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Ruggedness Evaluation of ASTM International Standard Test Methods for Shape Memory Materials: E3098 Standard Test Method for Mechanical Uniaxial Pre-strain and Thermal Free Recovery of Shape Memory Alloys

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Summary

This paper evaluates the ruggedness testing of the recently released ASTM International E3098 Standard Test Method for Mechanical Uniaxial Pre-strain and Thermal Free Recovery of Shape Memory Alloys. The ruggedness experiment was designed with eight runs in two replicates, consisting of seven factors: 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 strain rate factor had no effect on any result variable, whereas the minimum load factor had a large effect on several result variables including the austenite start and martensite finish temperatures as well as most of the strain measurements from the thermal cycle. The lower cycle temperature factor had a large effect on the stress at maximum strain during pre-straining (e_i), denoted by S_i, at ~7.2 MPa, as well as the A_f, at 5.47 °C. Closely following the LCT effect, $\dot{T}_{heat}$ was found to have a large effect on the austenite start temperature (A_s), at a value of ~2.72 °C. The testing methodology, analysis techniques, and resulting conclusions on the ruggedness of the test method are presented.

1.0 Introduction

Shape memory alloy (SMA) actuator properties have been measured and reported for hundreds of alloy systems, though currently those properties are 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). CASMART is comprised of over 25 international industry, government, and university partners, each uniquely contributing to the advancement of SMA research and development. Several contributions flourished from this consortium and laid the groundwork for numerous 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 the prior work by CASMART 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 (UPFR) (Ref. 4), represent a critical step toward the commercialization and production of SMA actuators. While several other standards exist based on the superelastic response, developed primarily for the medical industry (Refs. 5 to 9), E3097 and E3098 represent the very first universally accepted standards that define procedures for measuring shape memory effect (SME) 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 the testing methods defined by the standard and ensuing significances each testing variable has on the results. 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 members' prior experiences to provide guidance and a starting point. Thus, the goal of this work is to perform ruggedness tests on the second test method (E3098, i.e., UPFR) by using controlled experiments in which factor parameters are deliberately varied. Before executing a larger interlaboratory study, the controlled experiments are performed, mainly to anticipate and/or eliminate potential sources of inaccuracy, as well as to determine the level of measured property variation due to the variations in the method parameters (aside from material or operator variations). 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 was 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 based on 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 E3098 test method are presented. The work reported here is limited to tests conducted at the NASA Glenn Research Center using round dog-bone specimens with threaded ends (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 threaded ends and reduced 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

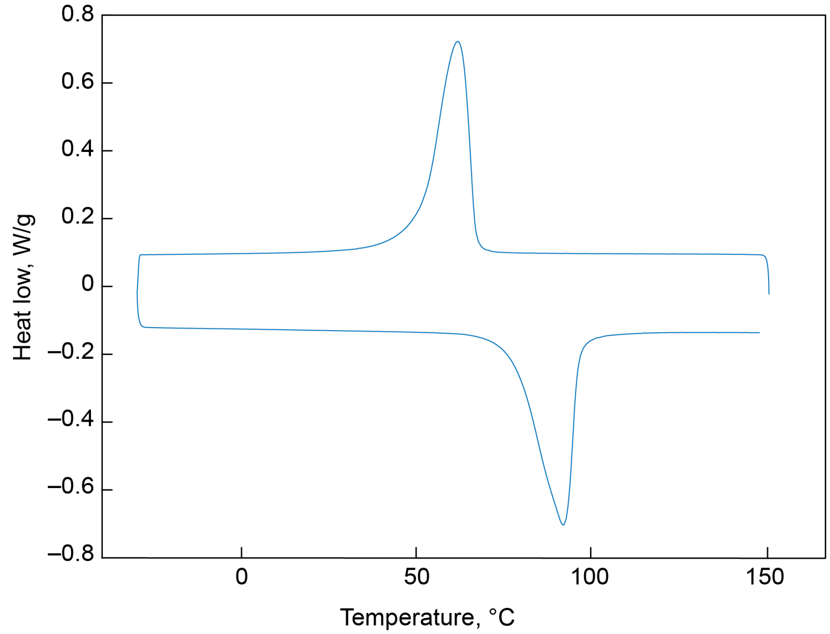


Figure 1.—Differential scanning calorimetry response of the 55.3Ni-44.7Ti wt% shape memory alloy tested.

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 UPFR test procedures outlined in the ASTM E3098 test method (Ref. 4) and only a summary is provided here. The initial step consists of a normalization phase where the specimen is mounted in the load frame at room temperature and force-controlled with a calculated stress 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*) at a rate that allows the gradient across the sample gage to be less than ±3 °C, and then held at this temperature and stress for a time sufficient to equilibrate both temperature and strain of the specimen and testing apparatus. 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 the normalization procedure, at *LCT*, the specimen should be at 10 °C or more below the martensitic finish temperature (M_f) or the temperature specified in the test plan or product specification to ensure it is fully martensitic. At this temperature, the specimen is strained at a suitable rate to the strain level specified in the test plan or product specification. The specimen is then unloaded to a stress of 7 MPa or less and held in force control to allow the strain and temperature to become equilibrated. While still controlling at this stress, the specimen is heated to its respective upper cycle temperature (*UCT*) and held for a defined hold time (t_{hold}). Finally, the specimen is cooled to its lower cycle temperature (*LCT*), capturing the specimen's related strain, stress, and temperature throughout. This procedure is schematically illustrated in Figure 2 along with the associated test result variables and in Figure 3, the thermal free recovery portion is shown to further illustrate the determination of transformation temperature via linear fitting of the data.

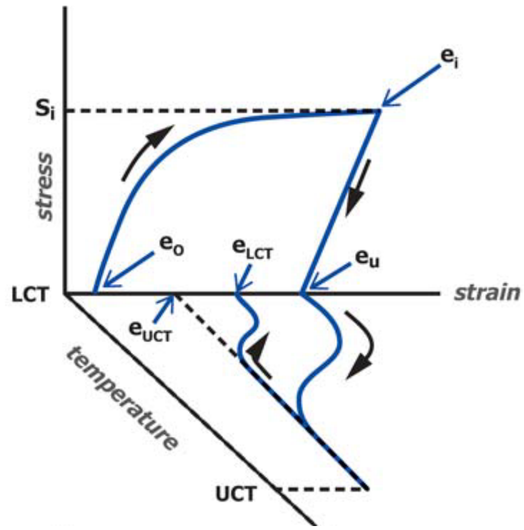


Figure 2.—Uniaxial pre-strain and thermal free recovery and associated test parameters (adopted from Ref. 4). For the thermal free recovery, LCT is the lower cycle temperature or minimum temperature of the thermal cycle and UCT is the upper cycle temperature or maximum temperature of the thermal cycle. Where e_0 is initial strain after normalizing prior to pre-straining, S_i is maximum stress at maximum loading strain (e_i), e_u is unloaded strain at lower cycle temperature after pre-straining and unloading but prior to heating, e_{UCT} is strain at the upper cycle temperature during the thermal free-recovery cycle, and e_{LCT} is strain at the lower cycle temperature.

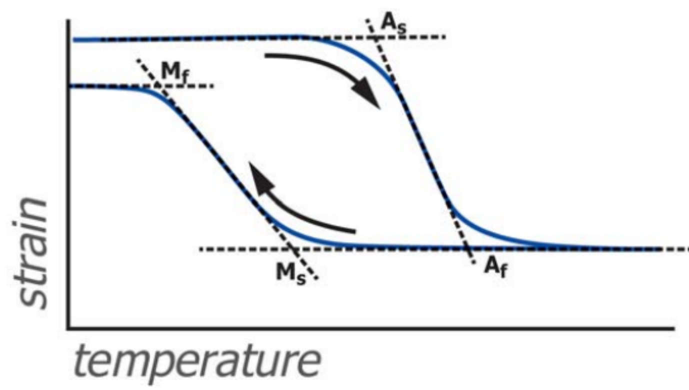


Figure 3.—Thermal free recovery cycle and associated test parameters after normalizing, and post pre-straining (load, unload steps) (adopted from Ref. 4). Where A_s is the austenite start temperature, A_f is the austenite finish temperature, M_s is the martensite start temperature, and M_f is the martensite finish 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 Settings						
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

2.4 Experiment Design

The fractional factorial test design and accompanying statistical analysis methods used were 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 and are modeled after the design table from ASTM E1169 (Ref. 10). The test factors that were expected to have the highest impact on the results are: $\dot{e}$, $\dot{T}_{heat}$, $\dot{T}_{cool}$, UCT, LCT, t_{hold}, and F_{min}. For each factor, the level settings, (–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.

3.0 Analysis Methods

All raw data files were analyzed and tabulated on a standardized format as defined by the AVSI team per ASTM E3098 (see Appendix B). These data sets were processed by a single analyst using NASA Glenn Research Center's SMA analyses tools based on tangent line fits, as partially outlined in References 4 and 11.

One critical note here is that although the test specimens subjected to this ruggedness evaluation were obtained from the same lot of material, significant variations were present in the behavior of the material during the isothermal loading and unloading as well as the heating and cooling cycles. As Figure 4 demonstrates, tests on two different samples subjected to the same test factor level settings (runs 2 and 10 from replicate 1 and 2, respectively) show significantly different behavior during the transformation portion of the heating cycle. The most likely causes of the differences in transformation behavior are sample inhomogeneity or texture, or multiaxiality of the stress due to an unintended torque on the sample threads during loading. Regardless of the cause, the differences in transformation behavior require a variation in analysis technique. For a single stage transformation (such as with run 2), a conventional single fit line for the transformation region is typically sufficient (Figure 4(a)). However, for a multi-stage transformation (as seen in run 10), a single fit line, whether averaged (Figure 4(b)), or aligned with the region of maximum slope (Figure 4(c)), does not provide a completely accurate representation of the transformation. When using an averaged fit (Figure 4(b)), the misalignment between the fit line and the

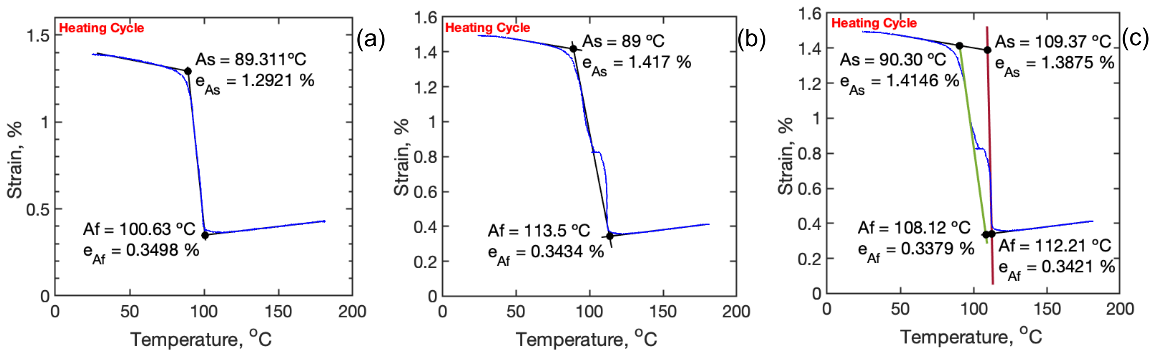


Figure 4.—Heating curves of runs 2 (a) and 10 (b,c), illustrating effect of material variation on behavior and subsequent transformation temperature fit line strategy. (a) single stage transformation with standard fit of transformation region, (b) multistage transformation with "averaged" fit of the transformation region, and (c) multistage transformation with separate fits of lower and upper transformation segments.

multiple transformation slopes can lead to over/under estimation of the transformation temperatures. Fitting to the highest slope in a curve with multiple transformation regions provides a good fit for the near transformation temperature, but in this case, could lead to a 20 °C discrepancy in the other transformation temperature (Figure 4(c)). Therefore, for many of the runs processed for this study, transformation temperatures were determined through the combination of fitting a "lower transformation fit" of the transformation region for A_s and M_f and an "upper transformation fit" for A_f and M_s, as shown in Figure 4(c).

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 statistically significant influence. Referring 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:

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

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 standard deviation 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_s. In this particular example, the standard deviation of the differences, s_d, is calculated as STDEV(1.070, 1.091, –1.755, –1.026, –0.507, –0.187, –0.912, –1.123) = 1.03170.

TABLE II.—RUGGEDNESS EXAMPLE CALCULATIONS FOR AUSTENITE START, A_s, 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	89.241	90.311	89.776	1.070
2	–1	+1	+1	+1	–1	+1	–1	89.212	90.303	89.758	1.091
3	–1	–1	+1	+1	+1	–1	+1	92.678	90.923	91.801	–1.755
4	+1	–1	–1	+1	+1	+1	–1	86.284	85.258	85.771	–1.026
5	–1	+1	–1	–1	+1	+1	+1	89.500	88.993	89.247	–0.507
6	+1	–1	+1	–1	–1	+1	+1	92.846	92.659	92.753	–0.187
7	+1	+1	–1	+1	–1	–1	+1	90.313	89.401	89.857	–0.912
8	–1	–1	–1	–1	–1	–1	–1	88.879	87.756	88.318	–1.123
+1 average	89.539	89.659	91.022	89.297	89.149	89.382	90.914	STDEV[a] of differences between replicates 1 and 2, s_d			1.03170
–1 average	89.781	89.660	88.298	90.023	90.171	89.938	88.406	Estimated STDEV of test results, s_{rep}			0.72952
Effect	–0.2414	–0.0011	2.7236	–0.7266	–1.0226	–0.5559	2.5086	Standard error of an effect, S_{effect}			0.36476

[a]Standard deviation.

TABLE III.—FACTOR RANKINGS AND CALCULATED VALUES FOR EFFECTS ON AUSTENITE START, A_s

Factor ranking	Factor	Effect	Student's *t*-value[a]	*p-value*,[b] percent	Half-normal plotting values (Ref. 10)
1	C	2.724	7.467	0.014	1.803
2	G	2.509	6.877	0.024	1.242
3	E	–1.023	–2.804	2.637	0.921
4	D	–0.727	–1.992	8.664	0.674
5	F	–0.556	–1.524	17.133	0.464
6	A	–0.241	–0.662	52.915	0.272
7	B	–0.001	–0.003	99.769	0.090

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

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.

Also reported in Table III are the student's *t*-values (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

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

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

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

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 replicate 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_s is shown in Figure 5. 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 influence 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 5).

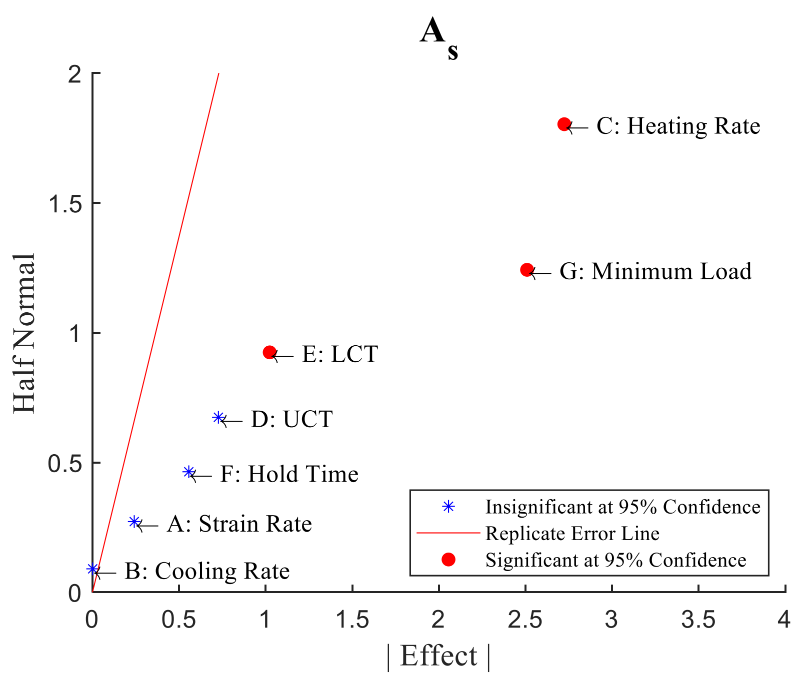


Figure 5.—Example half-normal plot with t-test results corresponding to result variable A_s (austenite start), for factors of A: strain rate, B: cooling rate, C: heating rate, D: upper cycle temperature (*UCT*), E: lower cycle temperature (*LCT*), F: hold time, and G: minimum load.

4.0 Results

4.1 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 pre-strain and recovery response. Although this is not part of the referenced standard, gaining familiarity through these initial baseline tests can better guide the experimental design. Figure 6 illustrates three test results obtained by straining samples to 1, 2, and 3 percent, unloading, and thermal cycling for recovery. It is apparent that the magnitude of the unloaded strain increases with the amount of pre-strain. Also, it can be seen that the transformation temperatures and the recovery strain increase with increasing pre-strain. A pre-strain of 3 percent results in a residual strain of approximately 0.5 percent while a pre-strain of 1 percent results in a lower residual strain below 0.1 percent. From these tests, a moderate pre-strain level of 2 percent was adopted for the ruggedness evaluation presented in this work.

