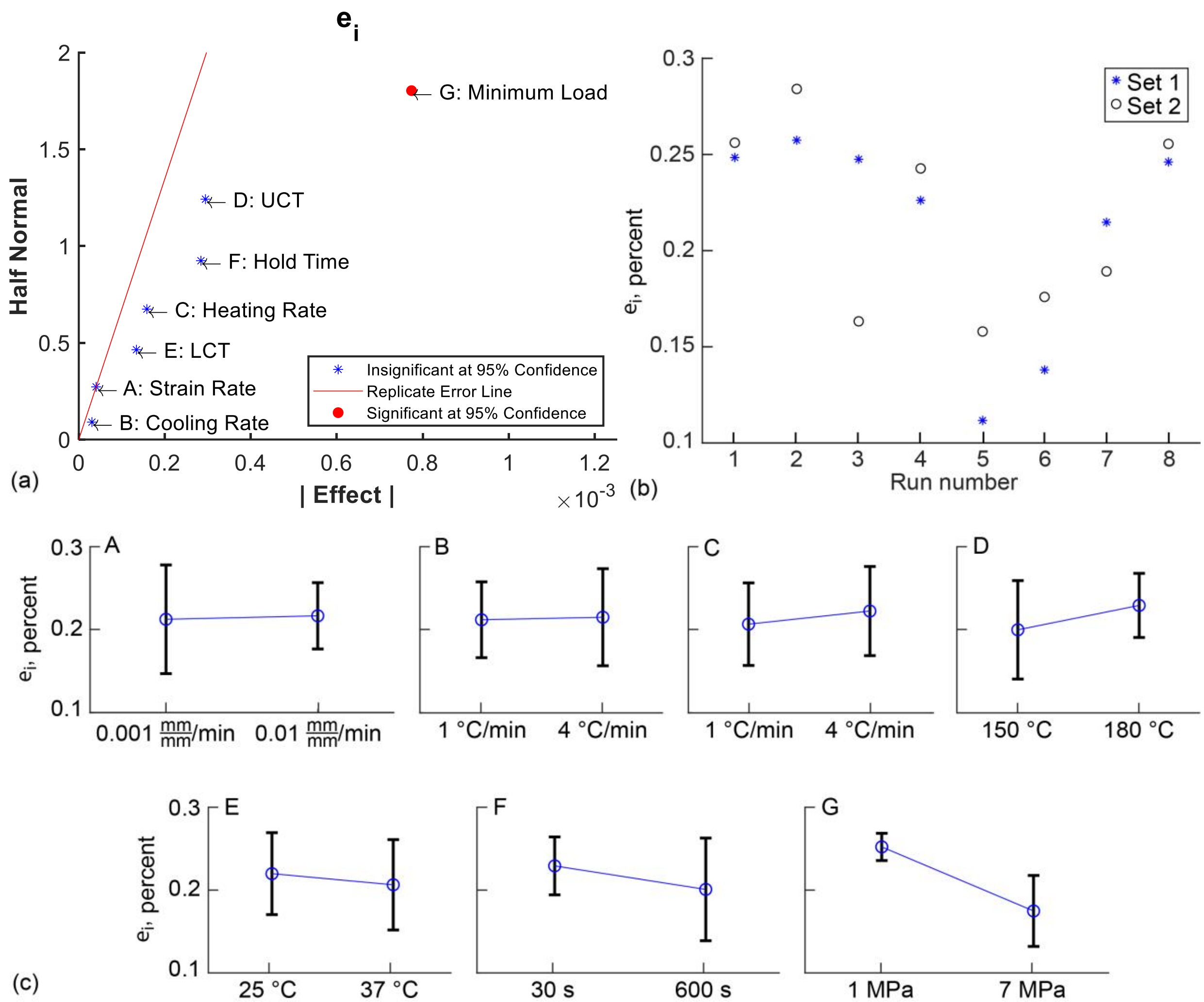

Figure 31.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for initial loading strain (at upper cycle temperature (*UCT*), at load), e_i. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, *UCT*; E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.

TABLE IV.—LIST OF RESULT VARIABLES SIGNIFICANTLY AFFECTED BY EACH FACTOR
[Numbers in parenthesis indicate importance ranking of factor for that result variable; that is, A_f (2nd) means given factor had second greatest effect on A_f.]

Factor	Effect of high level versus low level								
Strain rate, $\dot{e}$	Result variable	A_f[a] (3rd)	------------	-----------	-----------	---------	---------	-----------	---------
	Effect	-0.882	------------	-----------	-----------	---------	---------	-----------	---------
Cooling rate, $\dot{T}_{cool}$	Result variable	A_s[b] (1st)	A_f*[c] (2nd)	A_f (1st)	-----------	---------	---------	-----------	---------
	Effect	1.902	1.823	–1.787	-----------	---------	---------	-----------	---------
Heating rate, $\dot{T}_{heat}$	Result variable	A_f (2nd)	------------	-----------	-----------	---------	---------	-----------	---------
	Effect	–1.510	------------	-----------	-----------	---------	---------	-----------	---------
Upper cycle temperature, *UCT*	Result variable	A_f* (1st)	M_s*[d] (1st)	e_{Af}[e] (1st)	e_{ht}[f] (1st)	---------	---------	-----------	---------
	Effect	17.300	3.713	–0.00207	0.00206	---------	---------	-----------	---------
Lower cycle temperature, *LCT*	Result variable	M_f*[g] (1st)	------------	-----------	-----------	---------	---------	-----------	---------
	Effect	2.000	------------	-----------	-----------	---------	---------	-----------	---------
Hold time, t_{hold}	Result variable	-----------	------------	-----------	-----------	---------	---------	-----------	---------
	Effect	-----------	------------	-----------	-----------	---------	---------	-----------	---------
Minimum load, F_{min}	Result variable	A_f* (3rd)	e_{UCT}[h] (1st)	e_{LCT}[j] (1st)	e_{As}[k] (1st)	e_{Ms}[l] (1st)	e_i[m] (1st)	-----------	---------
	Effect	–1.6750	–0.00136	–0.00096	–0.00090	–0.00081	–0.00077	-----------	---------

[a]Austenite finish.
[b]Austenite start.
[c]Austenite finish tangent line and data intersect.
[d]Martensite start tangent line and data intersect.
[e]Strain at austenite finish temperature (fit line intersection point).
[f]Heating transformation strain.
[g]Martensite finish tangent line and data intersect.
[h]Strain at upper cycle temperature (*UCT*) (after full thermal cycle under load).
[i]Strain at martensite finish temperature (fit line intersection point).
[j]Strain at lower cycle temperature (after cooling under load).
[k]Strain at austenite start temperature (fit line intersection point).
[l]Strain at martensite start temperature (fit line intersection point).
[m]Initial loading strain (at *UCT*, at load).

A list of all result variables found to be significantly affected by each factor as well as the associated half-normal ranking for each result variable are shown in Table IV.

5.0 Discussions

The seven selected factors were deemed to be the most likely factors to affect the UCFTC test outcome, and their impact on each result variable is outlined in the previously presented data. It should be restated that the tests presented here are only a portion of the overall ruggedness evaluation as it does not consider other geometries, other SMAs, or other testing organizations, nor does it account for variations due to operator analysis (fit) technique. It is also noted that the experiments performed comprise only a fractional factorial and lack a foldover replicate to identify if the combination of any factors confound results. Additionally, the observed statistical significance of a factor does not completely confirm nor deny a physical, material effect on the selected alloy system studied, merely the presence of an observed effect in this experiment. Further testing is required to verify the mechanisms and nature of the effects seen.

The effects of strain rates on transformation parameters have been investigated extensively in constant-temperature, pseudoelastic conditions (Refs. 13 and 14), but little work exists detailing the effects of strain rate on thermally induced transformation. Given that the loading and unloading is taking place at only the *UCT* (austenite phase) and it is expected that the 100-MPa stress is still within the elastic portion of the material response, the strain rate should have a minimal effect. The rest of the test method is based on maintaining the stress at a constant level where the strain rates are no longer a factor. From Table III, it is shown that the strain rates have a minimal effect on the A_f by ~0.8817 °C, which can be considered a minimally important factor in the UCFTC test method.

Heating and cooling rates have been previously reported to influence the transformation temperatures of NiTi and NiTiCu alloys measured by DSC (Refs. 15 and 16), but as with many rate-dependent phenomena in SMAs, the exact mechanism is not fully understood. Referring to Table IV, the heating and cooling rates mainly impacted the transformation temperatures (A_s, A_f, and A_f*) by no more than ~1.9 °C. The results indicated a decrease in A_f and increase in A_s from a –1 to –4 °C/min cooling rate and a decrease of A_f from a +1 to +4 °C/min heating rate. Although the impact is minimal, the austenite temperatures, A_f in particular, are found to be the most sensitive to heating and cooling rate compared to other parameters.

Though varying *UCT* has been previously shown to have significant effects on actuator hysteresis and transformation temperatures (Ref. 17), the large effect of *UCT* on A_f* and M_s* is likely due to the lower *UCT* setting of 150 °C being placed too low for a tangent line to be fitted accurately to the linear austenite (or high-temperature) region, providing a necessarily different fit between low- and high-*UCT* values. For the high-*UCT* case, there is a larger linear region in the austenite, allowing for a more accurate fit to the fully transformed austenite, and therefore a better measurement of the austenite coefficient of thermal expansion (CTE) slope, whereas for the lower *UCT* case, there is some small amount of transformation still occurring at *UCT*, which is reflected in the slope of the fit line. Figure 32 illustrates this discrepancy in fits and how it is likely responsible for *UCT*'s effect on e_{Af} as well. Note that any factor that affects e_{Af} or e_{As} individually, and not together, will necessarily affect e_{ht} to the same degree (recalling $e_{ht} = e_{As} - e_{Af}$), explaining the effect on e_{ht}.

Similar to *UCT*, the effects of *LCT* are likely related to tangent line fitting and do not suggest any significant material property variation as there is only a significant effect on M_f*, and not M_f or e_{Mf}. In the low-*LCT* case, there is a greater linear martensite region present at temperatures below the transformation, allowing a better fit to the martensite, and therefore a lower slope. Thus, it is unsurprising that a fit line would be more likely to intersect the data farther to the left (at lower temperatures).