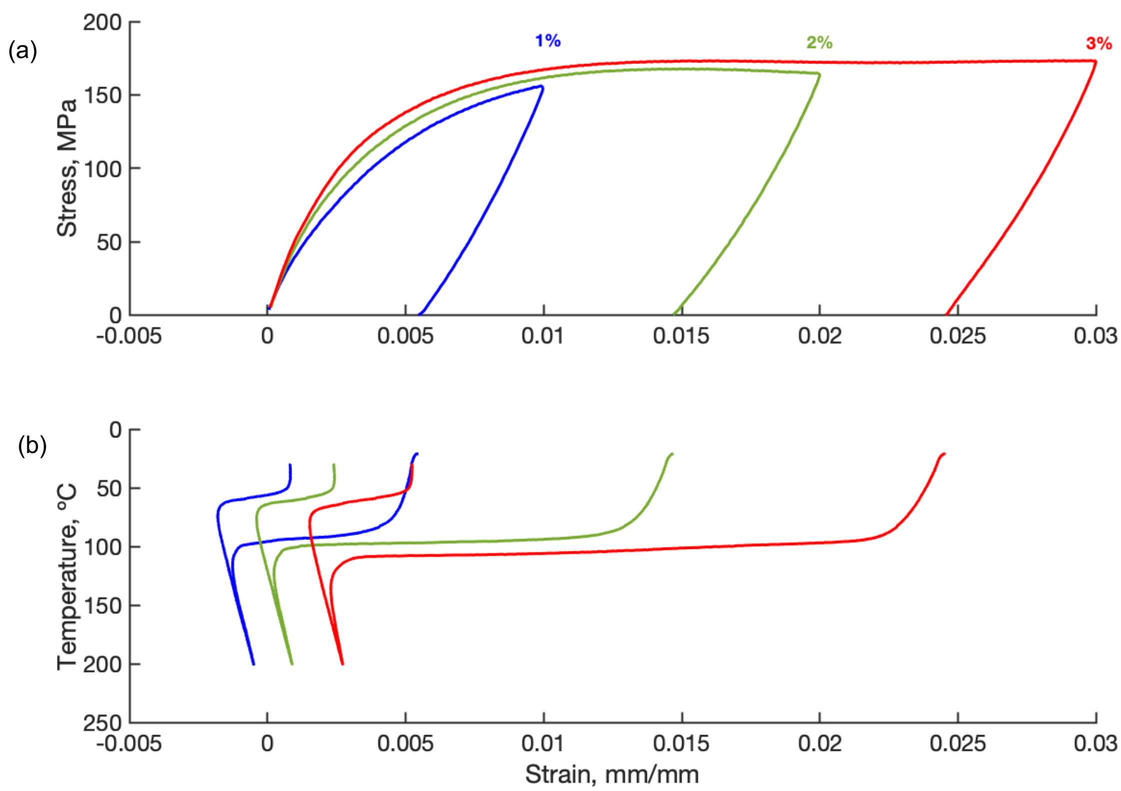


Figure 6.—Uniaxial pre-strain and thermal free recovery trials to different pre-strain levels, with (a) loading and unloading (pre-strain) portion of the test, and (b) thermal cycle portion for recovery.

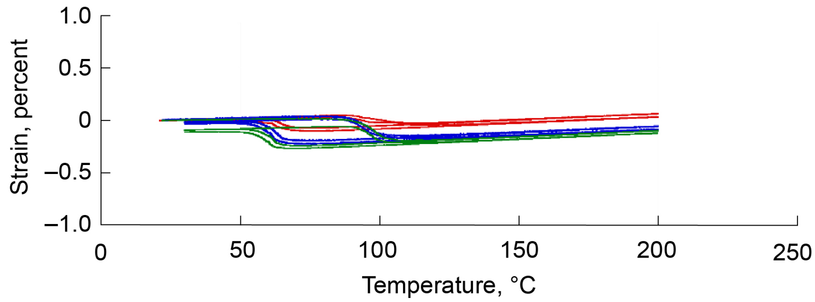


Figure 7.—Example normalization test for three different runs while holding stress at ~0 MPa.

The normalization test, which is conducted while holding a minimum load not to exceed 7 MPa, is shown in Figure 7. Although the stress here is kept at approximately 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).

4.2 Experiment Factor Verification

Several runs were analyzed to ensure that the seven factors used were properly maintained at their specific levels since evaluation of ruggedness is contingent on selected experimental factors varying only between the two settings selected. 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 8 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 corresponded to the required value of 0.001 mm/mm/min. As can be seen, strain rate data for all runs match the required values closely.

Figure 9 shows the cooling and heating rates used in these tests. 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.

Figure 10 shows the validation of the *LCT*, *UCT*, and hold times for several runs to better depict the differences between the upper and lower settings. Because the *LCT* was only slightly above room temperature, and induction was used for the heating method, a control algorithm was written which would cycle the induction unit on and off to maintain the sample at the *LCT* during the pre-strain, unload, and hold segments. It can be seen in Figure 10(a) that the *LCT* was successfully maintained within a ±1 °C variation from the target temperature. Once the sample was pre-strained and unloaded, it was maintained at the *LCT* for an additional 30 or 600 s as indicated by the vertical lines. The *UCT* and hold at *UCT* are shown in Figure 10(b) with the hold times depicted by the vertical lines. For all runs, *UCT* and *LCT* and the hold times were observed to match the required values, and temperature uniformity was maintained during the hold times, to within a reasonable tolerance of ±1 °C.

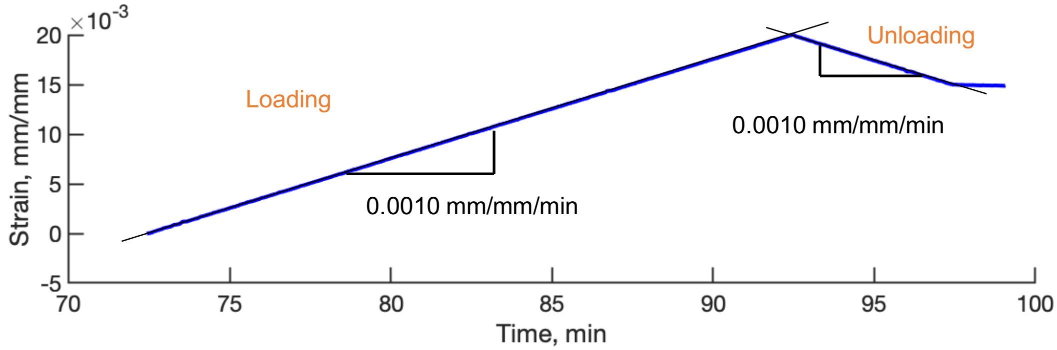


Figure 8.—Strain rate verification: strain versus time corresponding to run 3.

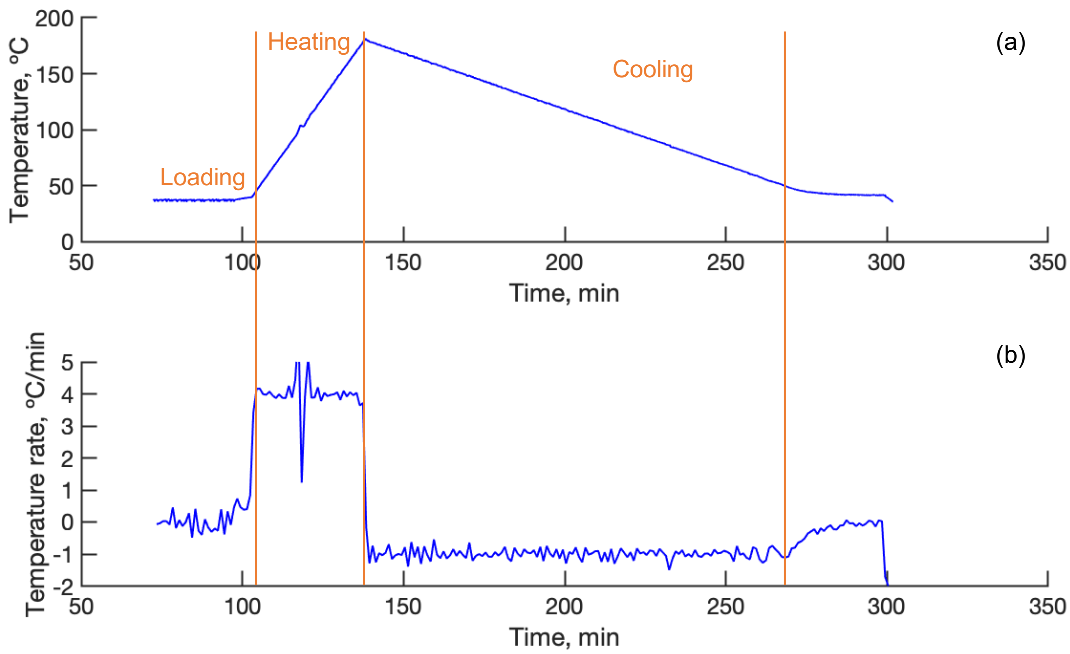
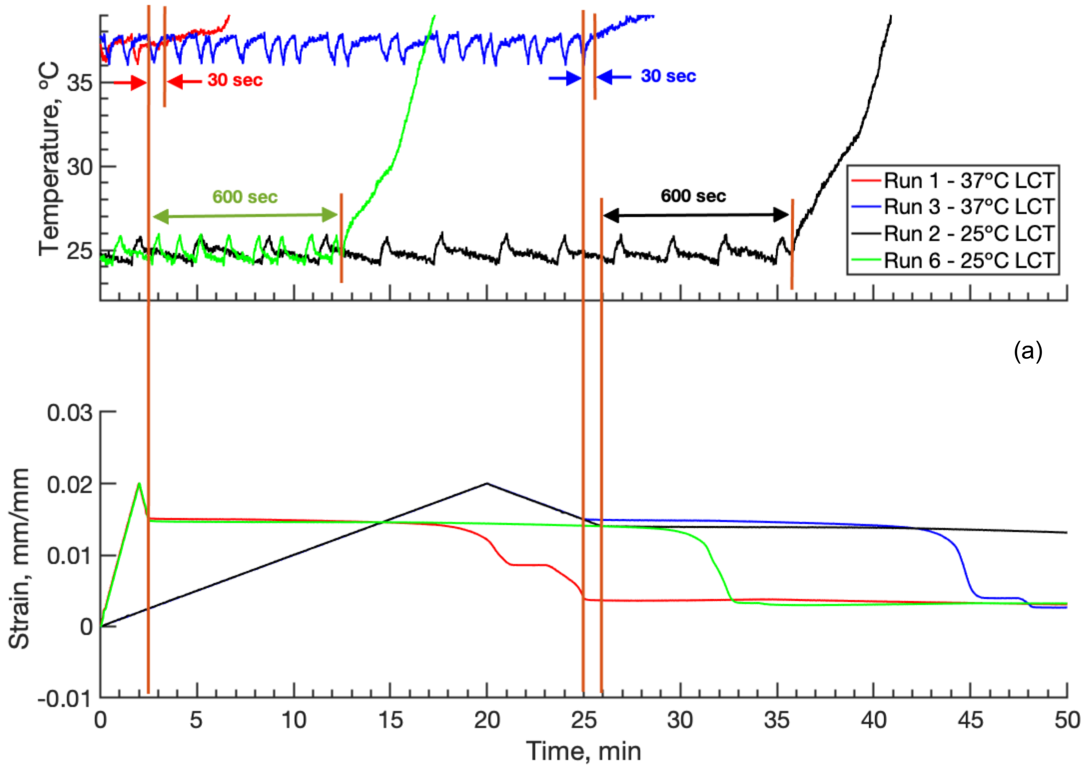


Figure 9.—Cooling and heating rate verification. (a) Temperature versus time. (b) Temperature rate versus time corresponding to run 3.



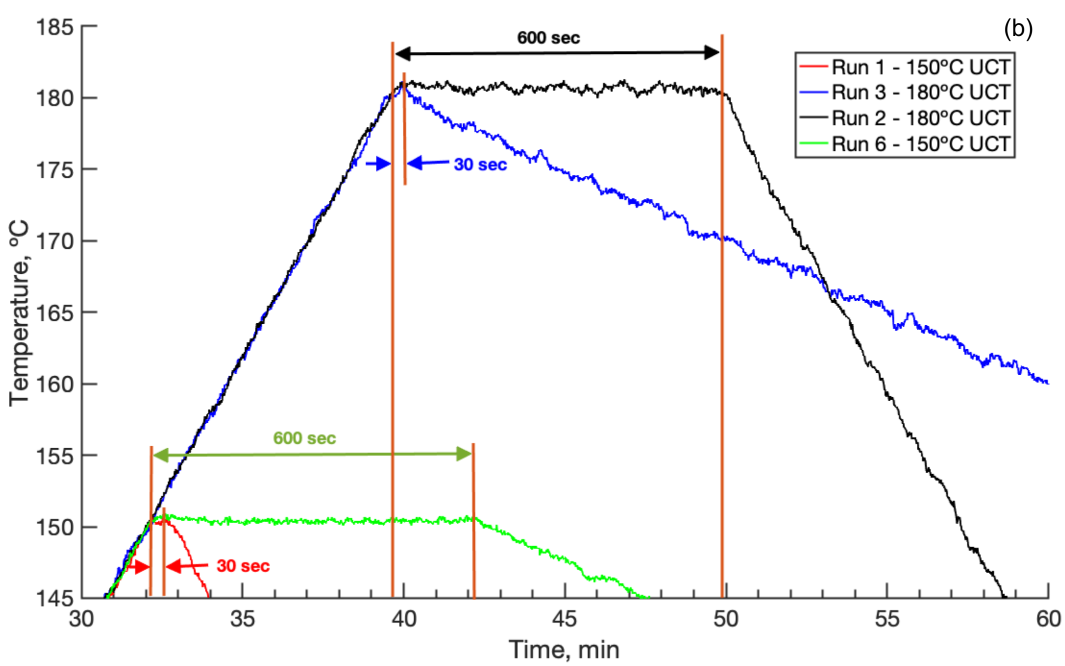


Figure 10.—Sample temperature versus hold time, *LCT*, and *UCT* verification. Vertical bars indicate 30-s and 600-s hold periods. (a) Lower cycle temperature. (b) Upper cycle temperature.

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 (17 in total, Figure 11 to Figure 27) 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.

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.

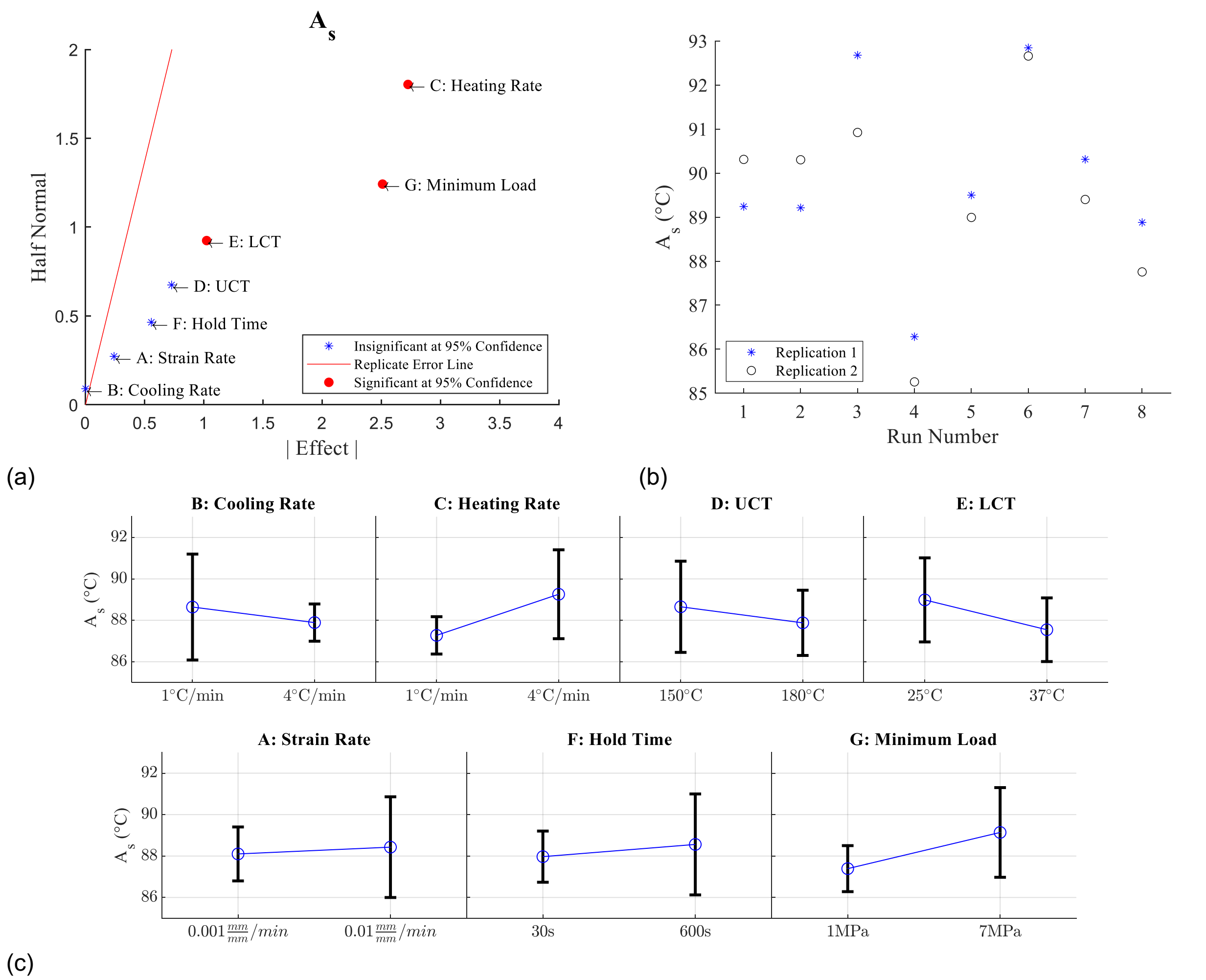


Figure 11.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low-and high-level settings for austenite start, A_s. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper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

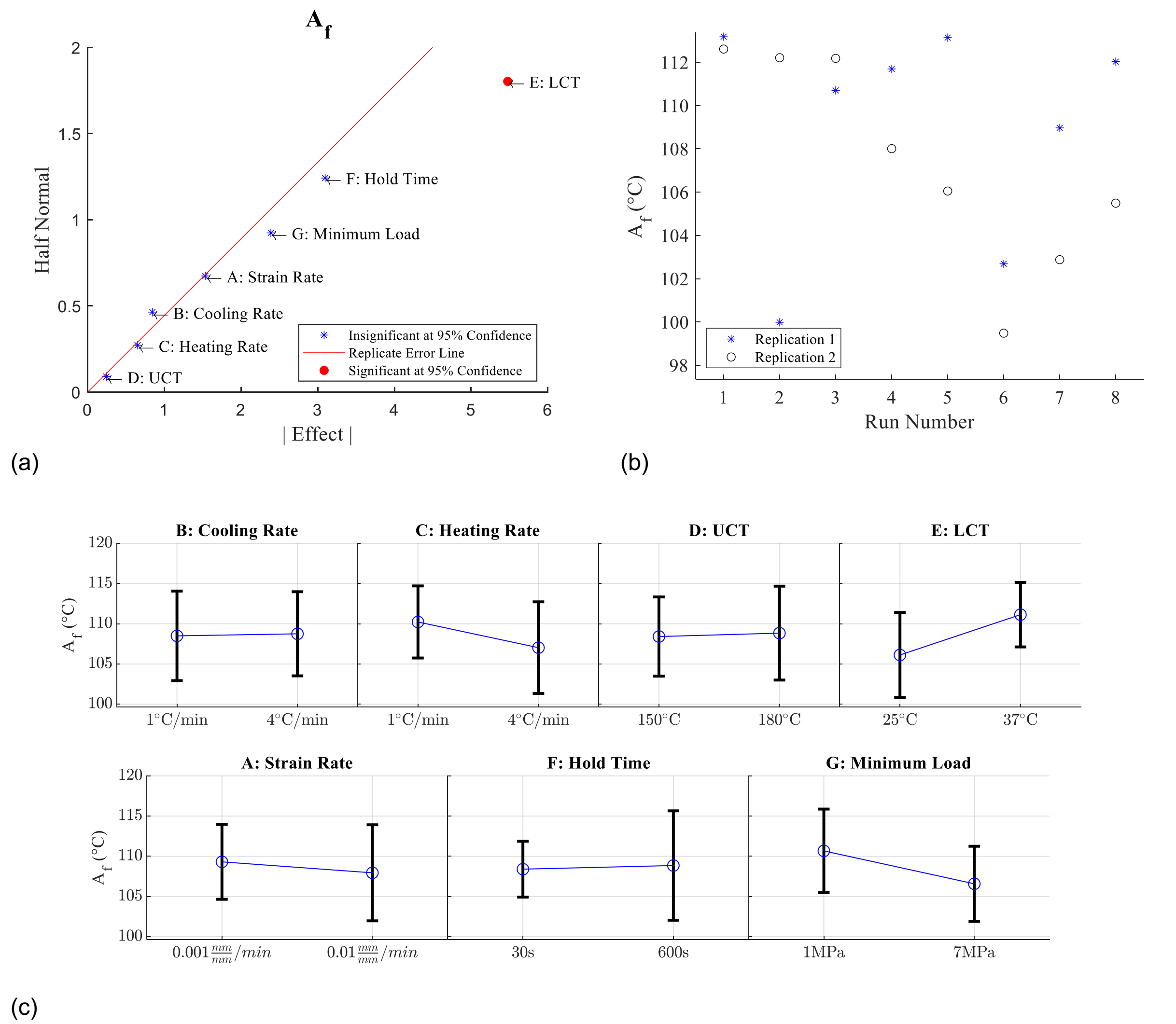


Figure 12.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low-and high-level settings for austenite finish, A_f. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper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

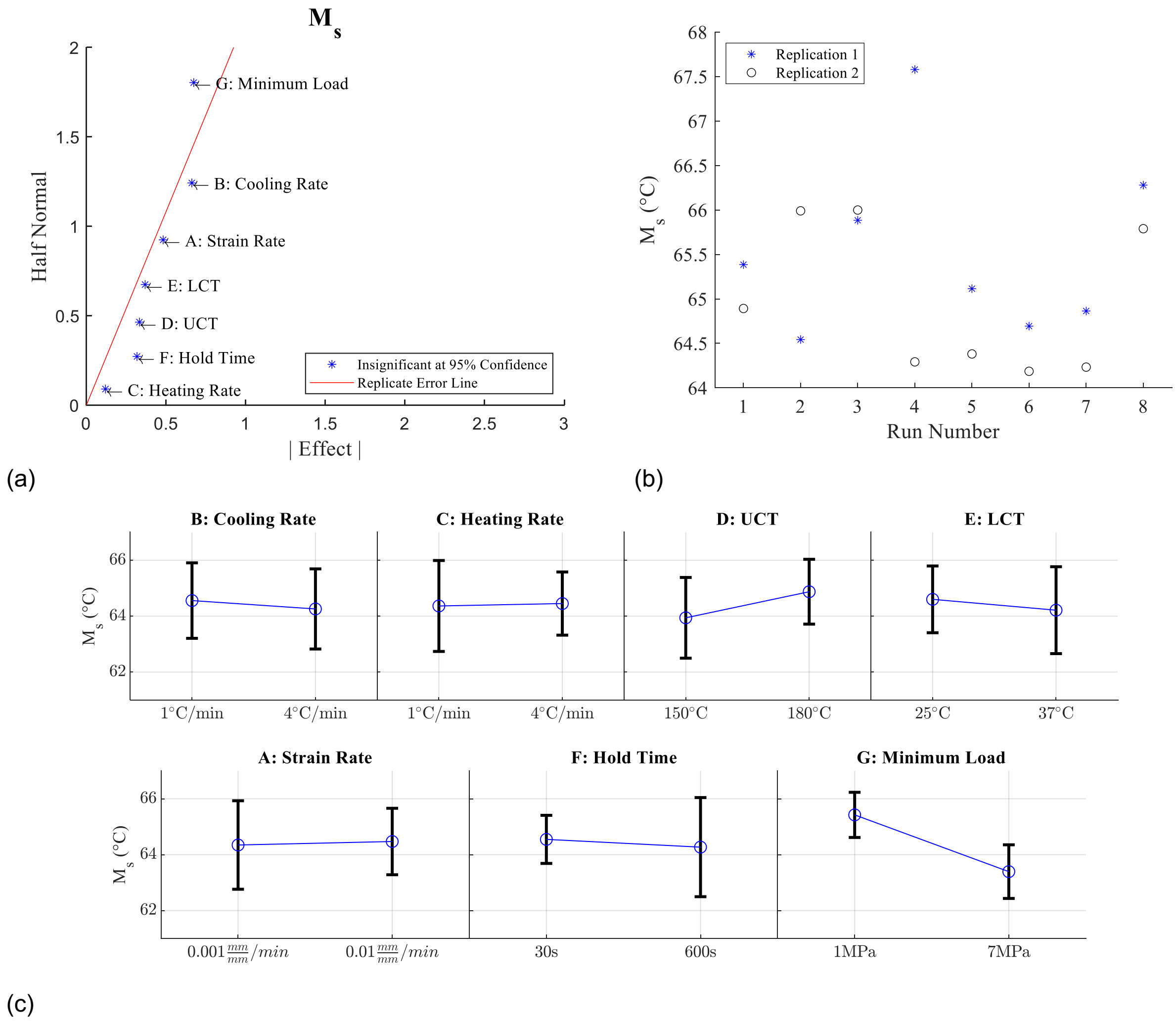
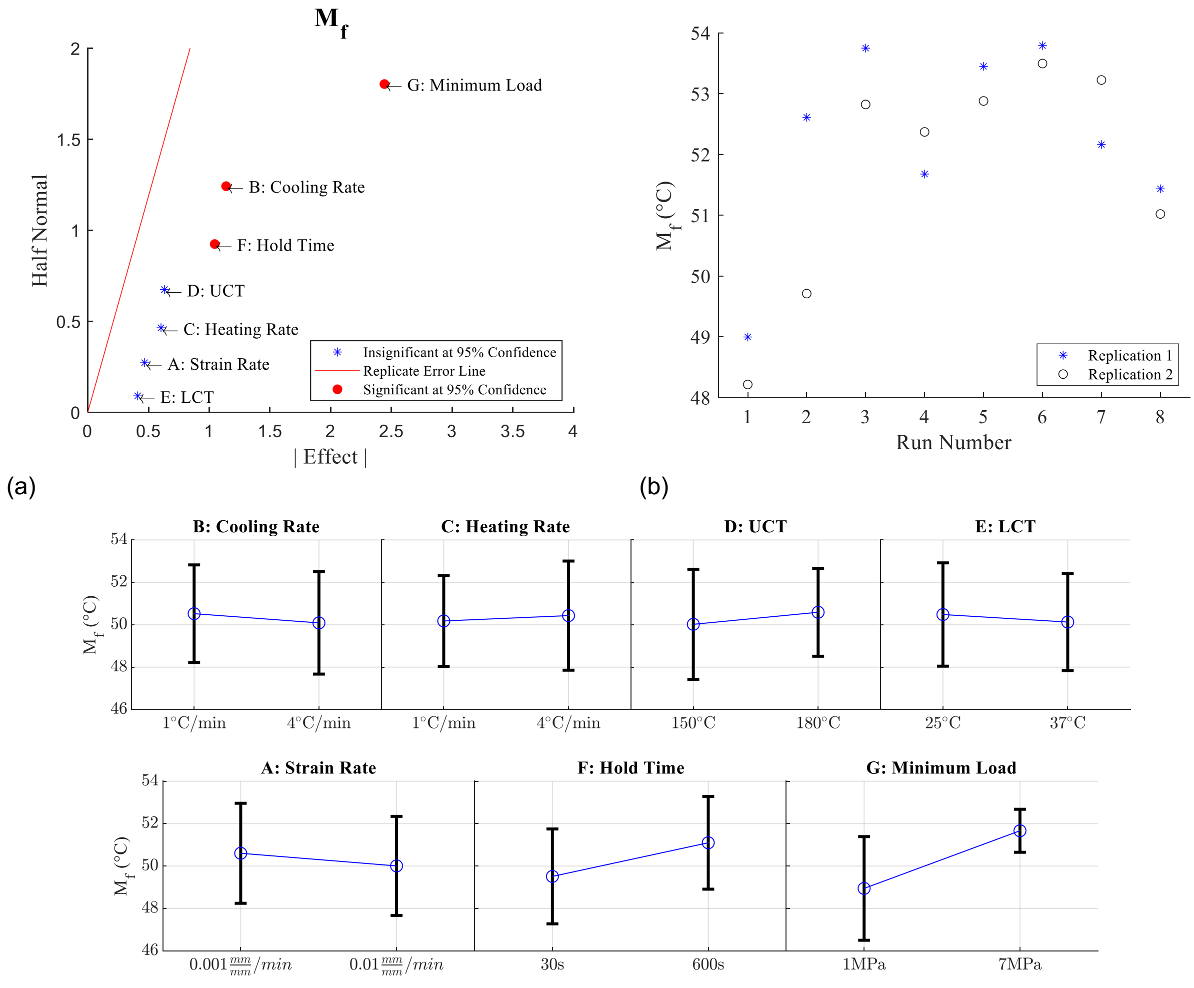


Figure 13.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low-and high-level settings for martensite start, M_s. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, upper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



(c)

Figure 14.—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.

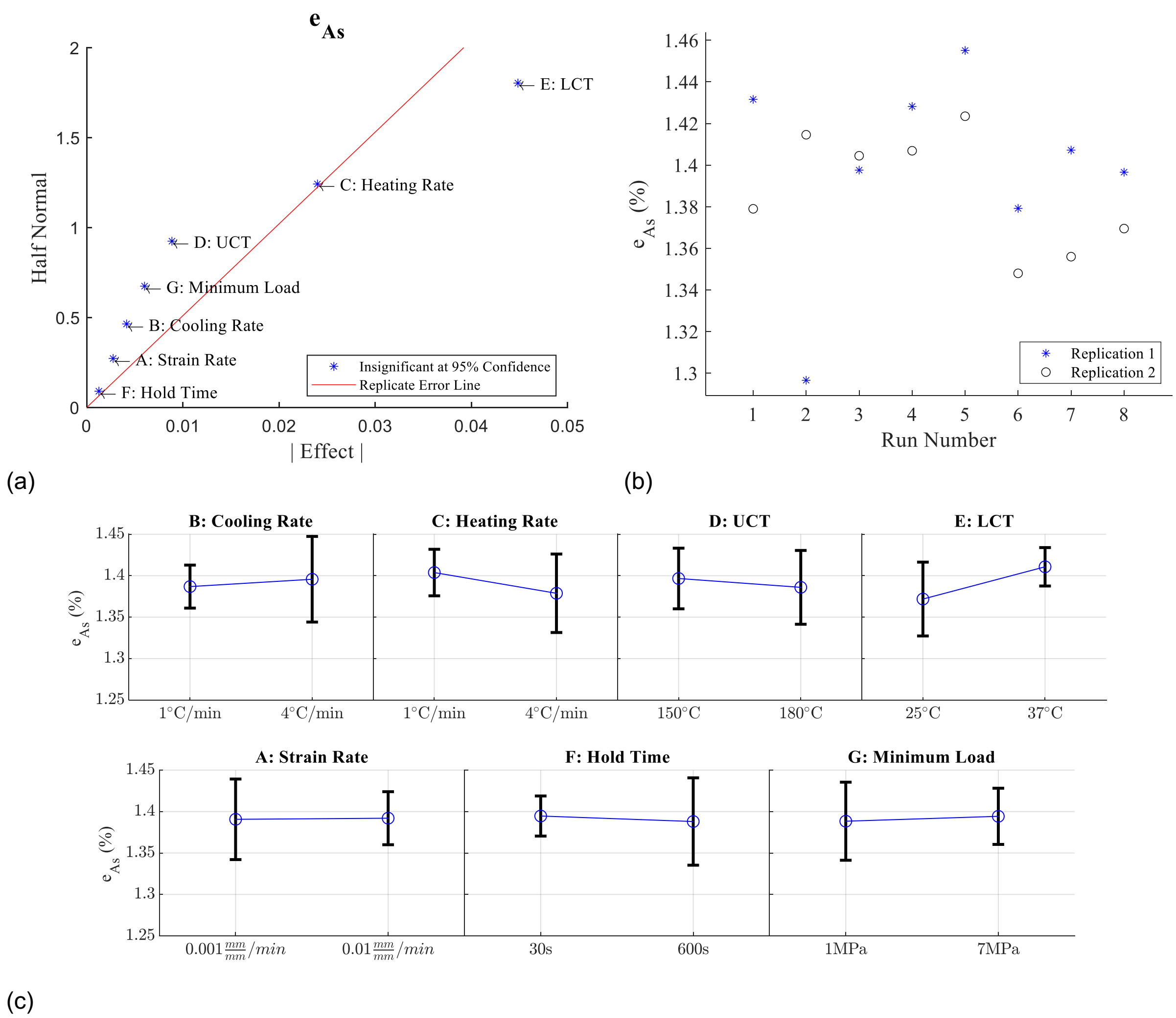


Figure 15.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low-and high-level settings for strain at austenite start temperature (fit line intersection point), e_{As}. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, 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.