Minimum load shows a significant influence on a wide variety of result variables, most of which are strains. The negative influence on such a wide variety of strains, occurring across the entire temperature range of the UCFTC test, suggests that higher minimum load during normalization shifts the entire hysteresis loop in the subsequent loaded cycle downward in the strain-temperature space, affecting the strain (Figure 33). Regardless of the mechanism of this effect, the primary understanding gained is that load applied during normalization heating has little effect on the material's actuation strains, as long as it is maintained below some nominal level (7 MPa for this study), but will likely alter the positioning of some transformation temperatures and their associated strains.

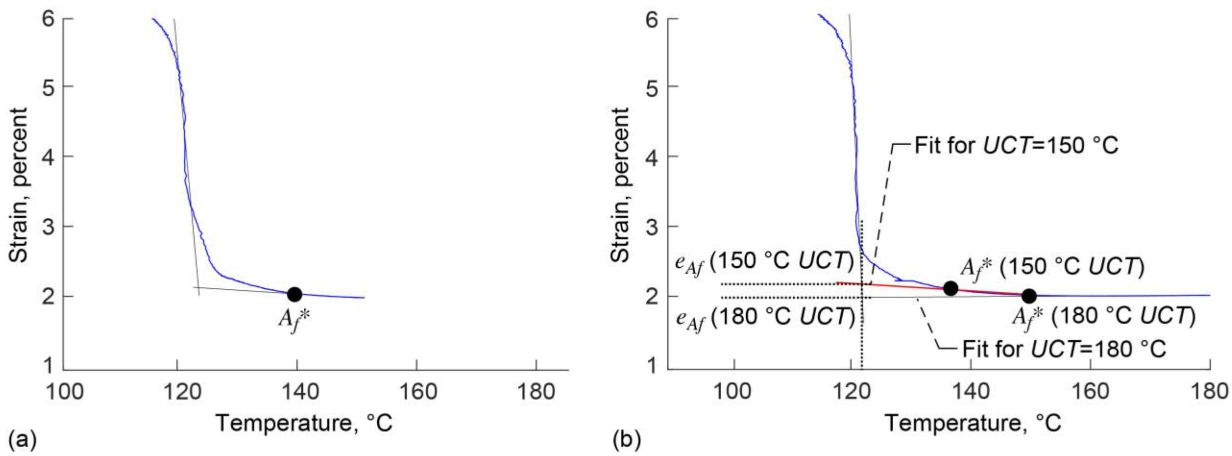

Figure 32.—Heating curves of runs 1 and 2, illustrating effect of upper cycle temperature (*UCT*) on transformation temperature fit lines.

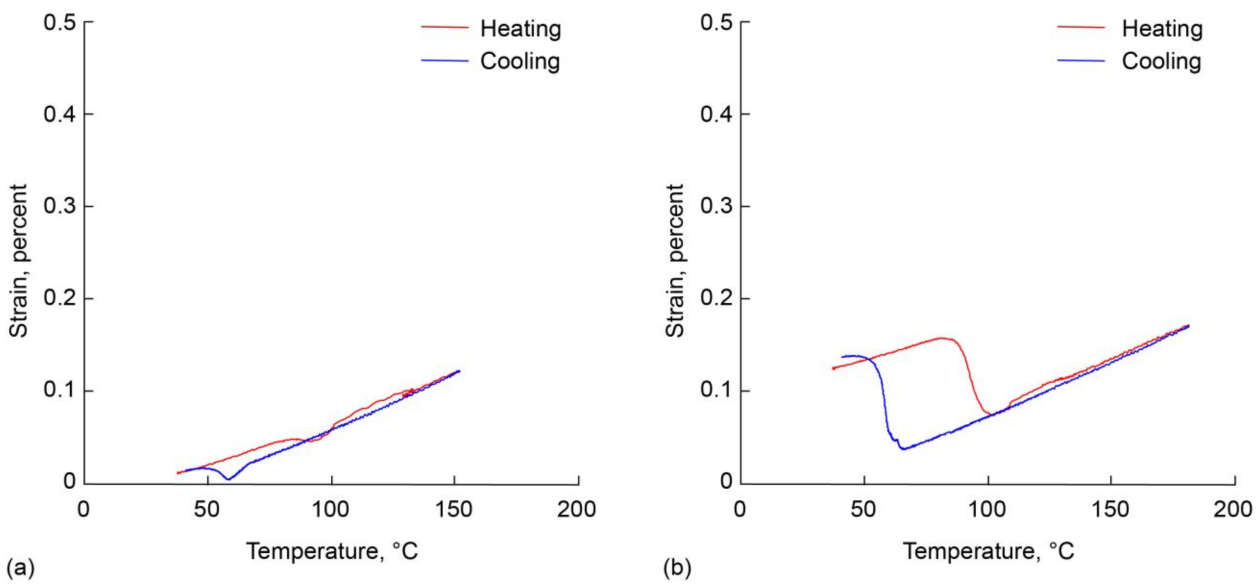

Figure 33.—Representative normalization curves. (a) G, minimum load setting of (–1). (b) G, minimum load setting of (+1).

6.0 Concluding Remarks

While vendors and test laboratories may use rates and limits outside of these presented here (after ensuring that they still obtain accurate results), this work was performed by using test factors and levels that should be sufficiently moderate to ensure good repeatability and accurate measurement of results for samples using the uniaxial constant force thermal cycling (UCFTC) test. For all factors, the magnitude of effect observed, even when statistically significant, was generally very minimal. Given that effects are specified in the units of the result variable observed (either °C or percent strain), the most significant effects shown in this work are relatively low compared to the differences frequently observed simply between two different analysts selecting linear fits to the same data to calculate transformation temperatures and strains. A difference in average A_s of 1.9 °C, for instance, while noteworthy, is not a critical change for most application purposes.

Most importantly, if a UCFTC test is performed in such a way that the entire transformation, including linear regimes in martensite and austenite, is obtained, the results of such a test are likely to be sufficiently rugged to variations in the testing factors evaluated in this experiment. Though a number of parameters may slightly change with testing factors such as temperature rates, strain rate, or minimum load, overall, the UCFTC test shows a commendable ruggedness to the factors tested in this work.

Additional work is warranted to evaluate the effect of geometry (e.g., wire, sheet, and rods), material lot (R-phase containing alloys and high-temperature alloys), analysis tools (e.g., during tangent line fitting), and other factors such as change in heating methods or loading equipment.

Appendix A.—Nomenclature

AVSI	Aerospace Vehicle Systems Institute
CASMART	Consortium for the Advancement of Shape Memory Alloy Research and Technology
CTE	coefficient of thermal expansion
DSC	differential scanning calorimetry
LeRCIP	Lewis' Educational and Research Collaborative Internship Project
OSTEM	Office of STEM
SMA	shape memory alloy
STDEV	standard deviation
UCFTC	uniaxial constant force thermal cycling

Symbols

Ave	average results
A_{50}	austenite 50 percent = $(A_f + A_s)/2$
A_f	austenite finish
A_f*	austenite finish tangent line and data intersect
A_s	austenite start
A_s*	austenite start tangent line and data intersect
e	strain
$\dot{e}$	strain rate
effect	error of an effect
e_0	initial strain (at upper cycle temperature after normalizing)
e_{act}	actuation strain = $e_{LCT} - e_{UCT}$
e_{Af}	strain at austenite finish temperature (fit line intersection point)
e_{As}	strain at austenite start temperature (fit line intersection point)
e_{ct}	cooling transformation strain = $e_{Mf} - e_{Ms}$
e_{ht}	heating transformation strain = $e_{As} - e_{Af}$
e_i	initial loading strain (at *UCT*, at load)
e_{LCT}	strain at lower cycle temperature (after cooling under load)
e_{Mf}	strain at martensite finish temperature (fit line intersection point)
e_{Ms}	strain at martensite start temperature (fit line intersection point)
e_{res}	residual strain = $e_{UCT} - e_i$
e_{UCT}	strain at upper cycle temperature (after full thermal cycle under load)
F_{min}	minimum load
HWIDTH	hysteresis width = $A_{50} - M_{50}$
$I_x(z,w)$	incomplete beta function
LCT	lower cycle temperature
M_{50}	martensite 50 percent = $(M_f + M_s)/2$
M_f	martensite finish
M_f*	martensite finish tangent line and data intersect
M_s	martensite start
M_s*	martensite start tangent line and data intersect
N	number of runs
p	probability
reps	number of replicates

R_f	R-phase finish
R_f*	R-phase finish tangent line and data intersect
R_s	R-phase start
R_s*	R-phase start tangent line and data intersect
s_d	standard deviation of differences between replicates 1 and 2
s_{rep}	estimated standard deviation of test results
S_{effect}	standard error of an effect
T	temperature
t	Student's t-value (see Ref. 10)
$\dot{T}_{cool}$	cooling rate
$\dot{T}_{heat}$	heating rate
t_{hold}	hold time
TSPAN	thermal transformation span = $A_f - M_f$
UCT	upper cycle temperature
ν	degrees of freedom

Appendix B.—Data Formats

This appendix contains representations of the standardized data format (Table V) and the raw data files (Table VI).