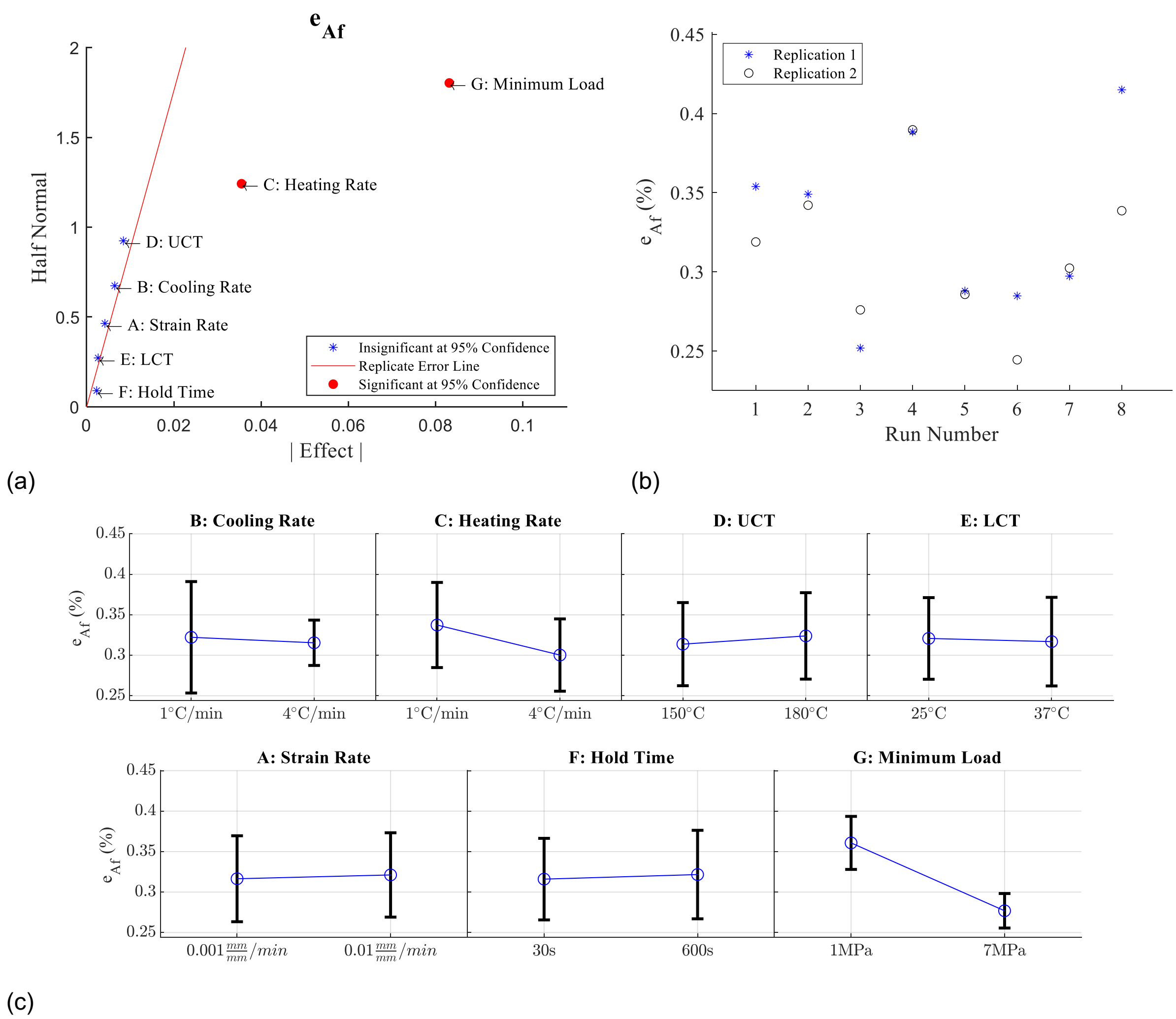
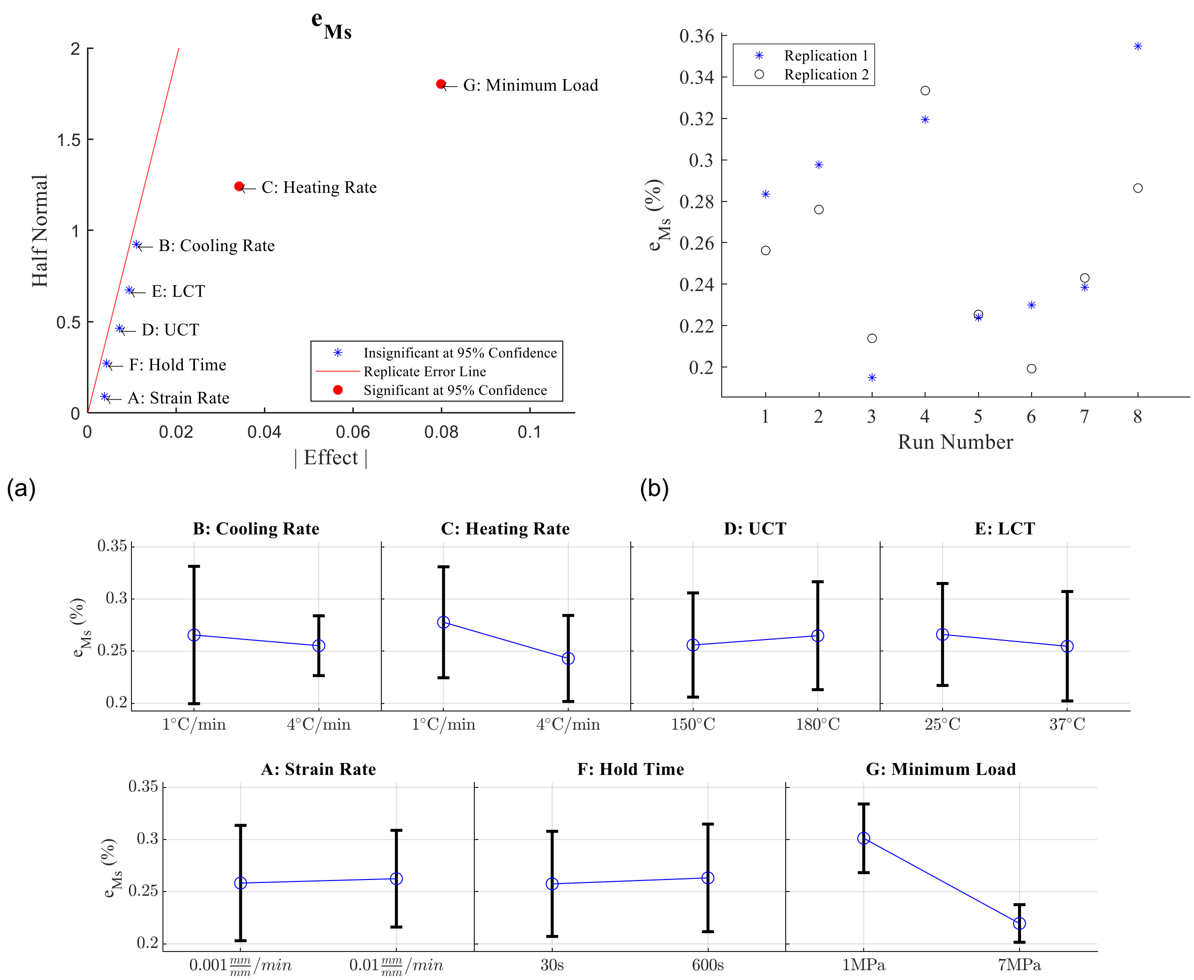


Figure 16.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low-and high-level settings for strain at austenite finish temperature (fit line intersection point), e_{Af}. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, 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.



(c)

Figure 17.—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.

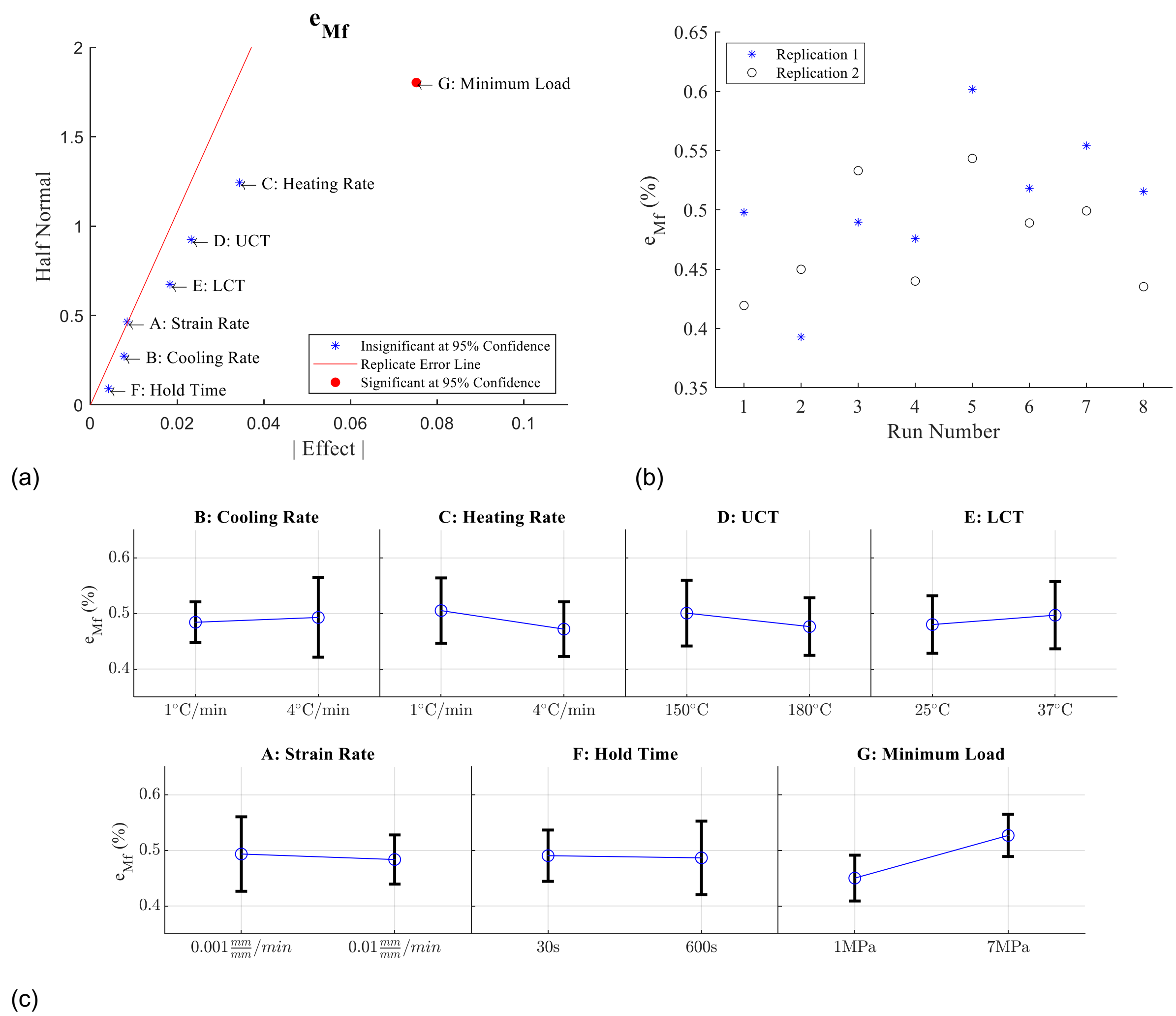


Figure 18.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low-and high-level settings for strain at martensite finish temperature (fit line intersection point), e_{Mf}. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for 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.

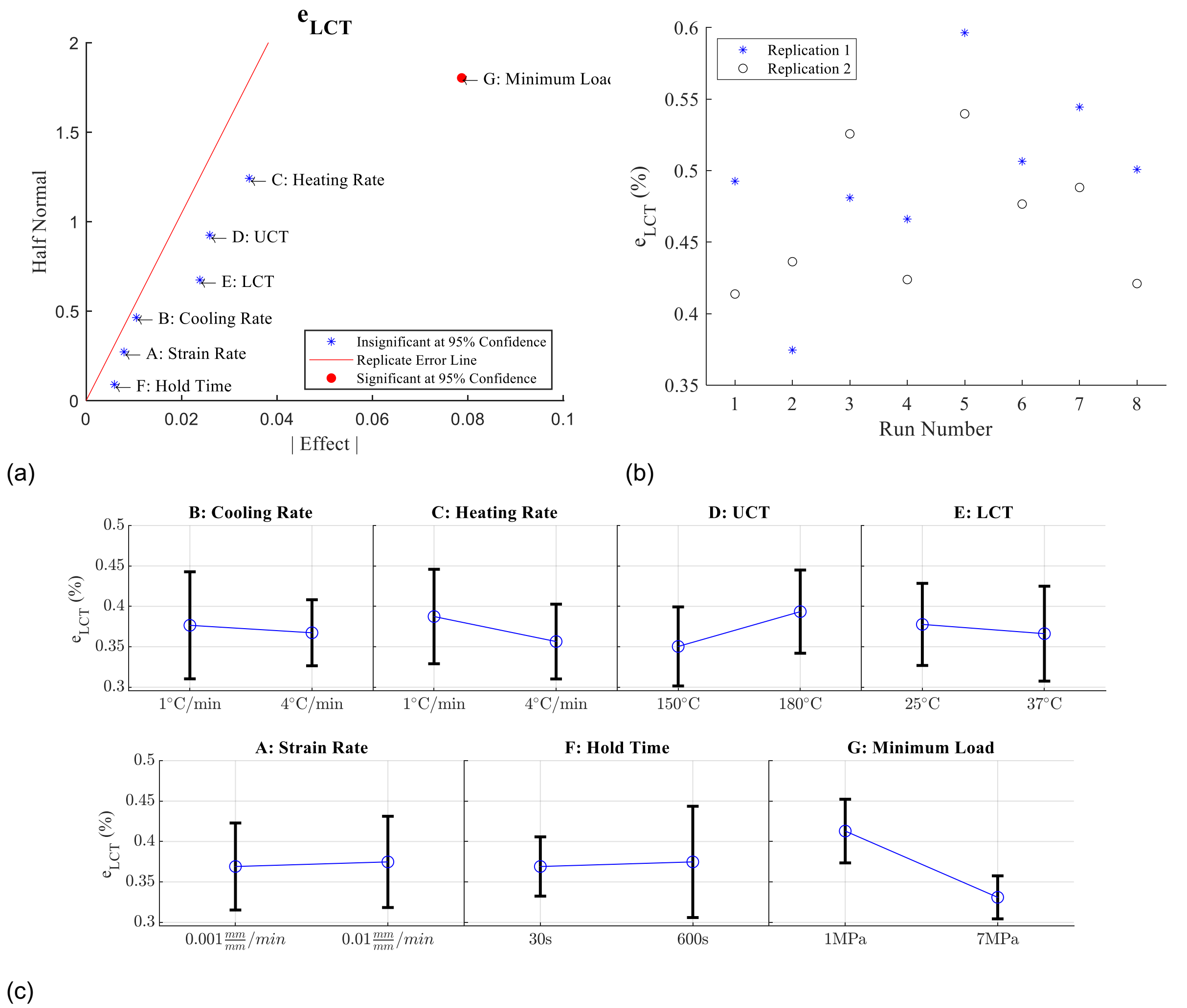
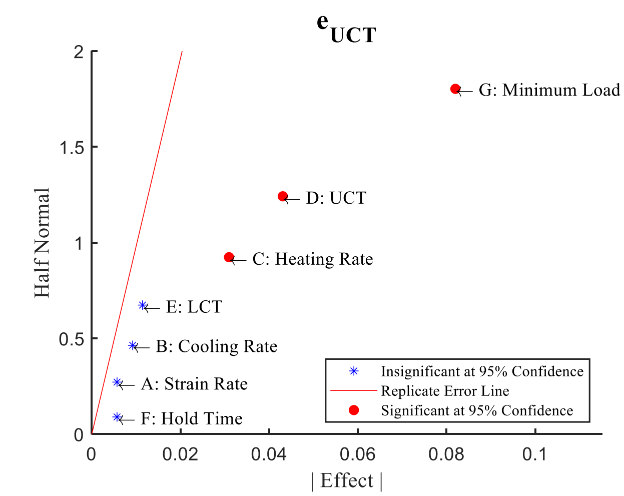
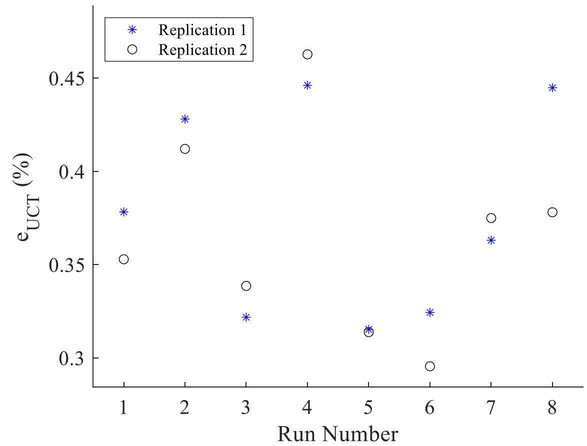
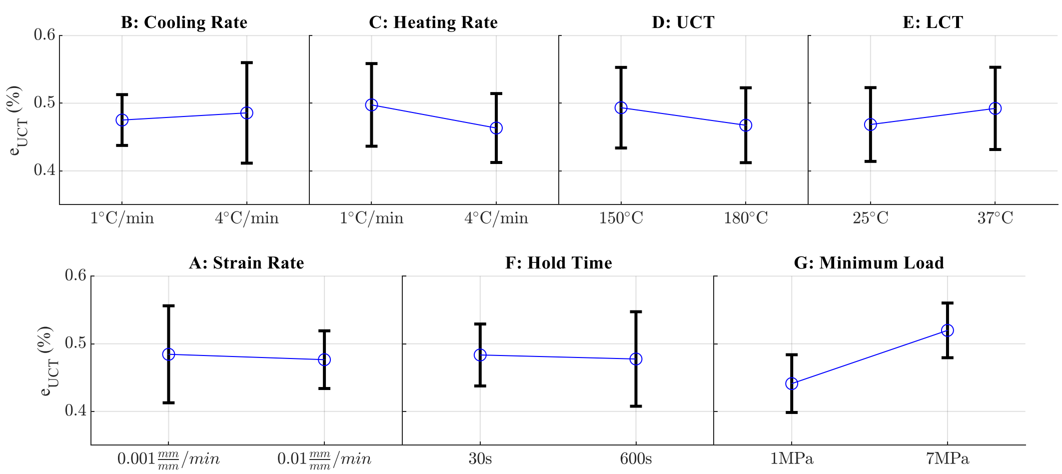


Figure 19.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low-and high-level settings for strain at lower cycle temperature (after full thermal cycle under no load/minimum load), e_{LCT}. (a) Half-normal plot. (b) Function of run number for two replicates. (c) 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.





(a) (b)



(c)

Figure 20.—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 heating under no-load/minimum 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.

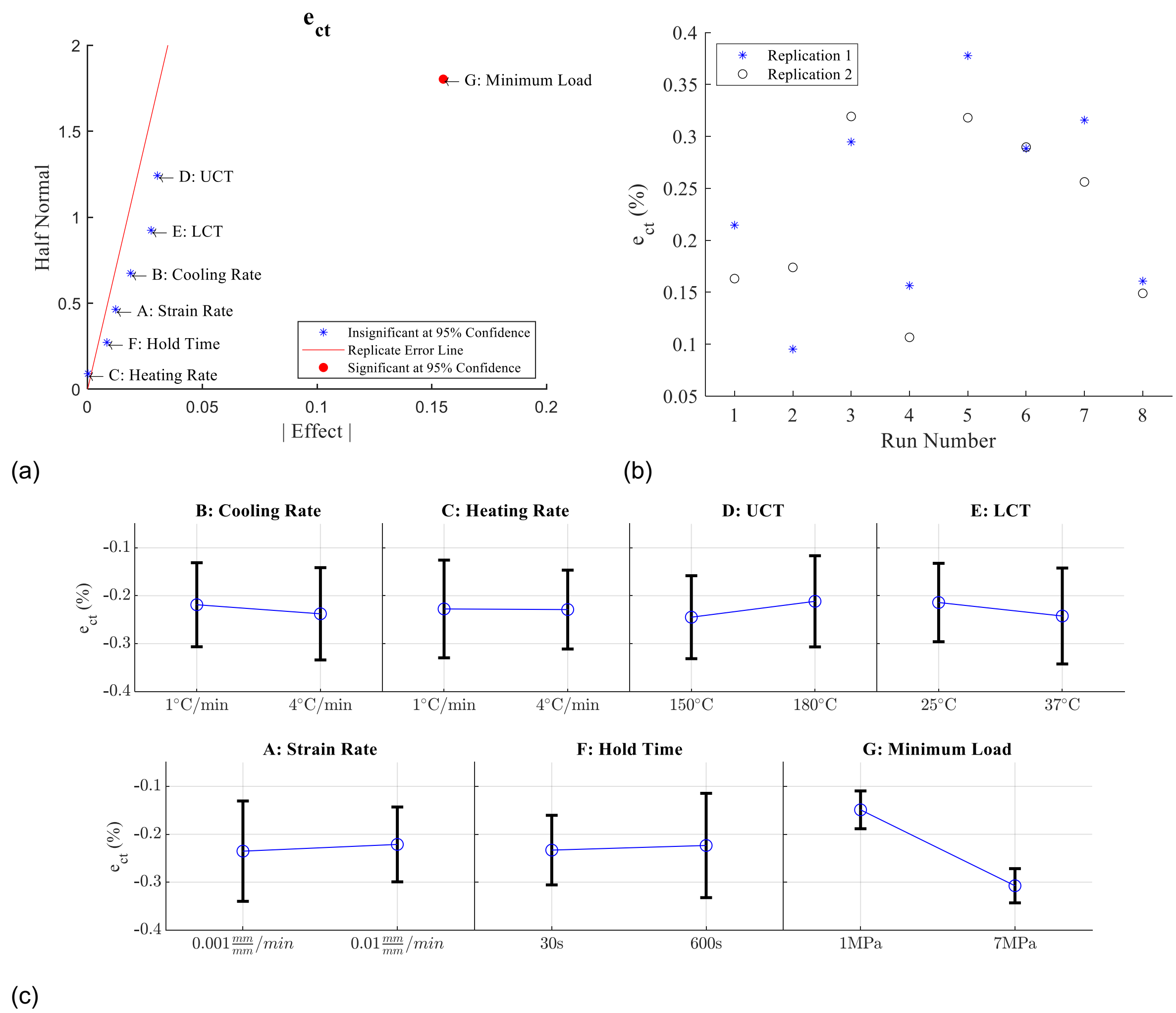
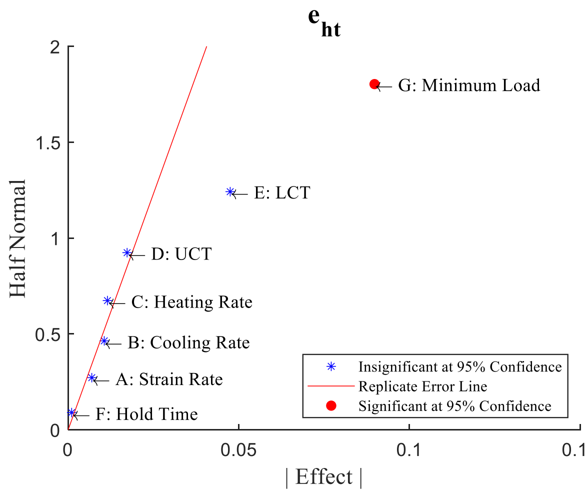
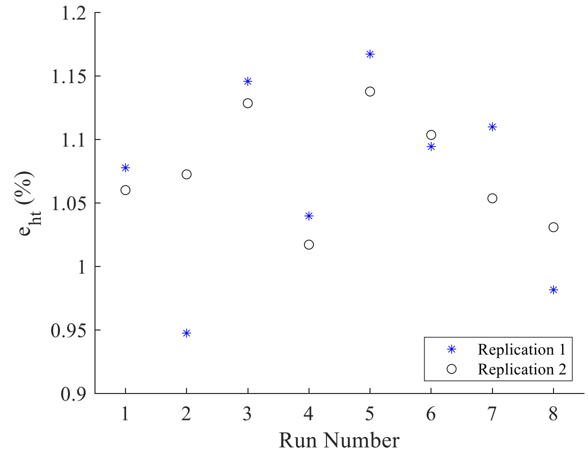


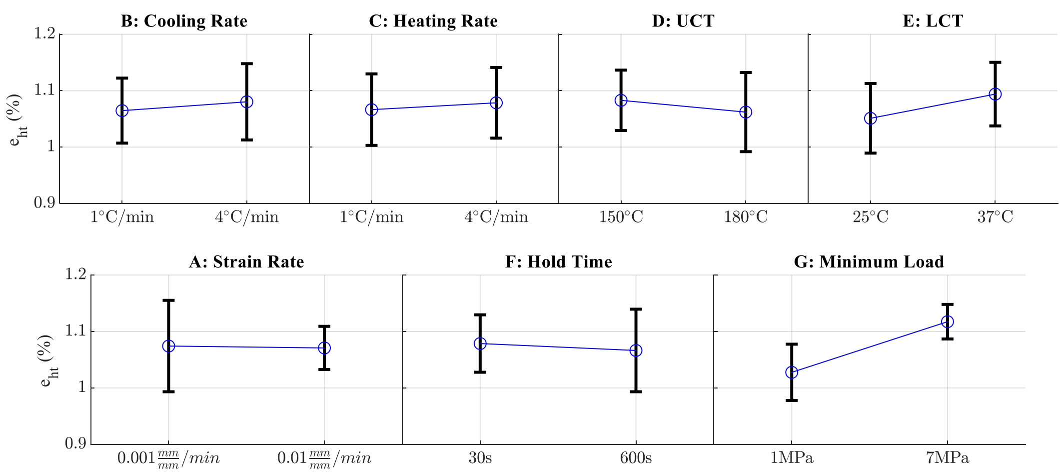
Figure 21.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low-and high-level settings for cooling transformation strain, e_{ct}. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating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



(a)



(b)



(c)

Figure 22.—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.

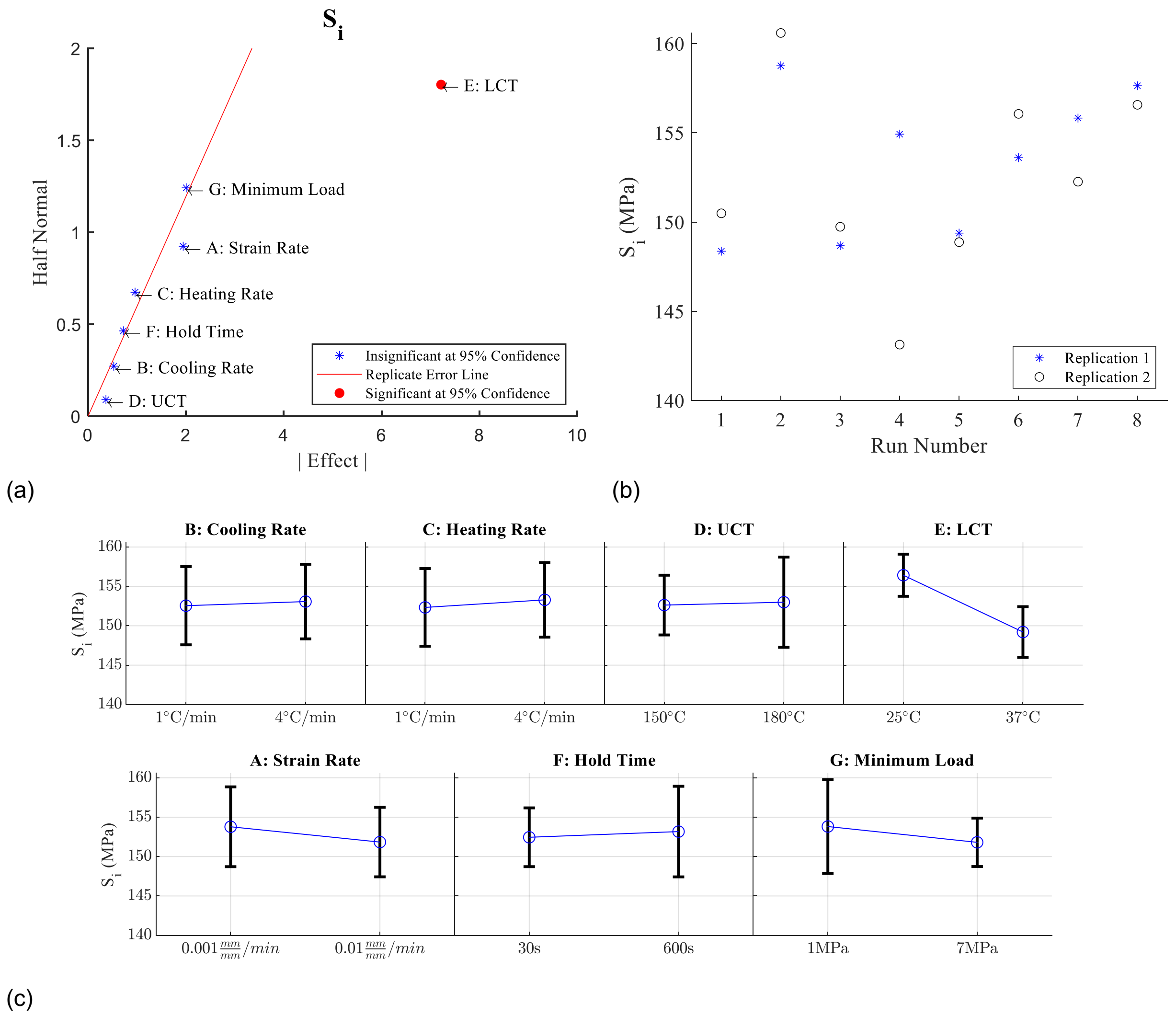
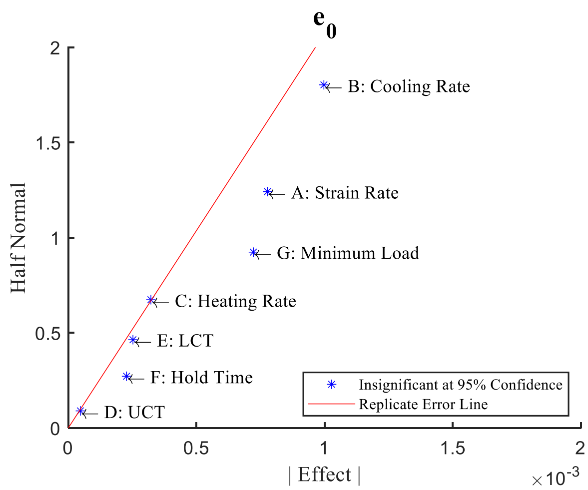
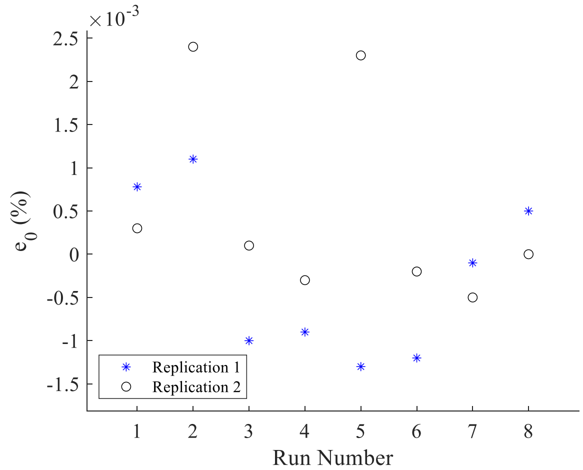


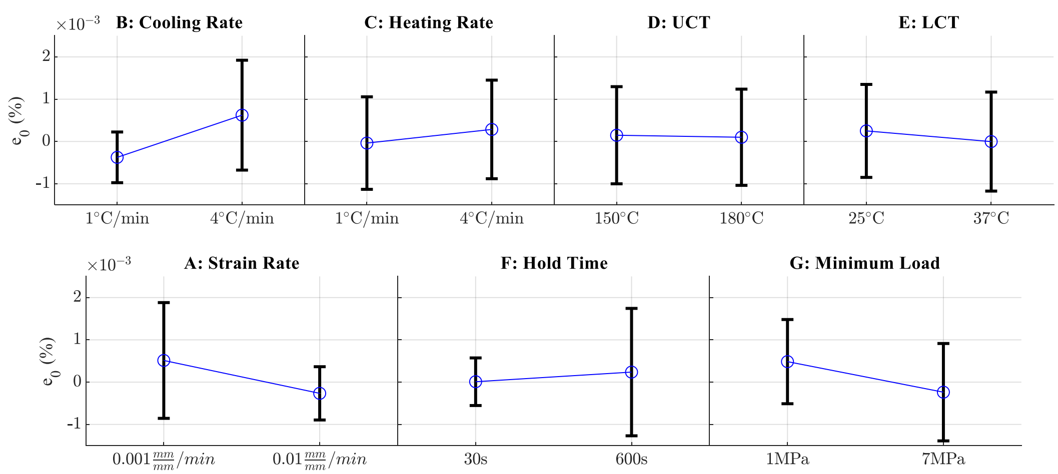
Figure 23.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low-and high-level settings for stress at maximum strain during pre-straining (e_i), S_i. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, UCT; E, lower cycle temperature (LCT); F, hold time; and G, minimum load.