TABLE V.—STANDARDIZED DATA FORMAT AS DEFINED BY THE AEROSPACE VECHICLE SYSTEMS INSTITUTE (AVSI) TEAM PER ASTM E3097

1	Test type	Uniaxial constant force thermal cycling (UCFTC)
2	Test note	Ruggedness tests
3	Test date	January 10, 2018
4	Lab	NASA–GRC–SH38B
5	Operator	O. Benafan
6	Material	NiTi, heat no. 836441
7	Sample identification	No. 8
8	Material condition	Hot rolled and heat treated (annealed)
9	Specimen geometry	Cylindrical dogbone (Ø = 0.1515 in., gage L = 0.75 in.)
10	Lower cycle temperature (*LCT*)	25
11	Upper cycle temperature (*UCT*)	150
12	Austenite start (A_s), °C	117.645
13	Austenite finish (A_f), °C	123.546
14	Martensite start (M_s), °C	70.628
15	Martensite finish (M_f), °C	68.807
16	Austenite start strain, e_{As}	0.06846
17	Austenite finish strain, e_{Af}	0.02233
18	Martensite start strain, e_{Ms}	0.00186
19	Martensite finish strain, e_{Mf}	0.06937
20	Strain at *LCT*, e_{LCT}	0.07101
21	Strain at *UCT*, e_{UCT}	0.02094
22	Cooling transformation strain, e_{ct}	0.06751
23	Heating transformation strain, e_{ht}	0.04613
24	Heating and cooling method	Induction
25	Temperature uniformity, °C	~2
26	Heating rate, °C/min	1
27	Cooling rate, °C/min	1
28	Strain measurement method	Mechanical extensometer with alumina rods
29	Strain rate (mm/mm per min)	0.001
30	Hold time(s)	30
31	Minimum load, MPa	1
32	Applied stress, MPa	100
33	Initial strain, e_0	0
34	Initial loading strain, e_i	0.002554

TABLE V.—STANDARDIZED DATA FORMAT AS DEFINED BY THE AEROSPACE VECHICLE SYSTEMS INSTITUTE (AVSI) TEAM PER ASTM E3097

35	Actuation strain, e_{act}	0.05007
36	Residual strain, e_{res}	0.018386
37	Method for A_{50} and M_{50} determination	(High temp + low temp)/2
38	A_s*, °C	74.5
39	A_f*, °C	140.2
40	M_s*, °C	73.5
41	M_f*, °C	47.2
42	Austenite 50 percent (A_{50}), °C	120.5955
43	Martensite 50 percent (M_{50}), °C	69.7175
44	Hysteresis width (HWIDTH), °C	50.878
45	Thermal transformation span (TSPAN), °C	54.739
46	Known A_f, °C	96
47	Known A_s, °C	77
48	Known R_f*, °C	
49	Known R_s*, °C	
50	Known R_s, °C	
51	Known R_f, °C	
52	Known M_s, °C	67
53	Known M_f, °C	50
54	Comments	Known transformation temperatures via DSC
55	User defined	
56	User defined	
57	User defined	
58	*** end header ***	

TABLE VI.—RAW DATA FILES

59	seconds	Deg C	MPa	%	user defined	user defined	user defined
60	time	temperature	stress	strain	user defined	user defined	user defined
61	1.0060222	21.154736	0.69224936	–0.0092264			
62	2.0060222	21.017036	0.83598107	–0.007681			
63	3.0060222	21.200634	0.61255819	–0.009124			
64	4.0060222	21.200634	0.7916289	–0.0078791			

Appendix C.—Run Replicates

This appendix contains plots of the run replicates (Figure 34 and Figure 35).

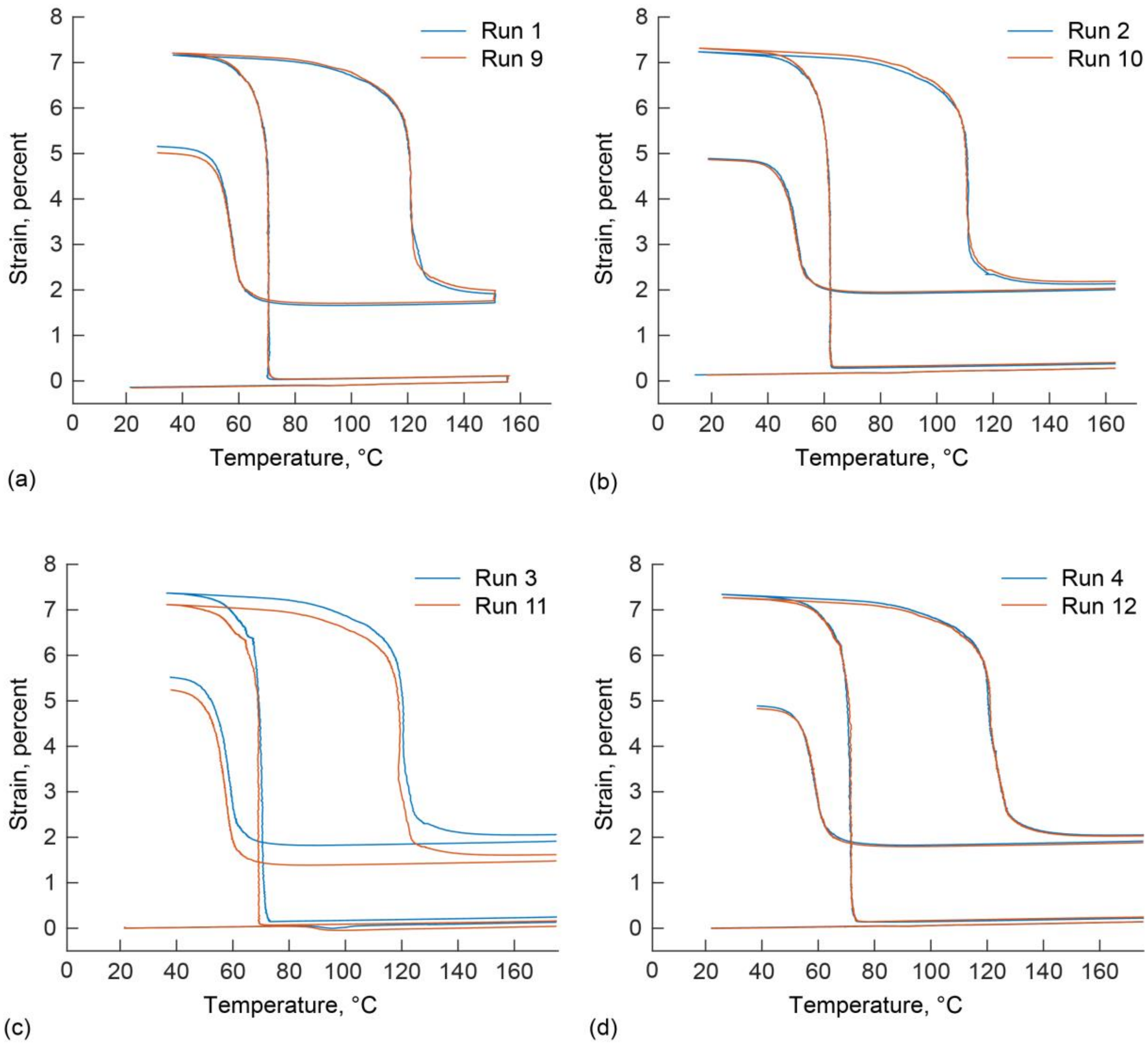

Figure 34.—Run replicate plots. (a) Runs 1 and 9. (b) Runs 2 and 10. (c) Runs 3 and 11. (d) Runs 4 and 12.

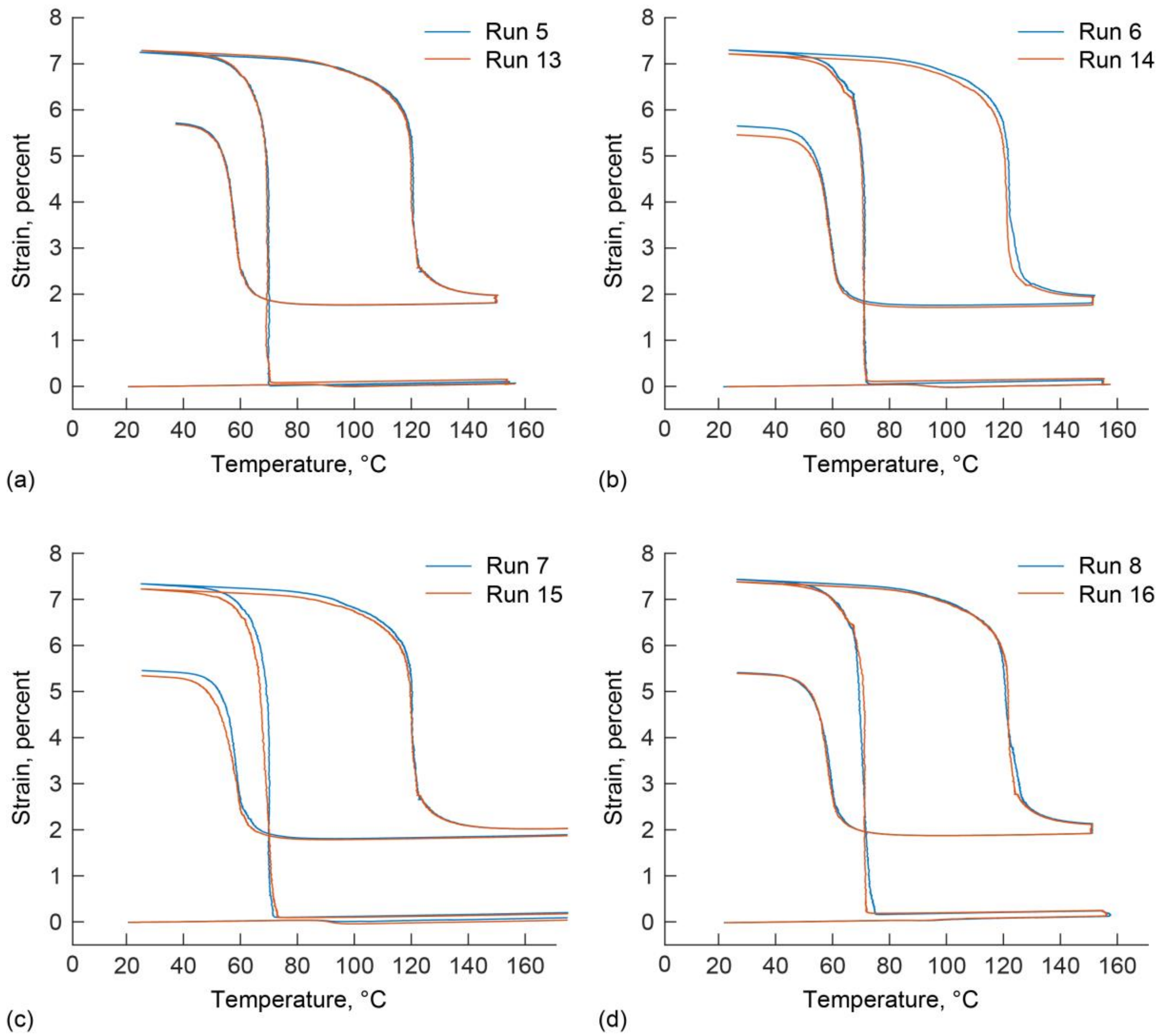

Figure 35.—Run replicate plots. (a) Runs 5 and 13. (b) Runs 6 and 14. (c) Runs 7 and 15. (d) Runs 8 and 16.