(a)

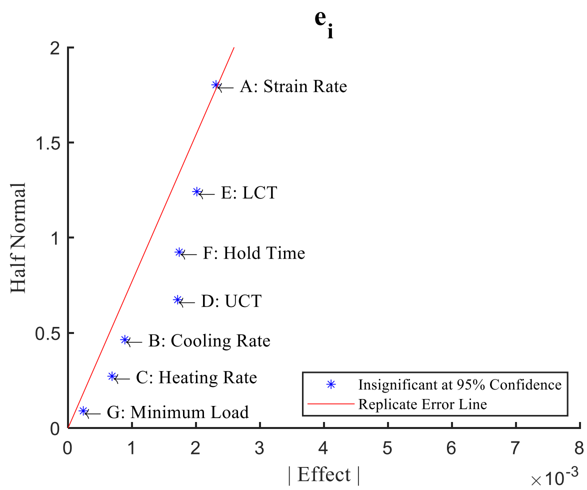


(b)

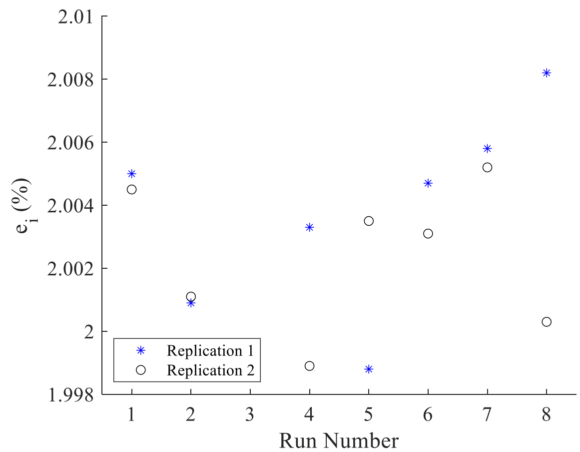


(c)

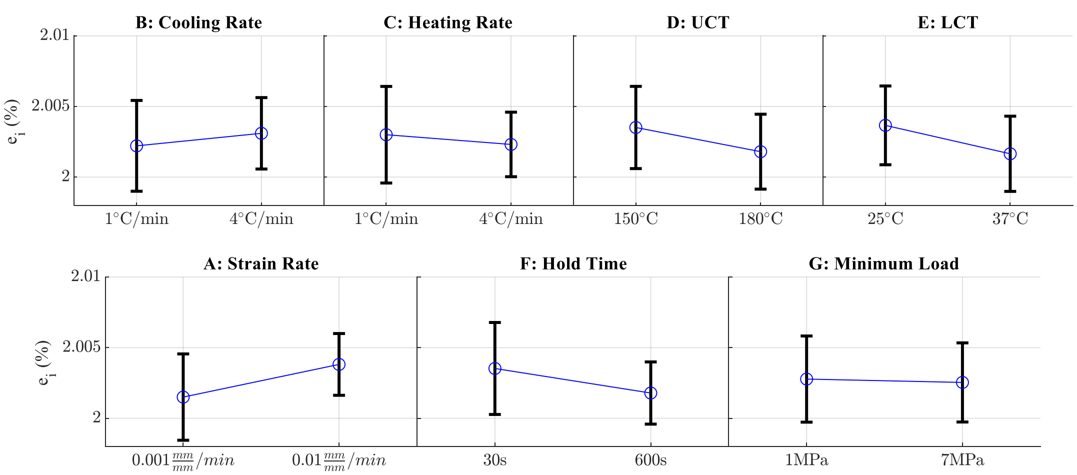
Figure 24.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for initial loading strain at lower cycle temperature (*LCT*), e_0. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D, *UCT*; E, lower cycle temperature (*LCT*); F, hold time; and G, minimum load.



(a)



(b)



(c)

Figure 25.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for maximum loading strain, 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.

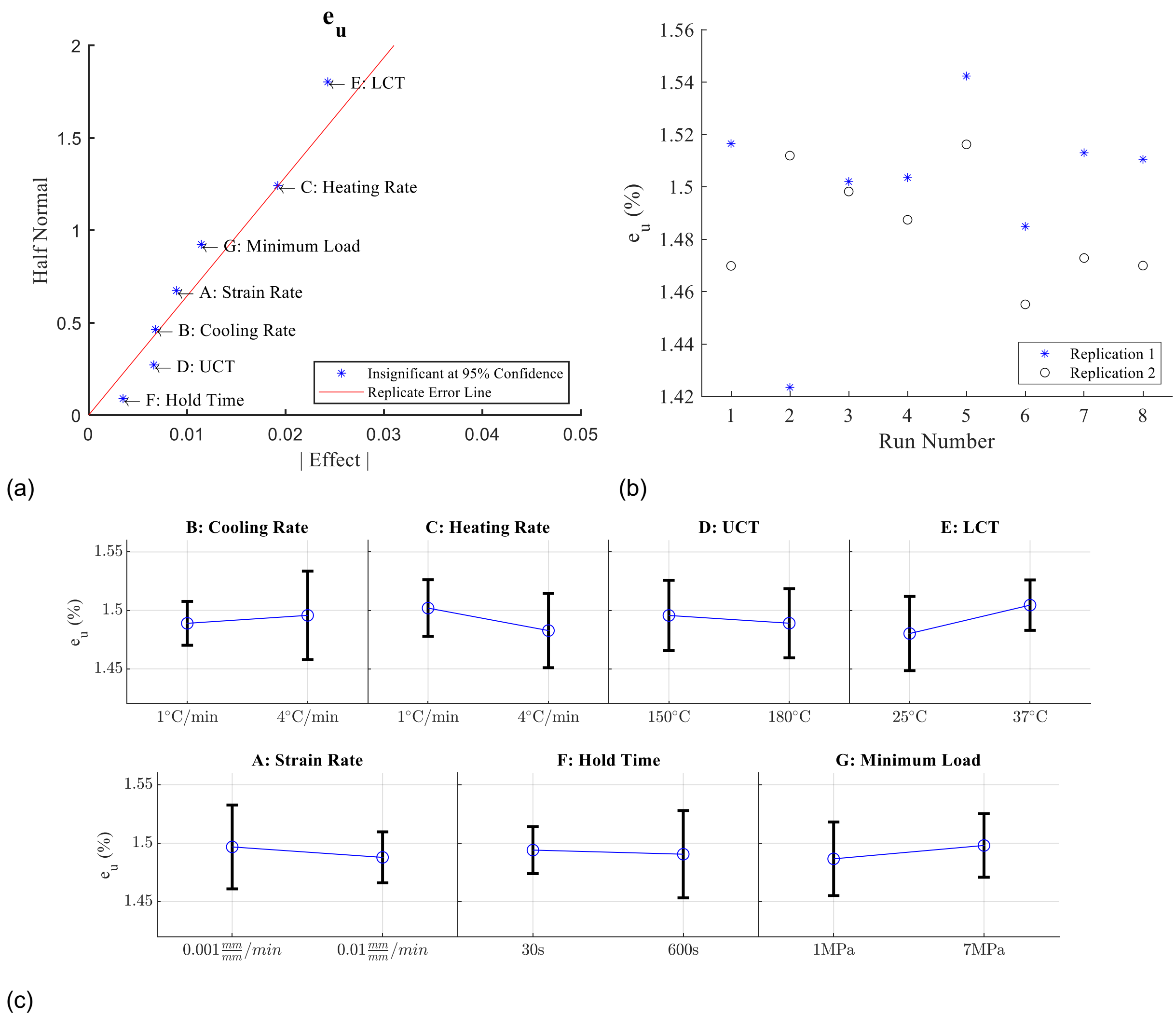


Figure 26.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low- and high-level settings for unloaded strain at lower cycle temperature (*LCT*) after pre-straining and unloading but prior to heating, e_u. (a) Half-normal plot. (b) Function of run number for two replicates. (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.

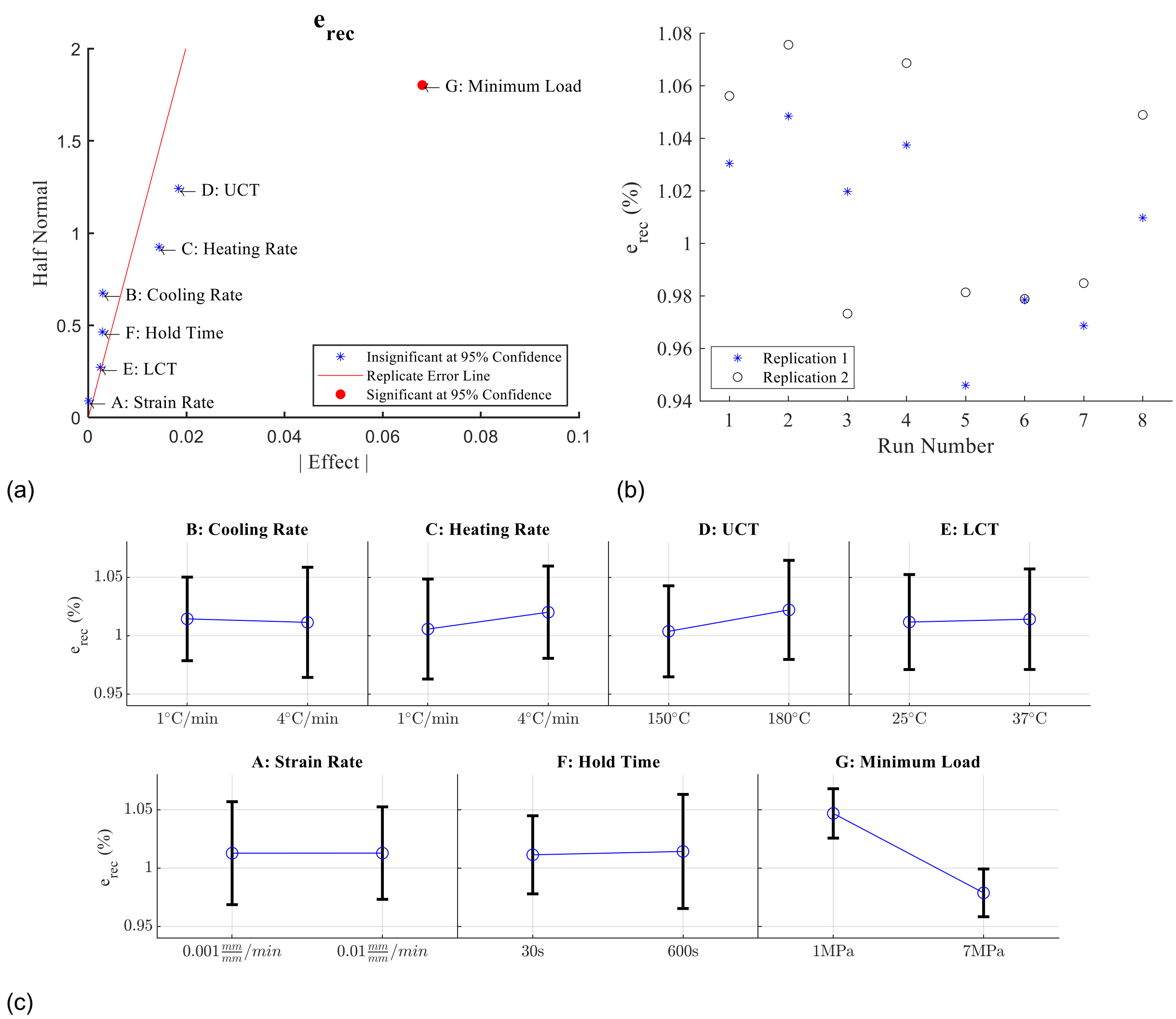


Figure 27.—Data, function of run number, and mean and standard deviation (STDEV) as a function of low-and high-level settings for recovery strain, e_{rec}. (a) Half-normal plot. (b) Function of run number for two replicates. (c) Mean and STDEV for A, strain rate; B, cooling rate; C, heating rate; D,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

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_s (2nd) means given factor had second greatest effect on A_s.]

Factor	Effect of High Level vs. Low Level Parameters per Factor										
Strain rate, $\dot{e}$	Result variable	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------
	Effect	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------
Cooling rate, $\dot{T}_{cool}$	Result variable	M_f[c] (2nd)	----------	----------	----------	----------	----------	----------	----------	----------	----------
	Effect	1.139	----------	----------	----------	----------	----------	----------	----------	----------	----------
Heating rate, $\dot{T}_{heat}$	Result variable	A_s[a] (1st)	e_{Af}[d] (2nd)	e_{Ms}[e] (2nd)	e_{UCT}[h] (3rd)	----------	----------	----------	----------	----------	----------
	Effect	2.724	0.03551	0.03419	0.03094	----------	----------	----------	----------	----------	----------
Upper cycle temperature, UCT	Result variable	e_{UCT}[h] (2nd)	----------	----------	----------	----------	----------	----------	----------	----------	----------
	Effect	0.04306	----------	----------	----------	----------	----------	----------	----------	----------	----------
Lower cycle temperature, LCT	Result variable	S_i[k] (1st)	A_f[b] (1st)	A_s[a] (3rd)	----------	----------	----------	----------	----------	----------	----------
	Effect	7.216	5.477	1.023	----------	----------	----------	----------	----------	----------	----------
Hold time, t_{hold}	Result variable	M_f[c] (3rd)	----------	----------	----------	----------	----------	----------	----------	----------	----------
	Effect	1.045	----------	----------	----------	----------	----------	----------	----------	----------	----------
Minimum load, F_{min}	Result variable	A_s[a] (2nd)	M_f[c] (1st)	e_{cl}[i] (1st)	e_{ht}[j] (1st)	e_{Af}[d] (1st)	e_{UCT}[h] (1st)	e_{Ms}[e] (1st)	e_{LCT}[g] (1st)	e_{Mf}[f] (1st)	e_{rec}[l] (1st)
	Effect	2.509	2.442	0.15502	0.08915	0.08314	0.08199	0.07982	0.07871	0.07520	0.06805

[a]Austenite start.
[b]Austenite finish.
[c]Martensite finish.
[d]Strain at austenite finish temperature (fit line intersection point).
[e]Strain at martensite start temperature (fit line intersection point).
[f]Strain at martensite finish temperature (fit line intersection point).
[g]Strain at lower cycle temperature (*LCT*) after full thermal cycle under minimum load.
[h]Strain at upper cycle temperature (*UCT*) after heating under minimum load.
[i]Cooling transformation strain ($e_{Mf} - e_{Ms}$).
[j]Heating transformation strain ($e_{As} - e_{Af}$).
[k]Stress at maximum strain during pre-straining (e_i).
[l]Residual strain recovered in the specimen after heating to *UCT* and cooling to *LCT* following pre-straining ($e_u - e_{LCT}$).

5.0 Discussions

The seven selected factors were deemed to be the most likely factors to affect the UPFR test outcome, and their impact on each result variable is outlined in the previously presented data. The tests presented here are only a portion of the overall ruggedness evaluation, as they do not consider other geometries, other SMAs, or other testing organizations, nor does it account for variations due to operator's analysis (fit) technique. The experiments performed were comprised from a fractional factorial and lack a foldover replicate to identify if the combination of any factors confounds 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, but merely the presence of an observed effect in this experiment. Further testing is required to verify the mechanisms and nature of the effects recorded.

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 rates on thermally induced transformations. The strain rate here should have a minimal effect, given that the loading and unloading occurs at the *LCT* (martensite phase), the strain rates used are still at a relatively slow rate, and the 2 percent pre-strain limit is likely within the detwinning (recoverable) region of the material response. The rest of the test method is based on appropriately controlling temperature and stress. From Table III, it is shown that the strain rates have a minimal effect on the A_s temperature (~0.24 °C) and can be considered a factor of low importance. Also from Table IV, it can be seen that for UPFR there are no result variables significantly affected by the strain rate.

Heating and cooling rates have previously been 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 mechanisms are not fully understood. Referring to Table IV, the heating and cooling rates mainly impacted the transformation temperatures and strains (M_f, A_s, e_{Af}, e_{Ms}, and e_{UCT}). Although the impact is minimal, the A_s temperature is most sensitive to changes in heating rate (~2.72 °C).

Although varying *UCT* has been known to have significant effects on actuator hysteresis and transformation temperatures in UCFTC type testing (Refs. 17 and 18), the large effect of *UCT* on e_{UCT} in these UPFR tests is likely due to the immediate relationship between *UCT* and e_{UCT}. For the high-level factor *UCT* case, there is a larger linear coefficient of thermal expansion (CTE) region in the austenite, allowing for more strain to occur. In addition, there is more thermal energy input by heating above 150 °C (up to 180 °C) which could be driving transformation of any residual martensite in the microstructure to austenite. Figure 28 illustrates this using the heating curve of Run 2, showing that if the UCT had been 150 °C versus 180 °C, the e_{UCT} would have been 0.399 percent instead of 0.428 percent.

The effects of *LCT* on S_i are likely due to the highly temperature dependent effects on material behavior (yield stress, detwinning plateau stress and strain, elongation, etc.) classically seen in NiTi shape memory alloys when tested at different temperatures around the transformation temperatures (Ref. 19). This temperature dependent change in the yield and martensite deformation behavior significantly affects the subsequent A_s and A_f temperatures during the heating cycle by as much as 5.48 °C.