Appendix D.— Calculated Effects, Ranks, and Significance per Factor

This appendix contains tables of calculated effects per factor as well as significant statistical calculations (Figures 36 - 81).

Ruggedness Example Calculations for A_s Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)											
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	117.877	118.655	118.266	0.778
2	-1	1	1	1	-1	1	-1	119.230	117.918	118.574	-1.312
3	-1	-1	1	1	1	-1	1	116.769	115.026	115.898	-1.743
4	1	-1	-1	1	1	1	-1	114.513	115.850	115.182	1.337
5	-1	1	-1	-1	1	1	1	118.889	117.113	118.001	-1.776
6	1	-1	1	-1	-1	1	1	117.259	117.095	117.177	-0.164
7	1	1	-1	1	-1	-1	1	117.578	116.820	117.199	-0.758
8	-1	-1	-1	-1	-1	-1	-1	114.708	117.645	116.177	2.937
Avg. of +1	116.956	118.010	117.479	116.713	116.837	117.233	117.069		s_d	1.668	
Avg. of -1	117.162	116.108	116.640	117.405	117.282	116.885	117.050		s_{rep}	1.179	
Effect	-0.206	1.902	0.839	-0.692	-0.445	0.349	0.019		S_{effect}	0.590	
| Effect |	0.206	1.902	0.839	0.692	0.445	0.349	0.019				
Rank	6	1	2	3	4	5	7				

Figure 36.—Ruggedness example calculations
for austenite start, A_s, results.

Statistical Significance of Effects Example Calculations for A_s Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	B	1.9019	1.9019	3.2253	3.2253	1.4546	1.803
2	C	0.8391	0.8391	1.4230	1.4230	19.7725	1.242
3	D	-0.6921	0.6921	-1.1738	1.1738	27.8877	0.921
4	E	-0.4451	0.4451	-0.7548	0.7548	47.4969	0.674
5	F	0.3486	0.3486	0.5912	0.5912	57.2978	0.464
6	A	-0.2064	0.2064	-0.3500	0.3500	73.6663	0.272
7	G	0.0191	0.0191	0.0324	0.0324	97.5048	0.090

Figure 37.—Factor rankings and calculated values
for effects on austenite start, A_s, results.

Ruggedness Example Calculations for A_{s*} Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)											
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	73.700	76.100	74.900	2.400
2	-1	1	1	1	-1	1	-1	79.000	73.500	76.250	-5.500
3	-1	-1	1	1	1	-1	1	76.000	68.400	72.200	-7.600
4	1	-1	-1	1	1	1	-1	73.500	74.200	73.850	0.700
5	-1	1	-1	-1	1	1	1	78.600	75.200	76.900	-3.400
6	1	-1	1	-1	-1	1	1	76.300	75.700	76.000	-0.600
7	1	1	-1	1	-1	-1	1	73.800	73.600	73.700	-0.200
8	-1	-1	-1	-1	-1	-1	-1	70.800	74.500	72.650	3.700
Avg. of +1	74.613	75.438	74.838	74.000	74.463	75.750	74.700		s_d	3.894	
Avg. of -1	74.500	73.675	74.275	75.113	74.650	73.363	74.413		s_{rep}	2.753	
Effect	0.112	1.762	0.563	-1.113	-0.188	2.387	0.288		S_{effect}	1.377	
| Effect |	0.112	1.762	0.563	1.113	0.188	2.387	0.288				
Rank	7	2	4	3	6	1	5				

Figure 38.—Ruggedness example calculations for austenite start tangent line and data intersect, A_s*, results.

Statistical Significance of Effects Example Calculations for A_{s*} Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	F	2.3875	2.3875	1.7343	1.7343	12.6458	1.803
2	B	1.7625	1.7625	1.2803	1.2803	24.1235	1.242
3	D	-1.1125	1.1125	-0.8081	0.8081	44.5610	0.921
4	C	0.5625	0.5625	0.4086	0.4086	69.5043	0.674
5	G	0.2875	0.2875	0.2088	0.2088	84.0520	0.464
6	E	-0.1875	0.1875	-0.1362	0.1362	89.5497	0.272
7	A	0.1125	0.1125	0.0817	0.0817	93.7157	0.090

Figure 39.—Factor rankings and calculated values for effects on austenite start tangent line and data intersect, A_s*, results.

Ruggedness Example Calculations for A_{50} Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)											
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	120.376	120.437	120.407	0.061
2	-1	1	1	1	-1	1	-1	120.515	120.100	120.308	-0.415
3	-1	-1	1	1	1	-1	1	120.261	119.112	119.687	-1.149
4	1	-1	-1	1	1	1	-1	120.806	121.178	120.992	0.372
5	-1	1	-1	-1	1	1	1	120.632	119.981	120.306	-0.651
6	1	-1	1	-1	-1	1	1	120.654	119.447	120.050	-1.207
7	1	1	-1	1	-1	-1	1	120.423	120.010	120.216	-0.413
8	-1	-1	-1	-1	-1	-1	-1	119.961	120.596	120.278	0.635
Avg. of +1	120.416	120.309	120.113	120.300	120.348	120.414	120.065		s_d	0.669	
Avg. of -1	120.145	120.252	120.448	120.260	120.213	120.147	120.496		s_{rep}	0.473	
Effect	0.271	0.058	-0.335	0.040	0.135	0.267	-0.431		S_{effect}	0.236	
| Effect |	0.271	0.058	0.335	0.040	0.135	0.267	0.431				
Rank	4	1	3	7	6	5	2				

Figure 40.—Ruggedness example calculations
for austenite 50%, A_{50}, results.

Statistical Significance of Effects Example Calculations for A_{50} Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	G	-0.4313	0.4313	-1.8242	1.8242	11.0886	1.803
2	C	-0.3353	0.3353	-1.4183	1.4183	19.9050	1.242
3	A	0.2714	0.2714	1.1480	1.1480	28.8689	0.921
4	F	0.2670	0.2670	1.1291	1.1291	29.6055	0.674
5	E	0.1348	0.1348	0.5701	0.5701	58.6421	0.464
6	B	0.0575	0.0575	0.2434	0.2434	81.4685	0.272
7	D	0.0401	0.0401	0.1695	0.1695	87.0178	0.090

Figure 41.—Factor rankings and calculated values
for effects on austenite 50%, A_{50}, results.

Ruggedness Example Calculations for A_f Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)											
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	122.876	122.219	122.547	-0.657
2	-1	1	1	1	-1	1	-1	121.800	122.282	122.041	0.482
3	-1	-1	1	1	1	-1	1	123.753	123.198	123.476	-0.555
4	1	-1	-1	1	1	1	-1	127.098	126.505	126.802	-0.593
5	-1	1	-1	-1	1	1	1	122.374	122.849	122.612	0.475
6	1	-1	1	-1	-1	1	1	124.048	121.798	122.923	-2.250
7	1	1	-1	1	-1	-1	1	123.267	123.199	123.233	-0.068
8	-1	-1	-1	-1	-1	-1	-1	125.214	123.546	124.380	-1.668
Avg. of +1	123.876	122.608	122.747	123.888	123.859	123.594	123.061		s_d	0.962	
Avg. of -1	123.127	124.395	124.257	123.115	123.144	123.409	123.942		s_{rep}	0.680	
Effect	0.749	-1.787	-1.510	0.772	0.715	0.185	-0.882		S_{effect}	0.340	
| Effect |	0.749	1.787	1.510	0.772	0.715	0.185	0.882				
Rank	5	1	2	4	6	7	3				

Figure 42.—Ruggedness example calculations for austenite finish, A_f, results.

Statistical Significance of Effects Example Calculations for A_f Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	B	-1.7868	1.7868	-5.2537	5.2537	0.1181	1.803
2	C	-1.5098	1.5098	-4.4392	4.4392	0.3011	1.242
3	G	-0.8817	0.8817	-2.5924	2.5924	3.5818	0.921
4	D	0.7723	0.7723	2.2708	2.2708	5.7413	0.674
5	A	0.7492	0.7492	2.2028	2.2028	6.3464	0.464
6	E	0.7147	0.7147	2.1014	2.1014	7.3718	0.272
7	F	0.1853	0.1853	0.5448	0.5448	60.2787	0.090

Figure 43.—Factor rankings and calculated values for effects on austenite finish, A_f, results.

Ruggedness Example Calculations for A_{f^*} Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)											
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	140.500	142.300	141.400	1.800
2	-1	1	1	1	-1	1	-1	154.000	159.600	156.800	5.600
3	-1	-1	1	1	1	-1	1	155.000	153.800	154.400	-1.200
4	1	-1	-1	1	1	1	-1	156.400	158.400	157.400	2.000
5	-1	1	-1	-1	1	1	1	139.400	139.500	139.450	0.100
6	1	-1	1	-1	-1	1	1	136.000	137.600	136.800	1.600
7	1	1	-1	1	-1	-1	1	157.700	158.000	157.850	0.300
8	-1	-1	-1	-1	-1	-1	-1	139.000	140.200	139.600	1.200
Avg. of +1	148.363	148.875	147.350	156.613	148.163	147.613	147.125		s_d	1.996	
Avg. of -1	147.563	147.050	148.575	139.313	147.763	148.313	148.800		s_{rep}	1.412	
Effect	0.800	1.825	-1.225	17.300	0.400	-0.700	-1.675		S_{effect}	0.706	
| Effect |	0.800	1.825	1.225	17.300	0.400	0.700	1.675				
Rank	5	2	4	1	7	6	3				

Figure 44.—Ruggedness example calculations for austenite finish tangent line/data intersect, A_f*, results.

Statistical Significance of Effects Example Calculations for A_{f^*} Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	D	17.3000	17.3000	24.5119	24.5119	0.0000	1.803
2	B	1.8250	1.8250	2.5858	2.5858	3.6166	1.242
3	G	-1.6750	1.6750	-2.3733	2.3733	4.9369	0.921
4	C	-1.2250	1.2250	-1.7357	1.7357	12.6203	0.674
5	A	0.8000	0.8000	1.1335	1.1335	29.4329	0.464
6	F	-0.7000	0.7000	-0.9918	0.9918	35.4328	0.272
7	E	0.4000	0.4000	0.5667	0.5667	58.8588	0.090

Figure 45.—Factor rankings and calculated values for effects on austenite finish tangent line/data intersect, A_f*, results.

Ruggedness Example Calculations for M_s Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)											
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	70.722	70.280	70.501	-0.442
2	-1	1	1	1	-1	1	-1	68.160	70.824	69.492	2.664
3	-1	-1	1	1	1	-1	1	71.210	69.188	70.199	-2.022
4	1	-1	-1	1	1	1	-1	68.304	71.347	69.826	3.043
5	-1	1	-1	-1	1	1	1	70.378	70.452	70.415	0.074
6	1	-1	1	-1	-1	1	1	70.815	70.209	70.512	-0.606
7	1	1	-1	1	-1	-1	1	71.008	72.454	71.731	1.446
8	-1	-1	-1	-1	-1	-1	-1	72.445	70.628	71.537	-1.817
Avg. of +1	70.642	70.535	70.176	70.312	70.235	70.061	70.714		s_d	1.917	
Avg. of -1	70.411	70.518	70.877	70.741	70.818	70.992	70.339		s_{rep}	1.355	
Effect	0.232	0.017	-0.701	-0.429	-0.583	-0.931	0.375		S_{effect}	0.678	
| Effect |	0.232	0.017	0.701	0.429	0.583	0.931	0.375				
Rank	6	7	2	4	3	1	5				

Figure 46.—Ruggedness example calculations for martensite start, M_s, results.

Statistical Significance of Effects Example Calculations for M_s							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	F	-0.9307	0.9307	-1.3733	1.3733	21.2032	1.803
2	C	-0.7010	0.7010	-1.0344	1.0344	33.5372	1.242
3	E	-0.5828	0.5828	-0.8599	0.8599	41.8325	0.921
4	D	-0.4293	0.4293	-0.6334	0.6334	54.6604	0.674
5	G	0.3755	0.3755	0.5540	0.5540	59.6814	0.464
6	A	0.2318	0.2318	0.3420	0.3420	74.2400	0.272
7	B	0.0165	0.0165	0.0244	0.0244	98.1228	0.090

Figure 47.—Factor rankings and calculated values for effects on martensite start, M_s, results.

Ruggedness Example Calculations for M_{s^*} Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)											
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	74.600	73.300	73.950	-1.300
2	-1	1	1	1	-1	1	-1	75.000	77.800	76.400	2.800
3	-1	-1	1	1	1	-1	1	72.700	74.400	73.550	1.700
4	1	-1	-1	1	1	1	-1	81.700	74.600	78.150	-7.100
5	-1	1	-1	-1	1	1	1	70.500	71.500	71.000	1.000
6	1	-1	1	-1	-1	1	1	72.000	73.000	72.500	1.000
7	1	1	-1	1	-1	-1	1	74.100	81.700	77.900	7.600
8	-1	-1	-1	-1	-1	-1	-1	73.900	73.500	73.700	-0.400
Avg. of +1	75.625	74.813	74.100	76.500	74.163	74.513	73.738		s_d	4.127	
Avg. of -1	73.663	74.475	75.188	72.788	75.125	74.775	75.550		s_{rep}	2.918	
Effect	1.962	0.337	-1.088	3.713	-0.963	-0.263	-1.812		S_{effect}	1.459	
| Effect |	1.962	0.337	1.088	3.713	0.963	0.263	1.812				
Rank	2	6	4	1	5	7	3				

Figure 48.—Ruggedness example calculations
for martensite start tangent line and data intersect, M_s*, results.

Statistical Significance of Effects Example Calculations for M_{s^*} Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	D	3.7125	3.7125	2.5442	2.5442	3.8427	1.803
2	A	1.9625	1.9625	1.3449	1.3449	22.0594	1.242
3	G	-1.8125	1.8125	-1.2421	1.2421	25.4191	0.921
4	C	-1.0875	1.0875	-0.7453	0.7453	48.0377	0.674
5	E	-0.9625	0.9625	-0.6596	0.6596	53.0600	0.464
6	B	0.3375	0.3375	0.2313	0.2313	82.3704	0.272
7	F	-0.2625	0.2625	-0.1799	0.1799	86.2333	0.090

Figure 49.—Factor rankings and calculated values
for effects on martensite start tangent line and data intersect, M_s*, results.

Ruggedness Example Calculations for M_{50} Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)											
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	69.182	69.385	69.283	0.203
2	-1	1	1	1	-1	1	-1	69.440	69.299	69.370	-0.141
3	-1	-1	1	1	1	-1	1	69.400	68.285	68.842	-1.115
4	1	-1	-1	1	1	1	-1	69.853	70.265	70.059	0.412
5	-1	1	-1	-1	1	1	1	69.478	68.710	69.094	-0.768
6	1	-1	1	-1	-1	1	1	69.471	69.313	69.392	-0.158
7	1	1	-1	1	-1	-1	1	69.460	68.239	68.849	-1.221
8	-1	-1	-1	-1	-1	-1	-1	69.069	69.718	69.393	0.648
Avg. of +1	69.396	69.149	69.222	69.280	69.320	69.478	69.044		s_d	0.700	
Avg. of -1	69.175	69.421	69.349	69.290	69.251	69.092	69.526		s_{rep}	0.495	
Effect	0.221	-0.273	-0.127	-0.010	0.069	0.386	-0.482		S_{effect}	0.247	
| Effect |	0.221	0.273	0.127	0.010	0.069	0.386	0.482				
Rank	4	3	5	7	6	2	1				

Figure 50.—Ruggedness example calculations for martensite 50%, M_{50}, results.

Statistical Significance of Effects Example Calculations for M_{50} Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	G	-0.4820	0.4820	-1.9476	1.9476	9.2494	1.803
2	F	0.3863	0.3863	1.5612	1.5612	16.2447	1.242
3	B	-0.2725	0.2725	-1.1012	1.1012	30.7212	0.921
4	A	0.2210	0.2210	0.8929	0.8929	40.1547	0.674
5	C	-0.1271	0.1271	-0.5136	0.5136	62.3344	0.464
6	E	0.0686	0.0686	0.2774	0.2774	78.9482	0.272
7	D	-0.0105	0.0105	-0.0423	0.0423	96.7419	0.090

Figure 51.—Factor rankings and calculated values for effects on martensite 50%, M_{50}, results.

Ruggedness Example Calculations for M_f Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)											
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	67.642	68.489	68.066	0.847
2	-1	1	1	1	-1	1	-1	70.720	67.774	69.247	-2.946
3	-1	-1	1	1	1	-1	1	67.590	67.382	67.486	-0.208
4	1	-1	-1	1	1	1	-1	71.401	69.183	70.292	-2.218
5	-1	1	-1	-1	1	1	1	68.578	66.967	67.773	-1.611
6	1	-1	1	-1	-1	1	1	68.126	68.416	68.271	0.290
7	1	1	-1	1	-1	-1	1	67.912	64.023	65.968	-3.889
8	-1	-1	-1	-1	-1	-1	-1	65.693	68.807	67.250	3.114
Avg. of +1	68.149	67.763	68.267	68.248	68.404	68.896	67.374		s_d	2.280	
Avg. of -1	67.939	68.325	67.821	67.840	67.684	67.192	68.714		s_{rep}	1.612	
Effect	0.210	-0.562	0.447	0.408	0.720	1.703	-1.339		S_{effect}	0.806	
| Effect |	0.210	0.562	0.447	0.408	0.720	1.703	1.339				
Rank	7	4	5	6	3	1	2				

Figure 52.—Ruggedness example calculations
for martensite finish, M_f, results.

Statistical Significance of Effects Example Calculations for M_f Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	F	1.7034	1.7034	2.1134	2.1134	7.2424	1.803
2	G	-1.3394	1.3394	-1.6618	1.6618	14.0508	1.242
3	E	0.7201	0.7201	0.8934	0.8934	40.1323	0.921
4	B	-0.5616	0.5616	-0.6967	0.6967	50.8439	0.674
5	C	0.4468	0.4468	0.5544	0.5544	59.6587	0.464
6	D	0.4083	0.4083	0.5066	0.5066	62.7999	0.272
7	A	0.2102	0.2102	0.2608	0.2608	80.1783	0.090

Figure 53.—Factor rankings and calculated values
for effects on martensite finish, M_f, results.

Ruggedness Example Calculations for M_{f*} Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)											
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	48.900	50.400	49.650	1.500
2	-1	1	1	1	-1	1	-1	50.000	48.000	49.000	-2.000
3	-1	-1	1	1	1	-1	1	51.600	51.000	51.300	-0.600
4	1	-1	-1	1	1	1	-1	49.000	46.200	47.600	-2.800
5	-1	1	-1	-1	1	1	1	51.700	47.700	49.700	-4.000
6	1	-1	1	-1	-1	1	1	46.400	47.400	46.900	1.000
7	1	1	-1	1	-1	-1	1	49.600	45.200	47.400	-4.400
8	-1	-1	-1	-1	-1	-1	-1	46.700	47.200	46.950	0.500
Avg. of +1	47.888	48.938	49.213	48.825	49.563	48.300	48.825		s_d	2.283	
Avg. of -1	49.238	48.188	47.913	48.300	47.563	48.825	48.300		s_{rep}	1.614	
Effect	-1.350	0.750	1.300	0.525	2.000	-0.525	0.525		S_{effect}	0.807	
| Effect |	1.350	0.750	1.300	0.525	2.000	0.525	0.525				
Rank	2	4	3	5	1	6	7				

Figure 54.—Ruggedness example calculations
for martensite finish tangent line and data intersect, M_f*, results.