Minimum load shows a statistically significant influence on a wide variety of result variables, most notably being transformation temperatures and the resulting strains. Although the minimum load has an obvious effect on the normalization curves (Figure 29), this does not seem to extend to the pre-strain and unload portion of the test. None of the factors that represent this portion (e_0, S_i, e_i, or e_u) exhibit a statistically significant effect with respect to minimum load. However, for this standard, the minimum load affects nearly all of the strain and temperature parameters of the subsequent free-recovery thermal cycle portion of the UPFR test. This suggests that stopping the unload at the higher minimum load during pre-straining shifts the entire hysteresis loop upward in strain-temperature space in the subsequent free-recovery thermal cycle thereby affecting the strain and temperature parameters. Regardless of the mechanism of this effect, the primary takeaway is that the minimum load maintained after unload and

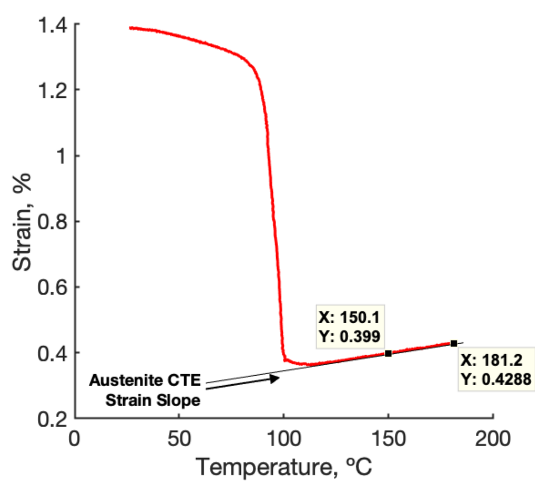


Figure 28.—Heating curve of Run 2 illustrating effect of upper cycle temperature (UCT) and coefficient of thermal expansion (CTE) on e_{UCT}.

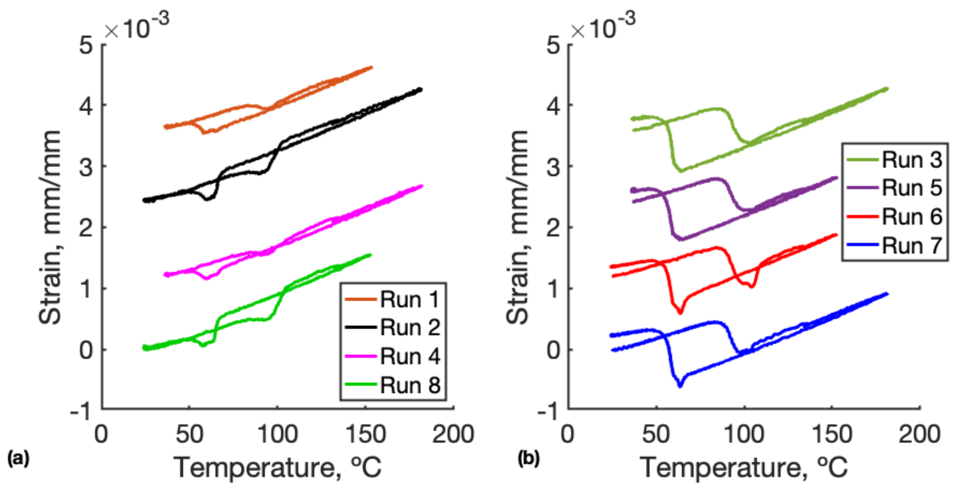


Figure 29.—Representative normalization curves. (a) G, minimum load setting of (–1). (b) G, minimum load setting of (+1).

during the free recovery thermal cycle has some effect on the material's actuation temperature and strains even if it is maintained below some nominal level (7 MPa for this study), with a maximum effect for this study of 2.5 °C and 0.15 percent strain.

6.0 Concluding Remarks

While vendors and test laboratories may use rates and limits outside of those presented here (after ensuring that they still obtain accurate results), this work was performed by using test factors and levels that should be sufficient to ensure good repeatability and accurate measurement of results for samples using the uniaxial pre-strain free thermal recovery (UPFR) test. For all factors, the magnitude of effect observed, even when statistically significant, was generally minimal. Given that effects are specified in the units of the result variable observed (either °C or % 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. For example, even the largest temperature effect observed, A_f change of 5.48 °C due to variation in *LCT*, is not a critical change for most actuation application purposes.

If a UPFR 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 several parameters may slightly change with testing factors such as temperature rates, strain rate, or minimum load per experimenting institution, overall the UPFR test shows a commendable ruggedness to the factors tested in this work.

Most importantly, this work shows that the analysis methodology can play a significant role in the measurement of transformation parameters. In particular, the given methodology used to fit the transformation region, "tangent lines drawn from the steepest portion of the strain verses temperature curve" (Ref. 4) may not be sufficient if the material exhibits a multistage transformation. In these cases, it may be necessary to fit multiple regions of the transformation in order to accurately capture the corresponding transformation temperatures and strains.

Additional work is warranted to evaluate the effect of geometry (e.g., wire, sheet, and rods), material lot (R-phase containing alloys, high-temperature alloys, and general sample-to-sample variability), 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
OSTEM	Office of Science, Technology, Engineering, and Math
SMA	shape memory alloy
STDEV	standard deviation
UCFTC	uniaxial constant force thermal cycling
UPFR	uniaxial pre-strain and thermal free recovery

Symbols

Ave	average results
A_f	austenite finish
A_s	austenite start
e	strain
$\dot{e}$	strain rate
$effect$	error of an effect
e_0	initial strain (at LCT after normalizing and prior to pre-straining)
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	maximum loading strain (at LCT during pre-straining)
e_{LCT}	strain at lower cycle temperature (after full thermal cycle under no load/minimum load)
e_{Mf}	strain at martensite finish temperature (fit line intersection point)
e_{Ms}	strain at martensite start temperature (fit line intersection point)
e_{rec}	recovery strain = $e_u - e_{LCT}$
e_T	transformation strain = $e_{As} - e_{Af}$
e_{TW}	two-way strain = $e_{LCT} - e_{UCT}$
e_u	unloaded strain at LCT after pre-straining and unloading but prior to heating
e_{UCT}	strain at upper cycle temperature (after heating under no load/minimum load)
F_{min}	minimum load
$I_x(z,w)$	incomplete beta function
LCT	lower cycle temperature
M_f	martensite finish
M_s	martensite start
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
S_i	stress at maximum strain during pre-straining (e_i)
T	temperature
t	Student's t-value (see Ref. 10)
$\dot{T}_{cool}$	cooling rate
$\dot{T}_{heat}$	heating rate
t_{hold}	hold time
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 E3098

1	Test type	Uniaxial Pre-strain and Thermal Free Recovery (UPFR)
2	Test note	Ruggedness Tests
3	Test date	February 16, 2018
4	Lab	NASA–GRC–SH38B
5	Operator	G. Bigelow
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	87.325
13	Austenite finish (A_f), °C	111.394
14	Martensite start (M_s), °C	66.082
15	Martensite finish (M_f), °C	46.443
16	Austenite start strain, e_{As}	1.4044
17	Austenite finish strain, e_{Af}	0.40949
18	Martensite start strain, e_{Ms}	0.35466
19	Martensite finish strain, e_{Mf}	0.51305
20	Strain at *LCT*, e_{LCT}	0.5008
21	Strain at *UCT*, e_{UCT}	0.4449
22	Cooling transformation strain, e_{ct}	–0.15839
23	Heating transformation strain, e_{ht}	0.99491
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	Specimen stress at maximum strain	157.642
33	Initial strain, e_0	0.0005
34	Maximum loading strain, e_i	2.0082

TABLE V.—CONCLUDED.

35	Unloading strain, e_u	1.5105
36	Recovery strain, e_{rec}	1.0097
37	Known A_f, °C	96.21
38	Known A_s, °C	76.11
39	Known R_f*, °C	--
40	Known R_s*, °C	--
42	Known R_s, °C	--
43	Known R_f, °C	--
44	Known M_s, °C	66.84
45	Known M_f, °C	49.60
46	Comments	Known transformation temperatures via DSC
47	User defined	--
48	User defined	--
49	User defined	--
50	*** end header ***	--

TABLE VI.—RAW DATA FILES

51	Seconds	Deg C	MPa	%	User defined	User defined	User defined
52	Time	Temperature	Stress	Strain	User defined	User defined	User defined
53	1.0060222	24.597191	1.031086	0.02599372	--------------	--------------	--------------
54	2.0060222	24.780788	1.2777672	0.02603172	--------------	--------------	--------------
55	3.0060222	25.010286	1.5433148	0.02598865	--------------	--------------	--------------
56	4.0060222	24.826689	1.5880705	0.02678314	--------------	--------------	--------------

Appendix C.—Run Replicates

This appendix contains plots of the run replicates (Figure 30 and Figure 31).

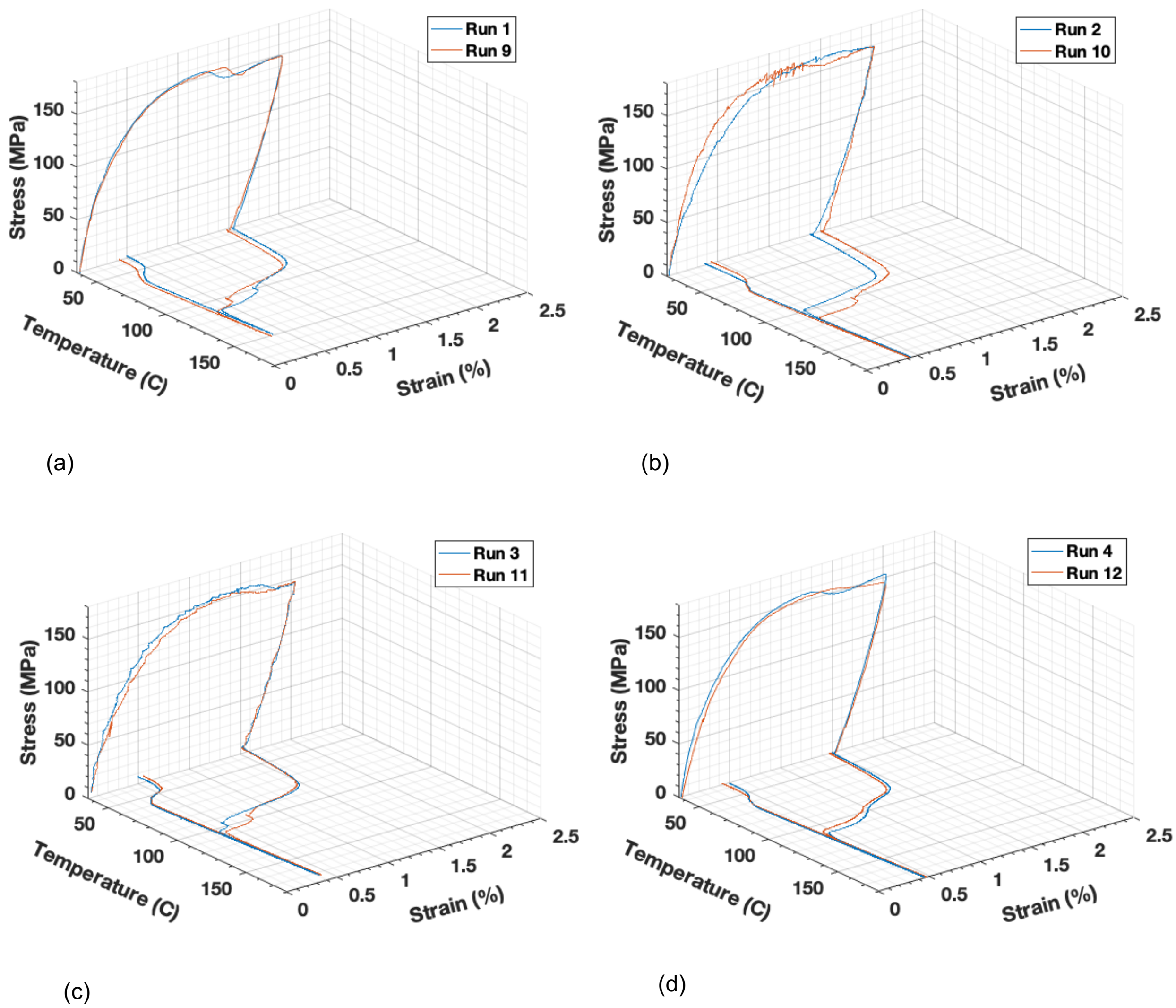


Figure 30.—Run replicate plots. (a) Runs 1 and 9. (b) Runs 2 and 10. (c) Runs 3 and 11. (d) Runs 4 and 12.

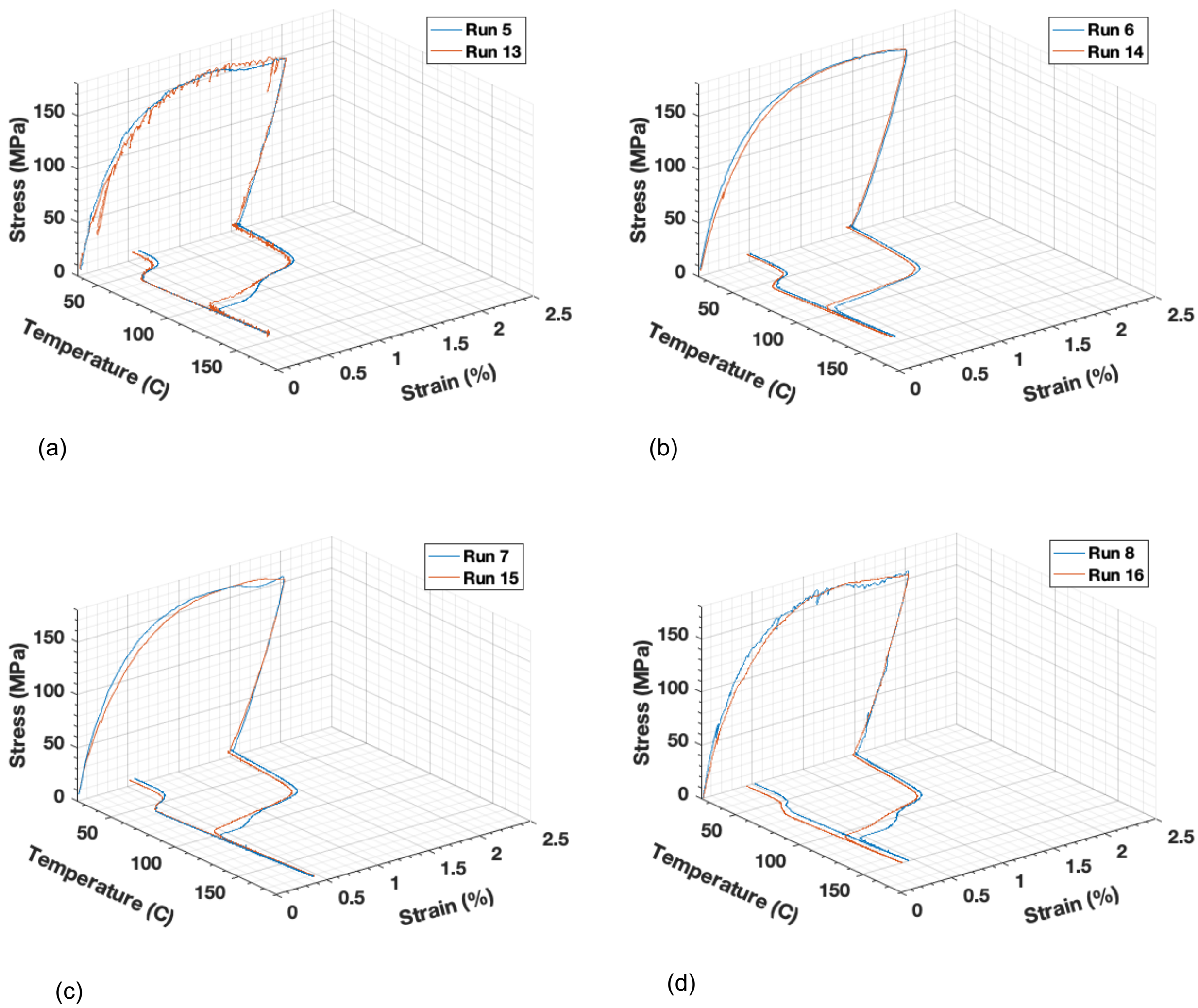


Figure 31.—Run replicate plots. (a) Runs 5 and 13. (b) Runs 6 and 14. (c) Runs 7 and 15. (d) Runs 8 and 16.

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

This appendix contains tables of calculated effects per factor as well as significant statistical calculations (Table VII to Table XL).