Statistical Significance of Effects Example Calculations for M_{f*} Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	E	2.0000	2.0000	2.4780	2.4780	4.2336	1.803
2	A	-1.3500	1.3500	-1.6726	1.6726	13.8318	1.242
3	C	1.3000	1.3000	1.6107	1.6107	15.1284	0.921
4	B	0.7500	0.7500	0.9292	0.9292	38.3690	0.674
5	D	0.5250	0.5250	0.6505	0.6505	53.6148	0.464
6	F	-0.5250	0.5250	-0.6505	0.6505	53.6148	0.272
7	G	0.5250	0.5250	0.6505	0.6505	53.6148	0.090

Figure 55.—Factor rankings and calculated values
for effects on martensite finish tangent line and data intersect, M_f*, results.

Ruggedness Example Calculations for HWIDTH Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)											
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	51.194	51.053	51.123	-0.142
2	-1	1	1	1	-1	1	-1	51.075	50.801	50.938	-0.274
3	-1	-1	1	1	1	-1	1	50.861	50.827	50.844	-0.034
4	1	-1	-1	1	1	1	-1	50.953	50.913	50.933	-0.041
5	-1	1	-1	-1	1	1	1	51.154	51.272	51.213	0.118
6	1	-1	1	-1	-1	1	1	51.183	50.134	50.659	-1.049
7	1	1	-1	1	-1	-1	1	50.963	51.771	51.367	0.809
8	-1	-1	-1	-1	-1	-1	-1	50.892	50.878	50.885	-0.014
Avg. of +1	51.020	51.160	50.891	51.020	51.028	50.935	51.020		s_d	0.509	
Avg. of -1	50.970	50.830	51.099	50.970	50.962	51.055	50.970		s_{rep}	0.360	
Effect	0.050	0.330	-0.208	0.051	0.066	-0.119	0.051		S_{effect}	0.180	
| Effect |	0.050	0.330	0.208	0.051	0.066	0.119	0.051				
Rank	7	1	2	6	4	3	5				

Figure 56.—Ruggedness example calculations for hysteresis width, *HWIDTH*, results.

Statistical Significance of Effects Example Calculations for HWIDTH Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	B	0.3301	0.3301	1.8324	1.8324	93.7813	1.803
2	C	-0.2082	0.2082	-1.1560	1.1560	35.0479	1.242
3	F	-0.1194	0.1194	-0.6628	0.6628	99.4006	0.921
4	E	0.0661	0.0661	0.3672	0.3672	13.9173	0.674
5	G	0.0507	0.0507	0.2814	0.2814	13.7509	0.464
6	D	0.0506	0.0506	0.2807	0.2807	75.1198	0.272
7	A	0.0504	0.0504	0.2800	0.2800	75.3227	0.090

Figure 57.—Factor rankings and calculated values for effects on hysteresis width, *HWIDTH*, results.

Ruggedness Example Calculations for TSPAN Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)										
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	55.234	53.730	54.482	-1.504
2	-1	1	1	1	-1	1	-1	51.080	54.508	52.794	3.428
3	-1	-1	1	1	1	-1	1	56.163	55.816	55.990	-0.347
4	1	-1	-1	1	1	1	-1	55.697	57.322	56.510	1.625
5	-1	1	-1	-1	1	1	1	53.796	55.882	54.839	2.086
6	1	-1	1	-1	-1	1	1	55.922	53.382	54.652	-2.540
7	1	1	-1	1	-1	-1	1	55.355	59.176	57.266	3.821
8	-1	-1	-1	-1	-1	-1	-1	59.521	54.739	57.130	-4.782
Avg. of +1	55.727	54.845	54.479	55.640	55.455	54.699	55.687		s_d	3.039	
Avg. of -1	55.188	56.070	56.436	55.276	55.460	56.217	55.229		s_{rep}	2.149	
Effect	0.539	-1.225	-1.957	0.364	-0.005	-1.518	0.458		S_{effect}	1.074	
| Effect |	0.539	1.225	1.957	0.364	0.005	1.518	0.458				
Rank	4	3	1	6	7	2	5				

Figure 58.—Ruggedness example calculations
for thermal transformation span, *TSPAN*, results.

Statistical Significance of Effects Example Calculations for TSPAN Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	C	-1.9566	1.9566	-1.8211	1.8211	11.1388	1.803
2	F	-1.5181	1.5181	-1.4130	1.4130	20.0549	1.242
3	B	-1.2252	1.2252	-1.1404	1.1404	29.1645	0.921
4	A	0.5390	0.5390	0.5017	0.5017	63.1276	0.674
5	G	0.4577	0.4577	0.4260	0.4260	68.2885	0.464
6	D	0.3640	0.3640	0.3388	0.3388	74.4721	0.272
7	E	-0.0054	0.0054	-0.0050	0.0050	99.6148	0.090

Figure 59.—Factor rankings and calculated values
for effects on thermal transformation span, *TSPAN*, results.

Ruggedness Example Calculations for e_{As} Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)											
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	0.06827	0.06870	0.06849	0.00043
2	-1	1	1	1	-1	1	-1	0.06797	0.06897	0.06847	0.00100
3	-1	-1	1	1	1	-1	1	0.06876	0.06649	0.06763	-0.00227
4	1	-1	-1	1	1	1	-1	0.06840	0.06764	0.06802	-0.00076
5	-1	1	-1	-1	1	1	1	0.06725	0.06771	0.06748	0.00046
6	1	-1	1	-1	-1	1	1	0.06759	0.06686	0.06723	-0.00073
7	1	1	-1	1	-1	-1	1	0.06823	0.06733	0.06778	-0.00090
8	-1	-1	-1	-1	-1	-1	-1	0.06903	0.06846	0.06875	-0.00057
Avg. of +1	0.06788	0.06805	0.06795	0.06797	0.06790	0.06780	0.06753		s_d	0.00103	
Avg. of -1	0.06808	0.06790	0.06801	0.06798	0.06806	0.06816	0.06843		s_{rep}	0.00073	
Effect	-0.00020	0.00015	-0.00006	-0.00001	-0.00015	-0.00036	-0.00090		S_{effect}	0.00036	
| Effect |	0.00020	0.00015	0.00006	0.00001	0.00015	0.00036	0.00090				
Rank	3	5	6	7	4	2	1				

Figure 60.—Ruggedness example calculations
for strain at austenite start temperature, e_{As}, results.

Statistical Significance of Effects Example Calculations for e_{As} Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	G	-0.00090	0.00090	-2.4826	2.4826	4.2047	1.803
2	F	-0.00036	0.00036	-0.9903	0.9903	35.5012	1.242
3	A	-0.00020	0.00020	-0.5570	0.5570	59.4849	0.921
4	E	-0.00015	0.00015	-0.4195	0.4195	68.7421	0.674
5	B	0.00015	0.00015	0.4126	0.4126	69.2224	0.464
6	C	-0.00006	0.00006	-0.1513	0.1513	88.4009	0.272
7	D	-0.00001	0.00001	-0.0275	0.0275	97.8822	0.090

Figure 61.—Factor rankings and calculated values
for effects on strain at austenite start temperature, e_{As}, results.

Ruggedness Example Calculations for e_{Af} Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)										
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	0.02175	0.02221	0.02198	0.00046
2	-1	1	1	1	-1	1	-1	0.02015	0.02067	0.02041	0.00052
3	-1	-1	1	1	1	-1	1	0.02010	0.01571	0.01791	-0.00439
4	1	-1	-1	1	1	1	-1	0.02006	0.01988	0.01997	-0.00018
5	-1	1	-1	-1	1	1	1	0.02080	0.02095	0.02088	0.00015
6	1	-1	1	-1	-1	1	1	0.02137	0.02065	0.02101	-0.00072
7	1	1	-1	1	-1	-1	1	0.01978	0.01974	0.01976	-0.00004
8	-1	-1	-1	-1	-1	-1	-1	0.02257	0.02233	0.02245	-0.00024
Avg. of +1	0.02068	0.02076	0.02033	0.01951	0.02018	0.02057	0.01989		s_d	0.00160	
Avg. of -1	0.02041	0.02033	0.02076	0.02158	0.02091	0.02052	0.02120		s_{rep}	0.00113	
Effect	0.00027	0.00042	-0.00044	-0.00207	-0.00073	0.00004	-0.00132		S_{effect}	0.00057	
| Effect |	0.00027	0.00042	0.00044	0.00207	0.00073	0.00004	0.00132				
Rank	6	5	4	1	3	7	2				

Figure 62.—Ruggedness example calculations for strain at austenite finish temperature, e_{Af}, results.

Statistical Significance of Effects Example Calculations for e_{Af} Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	D	-0.00207	0.00207	-3.6546	3.6546	0.8128	1.803
2	G	-0.00132	0.00132	-2.3245	2.3245	5.3045	1.242
3	E	-0.00073	0.00073	-1.2815	1.2815	24.0817	0.921
4	C	-0.00044	0.00044	-0.7733	0.7733	46.4627	0.674
5	B	0.00042	0.00042	0.7468	0.7468	47.9493	0.464
6	A	0.00027	0.00027	0.4773	0.4773	64.7715	0.272
7	F	0.00004	0.00004	0.0751	0.0751	94.2217	0.090

Figure 63.—Factor rankings and calculated values for effects on strain at austenite finish temperature, e_{Af}, results.

Ruggedness Example Calculations for e_{Ms} Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)											
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	0.00166	0.00174	0.00170	0.00008
2	-1	1	1	1	-1	1	-1	0.00147	0.00176	0.00162	0.00029
3	-1	-1	1	1	1	-1	1	0.00142	0.00060	0.00101	-0.00082
4	1	-1	-1	1	1	1	-1	0.00118	0.00139	0.00129	0.00021
5	-1	1	-1	-1	1	1	1	0.00018	0.00081	0.00050	0.00063
6	1	-1	1	-1	-1	1	1	0.00032	0.00108	0.00070	0.00077
7	1	1	-1	1	-1	-1	1	0.00097	0.00091	0.00094	-0.00006
8	-1	-1	-1	-1	-1	-1	-1	0.00167	0.00186	0.00177	0.00019
Avg. of +1	0.00116	0.00119	0.00126	0.00121	0.00112	0.00102	0.00079		s_d	0.00048	
Avg. of -1	0.00122	0.00119	0.00112	0.00116	0.00125	0.00135	0.00159		s_{rep}	0.00034	
Effect	-0.00006	0.00000	0.00013	0.00005	-0.00013	-0.00033	-0.00081		S_{effect}	0.00017	
| Effect |	0.00006	0.00000	0.00013	0.00005	0.00013	0.00033	0.00081				
Rank	5	7	3	6	4	2	1				

Figure 64.—Ruggedness example calculations
for strain at martensite start temperature, e_{Ms}, results.

Statistical Significance of Effects Example Calculations for e_{Ms} Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	G	-0.00081	0.00081	-4.7421	4.7421	0.2103	1.803
2	F	-0.00033	0.00033	-1.9498	1.9498	9.2197	1.242
3	C	0.00013	0.00013	0.7901	0.7901	45.5406	0.921
4	E	-0.00013	0.00013	-0.7773	0.7773	46.2448	0.674
5	A	-0.00006	0.00006	-0.3824	0.3824	71.3494	0.464
6	D	0.00005	0.00005	0.2838	0.2838	78.4761	0.272
7	B	0.00000	0.00000	-0.0071	0.0071	99.4504	0.090

Figure 65.—Factor rankings and calculated values
for effects on strain at martensite start temperature, e_{Ms}, results.

Ruggedness Example Calculations for e_{Mf} Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)											
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	0.06902	0.06928	0.06915	0.00026
2	-1	1	1	1	-1	1	-1	0.06890	0.06964	0.06927	0.00074
3	-1	-1	1	1	1	-1	1	0.06999	0.06746	0.06873	-0.00253
4	1	-1	-1	1	1	1	-1	0.06920	0.06894	0.06907	-0.00026
5	-1	1	-1	-1	1	1	1	0.06805	0.06856	0.06831	0.00051
6	1	-1	1	-1	-1	1	1	0.06865	0.06787	0.06826	-0.00078
7	1	1	-1	1	-1	-1	1	0.06896	0.06801	0.06849	-0.00095
8	-1	-1	-1	-1	-1	-1	-1	0.07002	0.06937	0.06970	-0.00065
Avg. of +1	0.06874	0.06880	0.06885	0.06889	0.06881	0.06873	0.06844		s_d	0.00104	
Avg. of -1	0.06900	0.06894	0.06889	0.06885	0.06893	0.06901	0.06930		s_{rep}	0.00074	
Effect	-0.00026	-0.00014	-0.00004	0.00003	-0.00012	-0.00029	-0.00085		S_{effect}	0.00037	
| Effect |	0.00026	0.00014	0.00004	0.00003	0.00012	0.00029	0.00085				
Rank	3	4	6	7	5	2	1				

Figure 66.—Ruggedness example calculations for strain at martensite finish temperature, e_{Mf}, results.

Statistical Significance of Effects Example Calculations for e_{Mf} Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	G	-0.00085	0.00085	-2.3137	2.3137	5.3894	1.803
2	F	-0.00029	0.00029	-0.7803	0.7803	46.0795	1.242
3	A	-0.00026	0.00026	-0.6989	0.6989	50.7192	0.921
4	B	-0.00014	0.00014	-0.3664	0.3664	72.4898	0.674
5	E	-0.00012	0.00012	-0.3121	0.3121	76.4049	0.464
6	C	-0.00004	0.00004	-0.1018	0.1018	92.1789	0.272
7	D	0.00003	0.00003	0.0950	0.0950	92.6985	0.090

Figure 67.—Factor rankings and calculated values for effect on strain at martensite finish temperature, e_{Mf}, results.

Ruggedness Example Calculations for e_{act} Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)											
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	0.05002	0.04970	0.04986	-0.00032
2	-1	1	1	1	-1	1	-1	0.05064	0.05029	0.05047	-0.00035
3	-1	-1	1	1	1	-1	1	0.05068	0.05263	0.05166	0.00195
4	1	-1	-1	1	1	1	-1	0.05049	0.05003	0.05026	-0.00046
5	-1	1	-1	-1	1	1	1	0.05020	0.05053	0.05037	0.00033
6	1	-1	1	-1	-1	1	1	0.05062	0.05021	0.05042	-0.00041
7	1	1	-1	1	-1	-1	1	0.05050	0.04945	0.04998	-0.00105
8	-1	-1	-1	-1	-1	-1	-1	0.05038	0.05007	0.05023	-0.00031
Avg. of +1	0.05013	0.05017	0.05060	0.05059	0.05054	0.05038	0.05060		s_d	0.00090	
Avg. of -1	0.05068	0.05064	0.05021	0.05022	0.05027	0.05043	0.05020		s_{rep}	0.00064	
Effect	-0.00055	-0.00047	0.00039	0.00037	0.00026	-0.00005	0.00040		S_{effect}	0.00032	
| Effect |	0.00055	0.00047	0.00039	0.00037	0.00026	0.00005	0.00040				
Rank	1	2	4	5	6	7	3				

Figure 68.—Ruggedness example calculations for actuation strain, e_{act}, results.

Statistical Significance of Effects Example Calculations for e_{act} Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	A	-0.00055	0.00055	-1.7290	1.7290	12.7434	1.803
2	B	-0.00047	0.00047	-1.4854	1.4854	18.1027	1.242
3	G	0.00040	0.00040	1.2575	1.2575	24.8913	0.921
4	C	0.00039	0.00039	1.2339	1.2339	25.7063	0.674
5	D	0.00037	0.00037	1.1710	1.1710	27.9909	0.464
6	E	0.00026	0.00026	0.8331	0.8331	43.2308	0.272
7	F	-0.00005	0.00005	-0.1650	0.1650	87.3576	0.090

Figure 69.—Factor rankings and calculated values for effects on actuation strain, e_{act}, results.

Ruggedness Example Calculations for e_{res} Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)											
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	0.01785	0.01851	0.01818	0.00066
2	-1	1	1	1	-1	1	-1	0.01786	0.01814	0.01800	0.00028
3	-1	-1	1	1	1	-1	1	0.01792	0.01444	0.01618	-0.00348
4	1	-1	-1	1	1	1	-1	0.01806	0.01769	0.01788	-0.00037
5	-1	1	-1	-1	1	1	1	0.01840	0.01799	0.01819	-0.00040
6	1	-1	1	-1	-1	1	1	0.01815	0.01743	0.01779	-0.00072
7	1	1	-1	1	-1	-1	1	0.01793	0.01818	0.01806	0.00025
8	-1	-1	-1	-1	-1	-1	-1	0.01863	0.01839	0.01851	-0.00024
Avg. of +1	0.01798	0.01811	0.01754	0.01753	0.01761	0.01797	0.01756		s_d	0.00128	
Avg. of -1	0.01772	0.01759	0.01816	0.01817	0.01809	0.01773	0.01814		s_{rep}	0.00091	
Effect	0.00026	0.00052	-0.00062	-0.00064	-0.00048	0.00024	-0.00058		S_{effect}	0.00045	
| Effect |	0.00026	0.00052	0.00062	0.00064	0.00048	0.00024	0.00058				
Rank	6	4	2	1	5	7	3				

Figure 70.—Ruggedness example calculations
for residual strain, e_{res}, results.

Statistical Significance of Effects Example Calculations for e_{res} Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	D	-0.00064	0.00064	-1.4130	1.4130	20.0544	1.803
2	C	-0.00062	0.00062	-1.3717	1.3717	21.2516	1.242
3	G	-0.00058	0.00058	-1.2895	1.2895	23.8184	0.921
4	B	0.00052	0.00052	1.1424	1.1424	29.0869	0.674
5	E	-0.00048	0.00048	-1.0630	1.0630	32.3078	0.464
6	A	0.00026	0.00026	0.5658	0.5658	58.9196	0.272
7	F	0.00024	0.00024	0.5190	0.5190	61.9792	0.090

Figure 71.—Factor rankings and calculated values
for effects on residual strain, e_{res}, results.

Ruggedness Example Calculations for e_{LCT} Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)											
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	0.07035	0.07077	0.07056	0.00042
2	-1	1	1	1	-1	1	-1	0.07107	0.07127	0.07117	0.00020
3	-1	-1	1	1	1	-1	1	0.07107	0.06870	0.06989	-0.00237
4	1	-1	-1	1	1	1	-1	0.07081	0.07015	0.07048	-0.00066
5	-1	1	-1	-1	1	1	1	0.06971	0.07010	0.06991	0.00039
6	1	-1	1	-1	-1	1	1	0.07015	0.06940	0.06978	-0.00075
7	1	1	-1	1	-1	-1	1	0.07058	0.06952	0.07005	-0.00106
8	-1	-1	-1	-1	-1	-1	-1	0.07147	0.07101	0.07124	-0.00046
Avg. of +1	0.07022	0.07042	0.07035	0.07040	0.07021	0.07033	0.06990		s_d	0.00093	
Avg. of -1	0.07055	0.07035	0.07042	0.07037	0.07056	0.07043	0.07086		s_{rep}	0.00066	
Effect	-0.00033	0.00008	-0.00007	0.00003	-0.00035	-0.00010	-0.00096		S_{effect}	0.00033	
| Effect |	0.00033	0.00008	0.00007	0.00003	0.00035	0.00010	0.00096				
Rank	3	5	6	7	2	4	1				

Figure 72.—Ruggedness example calculations for strain at lower cycle temperature, e_{LCT}, results.

Statistical Significance of Effects Example Calculations for e_{LCT} Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	G	-0.00096	0.00096	-2.9246	2.9246	2.2194	1.803
2	E	-0.00035	0.00035	-1.0715	1.0715	31.9506	1.242
3	A	-0.00033	0.00033	-1.0181	1.0181	34.2529	0.921
4	F	-0.00010	0.00010	-0.3089	0.3089	76.6421	0.674
5	B	0.00008	0.00008	0.2326	0.2326	82.2730	0.464
6	C	-0.00007	0.00007	-0.2173	0.2173	83.4140	0.272
7	D	0.00003	0.00003	0.0801	0.0801	93.8420	0.090

Figure 73.—Factor rankings and calculated values for effects on strain at lower cycle temperature, e_{LCT}, results.

Ruggedness Example Calculations for e_{UCT} Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)											
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	0.02033	0.02107	0.02070	0.00074
2	-1	1	1	1	-1	1	-1	0.02043	0.02098	0.02071	0.00055
3	-1	-1	1	1	1	-1	1	0.02039	0.01607	0.01823	-0.00432
4	1	-1	-1	1	1	1	-1	0.02032	0.02012	0.02022	-0.00020
5	-1	1	-1	-1	1	1	1	0.01951	0.01957	0.01954	0.00006
6	1	-1	1	-1	-1	1	1	0.01953	0.01919	0.01936	-0.00034
7	1	1	-1	1	-1	-1	1	0.02008	0.02007	0.02008	-0.00001
8	-1	-1	-1	-1	-1	-1	-1	0.02109	0.02094	0.02102	-0.00015
Avg. of +1	0.02009	0.02026	0.01975	0.01981	0.01967	0.01996	0.01930		s_d	0.00160	
Avg. of -1	0.01987	0.01971	0.02021	0.02015	0.02029	0.02001	0.02066		s_{rep}	0.00113	
Effect	0.00022	0.00055	-0.00046	-0.00035	-0.00062	-0.00005	-0.00136		S_{effect}	0.00057	
| Effect |	0.00022	0.00055	0.00046	0.00035	0.00062	0.00005	0.00136				
Rank	6	3	4	5	2	7	1				

Figure 74.—Ruggedness example calculations
for strain at upper cycle temperature, e_{UCT}, results.

Statistical Significance of Effects Example Calculations for e_{UCT} Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	G	-0.00136	0.00136	-2.3959	2.3959	4.7753	1.803
2	E	-0.00062	0.00062	-1.0866	1.0866	31.3191	1.242
3	B	0.00055	0.00055	0.9676	0.9676	36.5470	0.921
4	C	-0.00046	0.00046	-0.8177	0.8177	44.0451	0.674
5	D	-0.00035	0.00035	-0.6105	0.6105	56.0792	0.464
6	A	0.00022	0.00022	0.3813	0.3813	71.4279	0.272
7	F	-0.00005	0.00005	-0.0860	0.0860	93.3904	0.090

Figure 75.—Factor rankings and calculated values
for effects on strain at upper cycle temperature, e_{UCT}, results.

Ruggedness Example Calculations for e_{ct} Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)

Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	0.06736	0.06754	0.06745	0.00018
2	-1	1	1	1	-1	1	-1	0.06743	0.06788	0.06766	0.00045
3	-1	-1	1	1	1	-1	1	0.06857	0.06686	0.06772	-0.00171
4	1	-1	-1	1	1	1	-1	0.06802	0.06755	0.06779	-0.00047
5	-1	1	-1	-1	1	1	1	0.06787	0.06775	0.06781	-0.00012
6	1	-1	1	-1	-1	1	1	0.06834	0.06679	0.06756	-0.00155
7	1	1	-1	1	-1	-1	1	0.06799	0.06710	0.06754	-0.00089
8	-1	-1	-1	-1	-1	-1	-1	0.06835	0.06751	0.06793	-0.00084
Avg. of +1	0.06759	0.06761	0.06760	0.06767	0.06769	0.06770	0.06766		s_d	0.00078	
Avg. of -1	0.06778	0.06775	0.06777	0.06769	0.06767	0.06766	0.06770		s_{rep}	0.00055	
Effect	-0.00019	-0.00013	-0.00017	-0.00001	0.00002	0.00004	-0.00005		S_{effect}	0.00027	
| Effect |	0.00019	0.00013	0.00017	0.00001	0.00002	0.00004	0.00005				
Rank	1	3	2	7	6	5	4				

Figure 76.—Ruggedness example calculations for cooling transformation strain, e_{ct}, results.

Statistical Significance of Effects Example Calculations for e_{ct} Results

Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	A	-0.00019	0.00019	-0.7003	0.7003	50.6347	1.803
2	C	-0.00017	0.00017	-0.6245	0.6245	55.2073	1.242
3	B	-0.00013	0.00013	-0.4866	0.4866	64.1402	0.921
4	G	-0.00005	0.00005	-0.1708	0.1708	86.9205	0.674
5	F	0.00004	0.00004	0.1590	0.1590	87.8167	0.464
6	E	0.00002	0.00002	0.0620	0.0620	95.2320	0.272
7	D	-0.00001	0.00001	-0.0481	0.0481	96.3014	0.090

Figure 77.—Factor rankings and calculated values for effects on cooling transformation strain, e_{ct}, results.

Ruggedness Example Calculations for e_{ht} Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)											
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	0.04652	0.04649	0.04651	-0.00003
2	-1	1	1	1	-1	1	-1	0.04782	0.04830	0.04806	0.00048
3	-1	-1	1	1	1	-1	1	0.04866	0.05078	0.04972	0.00212
4	1	-1	-1	1	1	1	-1	0.04834	0.04776	0.04805	-0.00058
5	-1	1	-1	-1	1	1	1	0.04645	0.04676	0.04661	0.00031
6	1	-1	1	-1	-1	1	1	0.04622	0.04621	0.04622	-0.00001
7	1	1	-1	1	-1	-1	1	0.04845	0.04759	0.04802	-0.00086
8	-1	-1	-1	-1	-1	-1	-1	0.04646	0.04613	0.04630	-0.00033
Avg. of +1	0.04720	0.04730	0.04763	0.04846	0.04772	0.04723	0.04764		s_d	0.00091	
Avg. of -1	0.04767	0.04757	0.04724	0.04641	0.04715	0.04764	0.04723		s_{rep}	0.00065	
Effect	-0.00047	-0.00027	0.00038	0.00206	0.00057	-0.00040	0.00041		S_{effect}	0.00032	
| Effect |	0.00047	0.00027	0.00038	0.00206	0.00057	0.00040	0.00041				
Rank	3	7	6	1	2	5	4				

Figure 78.—Ruggedness example calculations for heating transformation strain, e_{ht}, results.

Statistical Significance of Effects Example Calculations for e_{ht} Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	D	0.00206	0.00206	6.3628	6.3628	0.0381	1.803
2	E	0.00057	0.00057	1.7705	1.7705	11.9956	1.242
3	A	-0.00047	0.00047	-1.4612	1.4612	18.7344	0.921
4	G	0.00041	0.00041	1.2757	1.2757	24.2775	0.674
5	F	-0.00040	0.00040	-1.2447	1.2447	25.3285	0.464
6	C	0.00038	0.00038	1.1829	1.1829	27.5469	0.272
7	B	-0.00027	0.00027	-0.8427	0.8427	42.7244	0.090

Figure 79.—Factor rankings and calculated values for effects on heating transformation, e_{ht}, results.

Ruggedness Example Calculations for e_i Results Assuming Uniaxial Constant Force Thermal Cycling (UCFTC)											
Run Number	**Strain Rate**	**Cooling Rate**	**Heating Rate**	**UCT**	**LCT**	**Hold Time**	**Minimum Load**	*Rep. 1*	*Rep. 2*	*Rep. 1 and Rep. 2*	
	A	**B**	**C**	**D**	**E**	**F**	**G**	Result	Result	Average	Difference
1	1	1	1	-1	1	-1	-1	0.00248	0.00256	0.00252	0.00008
2	-1	1	1	1	-1	1	-1	0.00257	0.00284	0.00271	0.00027
3	-1	-1	1	1	1	-1	1	0.00247	0.00163	0.00205	-0.00084
4	1	-1	-1	1	1	1	-1	0.00226	0.00243	0.00234	0.00017
5	-1	1	-1	-1	1	1	1	0.00111	0.00158	0.00135	0.00046
6	1	-1	1	-1	-1	1	1	0.00138	0.00176	0.00157	0.00038
7	1	1	-1	1	-1	-1	1	0.00215	0.00189	0.00202	-0.00026
8	-1	-1	-1	-1	-1	-1	-1	0.00246	0.00255	0.00251	0.00009
Avg. of +1	0.00211	0.00215	0.00221	0.00228	0.00207	0.00199	0.00175		s_d	0.00042	
Avg. of -1	0.00215	0.00212	0.00205	0.00199	0.00220	0.00227	0.00252		s_{rep}	0.00030	
Effect	-0.00004	0.00003	0.00016	0.00029	-0.00013	-0.00028	-0.00077		S_{effect}	0.00015	
| Effect |	0.00004	0.00003	0.00016	0.00029	0.00013	0.00028	0.00077				
Rank	6	7	4	2	5	3	1				

Figure 80.—Ruggedness example calculations
for initial loading strain at UCT, e_i, results.

Statistical Significance of Effects Example Calculations for e_i Results							
Rank	Factor	Effect	| Effect |	Student's *t*	| Student's *t* |	Two Tailed *p-value (%)*	Half-Normal Plotting Values
1	G	-0.00077	0.00077	-5.2107	5.2107	0.1238	1.803
2	D	0.00029	0.00029	1.9838	1.9838	8.7691	1.242
3	F	-0.00028	0.00028	-1.9131	1.9131	9.7315	0.921
4	C	0.00016	0.00016	1.0664	1.0664	32.1644	0.674
5	E	-0.00013	0.00013	-0.9031	0.9031	39.6486	0.464
6	A	-0.00004	0.00004	-0.2719	0.2719	79.3577	0.272
7	B	0.00003	0.00003	0.2062	0.2062	84.2499	0.090

Figure 81.—Factor rankings and calculated values
for effects on initial loading strain at UCT, e_i, results.

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