TABLE VII.—RUGGEDNESS EXAMPLE CALCULATIONS FOR AUSTENITE START, AS, RESULTS

Ruggedness Example Calculations for A_S Results Assuming Uniaxial Pre-Strain Free Recovery (UPFR)											
Run Number	**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	89.241	90.311	89.776	1.070
2	–1	+1	+1	+1	–1	+1	–1	89.212	90.303	89.758	1.091
3	–1	–1	+1	+1	+1	–1	+1	92.678	90.923	91.801	–1.755
4	+1	–1	–1	+1	+1	+1	–1	86.284	85.258	85.771	–1.026
5	–1	+1	–1	–1	+1	+1	+1	89.500	88.993	89.247	–0.507
6	+1	–1	+1	–1	–1	+1	+1	92.846	92.659	92.753	–0.187
7	+1	+1	–1	+1	–1	–1	+1	90.313	89.401	89.857	–0.912
8	–1	–1	–1	–1	–1	–1	–1	88.879	87.756	88.318	–1.123
Avg. of +1	89.539	89.659	91.022	89.297	89.149	89.382	90.914				
Avg. of –1	89.781	89.660	88.298	90.023	90.171	89.938	88.406		s_d	1.03170	
Main Effect	–0.2414	–0.0011	2.7236	–0.7266	–1.0226	–0.5559	2.5086		s_{rep}	0.72952	
| Main Effect |	0.2414	0.0011	2.7236	0.7266	1.0226	0.5559	2.5086		S_{effect}	0.36476	
Rank	6	7	1	4	3	5	2				

TABLE VIII.—FACTOR RANKINGS AND CALCULATED VALUES FOR EFFECTS ON AUSTENITE START, A_S, RESULTS

Statistical Significance of Effects—Example Calculations for A_S Results							
Factor ranking	**Factor**	**Effect**	**| Effect |**	**Student's *t*-value**	**| Student's *t*-value |**	**Two tailed *p-value*, (%)**	**Half-normal plotting values**
1	C	2.724	2.724	7.467	7.467	0.014	1.803
2	G	2.509	2.509	6.877	6.877	0.024	1.242
3	E	–1.023	1.023	–2.804	2.804	2.637	0.921
4	D	–0.727	0.727	–1.992	1.992	8.664	0.674
5	F	–0.556	0.556	–1.524	1.524	17.133	0.464
6	A	–0.241	0.241	–0.662	0.662	52.915	0.272
7	B	–0.001	0.001	–0.003	0.003	99.769	0.090

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

Ruggedness Example Calculations for A_f Results Assuming Uniaxial Pre-Strain Free Recovery (UPFR)											
Run Number	**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	113.180	112.610	112.895	–0.570
2	–1	+1	+1	+1	–1	+1	–1	99.987	112.210	106.099	12.223
3	–1	–1	+1	+1	+1	–1	+1	110.700	112.180	111.440	1.480
4	+1	–1	–1	+1	+1	+1	–1	111.690	108.010	109.850	–3.680
5	–1	+1	–1	–1	+1	+1	+1	113.140	106.050	109.595	–7.090
6	+1	–1	+1	–1	–1	+1	+1	102.690	99.484	101.087	–3.206
7	+1	+1	–1	+1	–1	–1	+1	108.970	102.880	105.925	–6.090
8	–1	–1	–1	–1	–1	–1	–1	112.030	105.490	108.760	–6.540
Avg. of +1	107.439	108.628	107.880	108.328	110.945	106.658	107.012				
Avg. of –1	108.973	107.784	108.533	108.084	105.468	109.755	109.401			s_d	6.36032
Main Effect	–1.534	0.844	–0.652	0.244	5.477	–3.097	–2.389			s_{rep}	4.49742
| Main Effect |	1.534	0.844	0.652	0.244	5.477	3.097	2.389			S_{effect}	2.24871
Rank	4	5	6	7	1	2	3				

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

Statistical Significance of Effects—Example Calculations for A_f Results							
Factor ranking	**Factor**	**Effect**	**| Effect |**	**Student's *t*-value**	**| Student's *t*-value |**	**Two tailed *p-value*, (%)**	**Half-normal plotting values**
1	C	5.477	5.477	2.436	2.436	4.502	1.803
2	G	–3.097	3.097	–1.377	1.377	21.093	1.242
3	E	–2.389	2.389	–1.062	1.062	32.350	0.921
4	D	–1.534	1.534	–0.682	0.682	51.716	0.674
5	F	0.844	0.844	0.375	0.375	71.876	0.464
6	A	–0.652	0.652	–0.290	0.290	78.022	0.272
7	B	0.244	0.244	0.109	0.109	91.626	0.090

TABLE XI.—RUGGEDNESS EXAMPLE CALCULATIONS FOR MARTENSITE START, M_S, RESULTS

Ruggedness Example Calculations for M_S Results Assuming Uniaxial Pre-Strain Free Recovery (UPFR)											
Run Number	**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	65.385	64.892	65.139	–0.493
2	–1	+1	+1	+1	–1	+1	–1	64.543	65.990	65.267	1.447
3	–1	–1	+1	+1	+1	–1	+1	65.884	65.999	65.942	0.115
4	+1	–1	–1	+1	+1	+1	–1	67.579	64.292	65.936	–3.287
5	–1	+1	–1	–1	+1	+1	+1	65.115	64.381	64.748	–0.734
6	+1	–1	+1	–1	–1	+1	+1	64.694	64.186	64.440	–0.508
7	+1	+1	–1	+1	–1	–1	+1	64.864	64.233	64.549	–0.631
8	–1	–1	–1	–1	–1	–1	–1	66.279	65.789	66.034	–0.490
Avg. of +1	65.016	64.925	65.197	65.423	65.441	65.098	64.920				
Avg. of –1	65.498	65.588	65.317	65.090	65.072	65.416	65.594	s_d		1.30747	
Main Effect	–0.4819	–0.6624	–0.1199	0.3329	0.3686	–0.3181	–0.6741	s_{rep}		0.92452	
| Main Effect |	0.4819	0.6624	0.1199	0.3329	0.3686	0.3181	0.6741	S_{effect}		0.46226	
Rank	3	2	7	5	4	6	1				

TABLE XII.—FACTOR RANKINGS AND CALCULATED VALUES FOR EFFECTS ON MARTENSITE START, M_S, RESULTS

Statistical Significance of Effects—Example Calculations for M_S Results							
Factor ranking	**Factor**	**Effect**	**| Effect |**	**Student's *t*-value**	**| Student's *t*-value |**	**Two tailed *p-value*, (%)**	**Half-normal plotting values**
1	C	–0.674	0.674	–1.458	1.458	18.820	1.803
2	G	–0.662	0.662	–1.433	1.433	19.497	1.242
3	E	–0.482	0.482	–1.042	1.042	33.206	0.921
4	D	0.369	0.369	0.797	0.797	45.163	0.674
5	F	0.333	0.333	0.720	0.720	49.486	0.464
6	A	–0.318	0.318	–0.688	0.688	51.360	0.272
7	B	–0.120	0.120	–0.259	0.259	80.309	0.090

TABLE XIII.—RUGGEDNESS EXAMPLE CALCULATIONS FOR MARTENSITE FINISH, M_f, RESULTS

Ruggedness Example Calculations for M_f Results Assuming Uniaxial Pre-Strain Free Recovery (UPFR)											
Run Number	**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	48.998	48.217	48.608	–0.781
2	–1	+1	+1	+1	–1	+1	–1	52.611	49.712	51.162	–2.899
3	–1	–1	+1	+1	+1	–1	+1	53.749	52.823	53.286	–0.926
4	+1	–1	–1	+1	+1	+1	–1	51.678	52.371	52.025	0.693
5	–1	+1	–1	–1	+1	+1	+1	53.449	52.880	53.165	–0.569
6	+1	–1	+1	–1	–1	+1	+1	53.791	53.496	53.644	–0.295
7	+1	+1	–1	+1	–1	–1	+1	52.163	53.225	52.694	1.062
8	–1	–1	–1	–1	–1	–1	–1	51.435	51.021	51.228	–0.414
Avg. of +1	51.742	51.407	51.675	52.292	51.771	52.499	53.197				
Avg. of –1	52.210	52.546	52.278	51.661	52.182	51.454	50.755	S_d		1.19109	
Main Effect	–0.4676	–1.1386	–0.6031	0.6306	–0.4111	1.0446	2.4416	S_{rep}		0.84223	
| Main Effect |	0.4676	1.1386	0.6031	0.6306	0.4111	1.0446	2.4416	S_{effect}		0.42111	
Rank	6	2	5	4	7	3	1				

TABLE XIV.—FACTOR RANKINGS AND CALCULATED VALUES FOR EFFECTS ON MARTENSITE FINISH, M_f, RESULTS

Statistical Significance of Effects—Example Calculations for M_f Results							
Factor ranking	**Factor**	**Effect**	**| Effect |**	**Student's *t*-value**	**| Student's *t*-value |**	**Two tailed *p-value*, (%)**	**Half-normal plotting values**
1	C	2.442	2.442	5.798	5.798	0.067	1.803
2	G	–1.139	1.139	–2.704	2.704	3.046	1.242
3	E	1.045	1.045	2.481	2.481	4.215	0.921
4	D	0.631	0.631	1.498	1.498	17.780	0.674
5	F	–0.603	0.603	–1.432	1.432	19.524	0.464
6	A	–0.468	0.468	–1.110	1.110	30.367	0.272
7	B	–0.411	0.411	–0.976	0.976	36.158	0.090

TABLE XV.—RUGGEDNESS EXAMPLE CALCULATIONS FOR STRAIN AT AUSTENITE START TEMPERATURE, e_{As}, RESULTS

Ruggedness Example Calculations for e_{As} Results Assuming Uniaxial Pre-Strain Free Recovery (UPFR)											
Run Number	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	1.43160	1.37900	1.40530	–0.05260
2	–1	+1	+1	+1	–1	+1	–1	1.29660	1.41460	1.35560	0.11800
3	–1	–1	+1	+1	+1	–1	+1	1.39760	1.40450	1.40105	0.00690
4	+1	–1	–1	+1	+1	+1	–1	1.42820	1.40690	1.41755	–0.02130
5	–1	+1	–1	–1	+1	+1	+1	1.45510	1.42350	1.43930	–0.03160
6	+1	–1	+1	–1	–1	+1	+1	1.37920	1.34800	1.36360	–0.03120
7	+1	+1	–1	+1	–1	–1	+1	1.40720	1.35600	1.38160	–0.05120
8	–1	–1	–1	–1	–1	–1	–1	1.39660	1.36950	1.38305	–0.02710
Avg. of +1	1.39201	1.39545	1.38139	1.38895	1.41580	1.39401	1.39639				
Avg. of –1	1.39475	1.39131	1.40538	1.39781	1.37096	1.39275	1.39038		s_d	0.05543	
Main Effect	–0.00274	0.00414	–0.02399	–0.00886	0.04484	0.00126	0.00601		s_{rep}	0.03919	
| Main Effect |	0.00274	0.00414	0.02399	0.00886	0.04484	0.00126	0.00601		S_{effect}	0.01960	
Rank	6	5	2	3	1	7	4				

TABLE XVI.—FACTOR RANKINGS AND CALCULATED VALUES FOR EFFECTS ON STRAIN AT AUSTENITE START TEMPERATURE, e_{As}, RESULTS

Statistical Significance of Effects—Example Calculations for e_{As} Results							
Factor ranking	Factor	Effect	| Effect |	Student's *t*-value	| Student's *t*-value |	Two tailed *p-value*, (%)	Half-normal plotting values
1	C	0.04484	0.04484	2.288	2.288	5.597	1.803
2	G	–0.02399	0.02399	–1.224	1.224	26.055	1.242
3	E	–0.00886	0.00886	–0.452	0.452	66.494	0.921
4	D	0.00601	0.00601	0.307	0.307	76.778	0.674
5	F	0.00414	0.00414	0.211	0.211	83.890	0.464
6	A	–0.00274	0.00274	–0.140	0.140	89.260	0.272
7	B	0.00126	0.00126	0.064	0.064	95.076	0.090

TABLE XVII.—RUGGEDNESS EXAMPLE CALCULATIONS FOR STRAIN AT AUSTENITE FINISH TEMPERATURE, e_{Af}, RESULTS

Ruggedness Example Calculations for e_{Af} Results Assuming Uniaxial Pre-Strain Free Recovery (UPFR)											
Run Number	**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	0.35390	0.31888	0.33639	–0.03502
2	–1	+1	+1	+1	–1	+1	–1	0.34904	0.34208	0.34556	–0.00696
3	–1	–1	+1	+1	+1	–1	+1	0.25185	0.27600	0.26393	0.02415
4	+1	–1	–1	+1	+1	+1	–1	0.38840	0.38971	0.38906	0.00131
5	–1	+1	–1	–1	+1	+1	+1	0.28795	0.28578	0.28687	–0.00217
6	+1	–1	+1	–1	–1	+1	+1	0.28481	0.24445	0.26463	–0.04036
7	+1	+1	–1	+1	–1	–1	+1	0.29731	0.30233	0.29982	0.00502
8	–1	–1	–1	–1	–1	–1	–1	0.41497	0.33861	0.37679	–0.07636
Avg. of +1	0.32247	0.31716	0.30263	0.32459	0.31906	0.32153	0.27881				
Avg. of –1	0.31829	0.32360	0.33813	0.31617	0.32170	0.31923	0.36195	s_d		0.03213	
Main Effect	0.00419	–0.00644	–0.03551	0.00842	–0.00264	0.00230	–0.08314	s_{rep}		0.02272	
| Main Effect |	0.00419	0.00644	0.03551	0.00842	0.00264	0.00230	0.08314	S_{effect}		0.01136	
Rank	5	4	2	3	6	7	1				

TABLE XVIII.—FACTOR RANKINGS AND CALCULATED VALUES FOR EFFECTS ON STRAIN AT AUSTENITE FINISH TEMPERATURE, e_{Af}, RESULTS

Statistical Significance of Effects—Example Calculations for e_{Af} Results							
Factor ranking	**Factor**	**Effect**	**| Effect |**	**Student's *t*-value**	**| Student's *t*-value |**	**Two tailed *p-value*, (%)**	**Half-normal plotting values**
1	G	–0.08314	0.08314	–7.320	7.320	0.016	1.803
2	C	–0.03551	0.03551	–3.126	3.126	1.670	1.242
3	D	0.00842	0.00842	0.741	0.741	48.281	0.921
4	B	–0.00644	0.00644	–0.567	0.567	58.843	0.674
5	A	0.00419	0.00419	0.369	0.369	72.304	0.464
6	E	–0.00264	0.00264	–0.233	0.233	82.243	0.272
7	F	0.00230	0.00230	0.202	0.202	84.566	0.090

TABLE XIX.—RUGGEDNESS EXAMPLE CALCULATIONS FOR STRAIN AT MARTENSITE START TEMPERATURE, e_{Ms}, RESULTS

Ruggedness Example Calculations for e_{Ms} Results Assuming Uniaxial Pre-Strain Free Recovery (UPFR)											
Run Number	**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	0.28344	0.25627	0.26986	–0.02717
2	–1	+1	+1	+1	–1	+1	–1	0.29761	0.27601	0.28681	–0.02160
3	–1	–1	+1	+1	+1	–1	+1	0.19495	0.21388	0.20442	0.01893
4	+1	–1	–1	+1	+1	+1	–1	0.31944	0.33341	0.32643	0.01397
5	–1	+1	–1	–1	+1	+1	+1	0.22396	0.22540	0.22468	0.00144
6	+1	–1	+1	–1	–1	+1	+1	0.22993	0.19926	0.21460	–0.03067
7	+1	+1	–1	+1	–1	–1	+1	0.23846	0.24301	0.24074	0.00455
8	–1	–1	–1	–1	–1	–1	–1	0.35485	0.28637	0.32061	–0.06848
Avg. of +1	0.26290	0.25552	0.24392	0.26460	0.25634	0.26313	0.22111				
Avg. of –1	0.25913	0.26651	0.27811	0.25744	0.26569	0.25890	0.30093		s_d	0.02909	
Main Effect	0.00377	–0.01099	–0.03419	0.00716	–0.00934	0.00422	–0.07982		s_{rep}	0.02057	
| Main Effect |	0.00377	0.01099	0.03419	0.00716	0.00934	0.00422	0.07982		S_{effect}	0.01029	
Rank	7	3	2	5	4	6	1				

TABLE XX.—FACTOR RANKINGS AND CALCULATED VALUES FOR EFFECTS ON STRAIN AT MARTENSITE START TEMPERATURE, e_{Ms}, RESULTS

Statistical Significance of Effects—Example Calculations for e_{Ms} Results							
Factor ranking	**Factor**	**Effect**	**| Effect |**	**Student's *t*-value**	**| Student's *t*-value |**	**Two tailed *p-value*, (%)**	**Half-normal plotting values**
1	G	–0.07982	0.07982	–7.760	7.760	0.011	1.803
2	C	–0.03419	0.03419	–3.324	3.324	1.270	1.242
3	B	–0.01099	0.01099	–1.069	1.069	32.054	0.921
4	E	–0.00934	0.00934	–0.908	0.908	39.406	0.674
5	D	0.00716	0.00716	0.696	0.696	50.887	0.464
6	F	0.00422	0.00422	0.411	0.411	69.336	0.272
7	A	0.00377	0.00377	0.367	0.367	72.446	0.090

TABLE XXI.—RUGGEDNESS EXAMPLE CALCULATIONS FOR STRAIN AT MARTENSITE FINISH TEMPERATURE, e_{Mf}, RESULTS

Ruggedness Example Calculations for e_{Mf} Results Assuming Uniaxial Pre-Strain Free Recovery (UPFR)											
Run Number	**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	0.49798	0.41939	0.45869	–0.07859
2	–1	+1	+1	+1	–1	+1	–1	0.39285	0.44992	0.42139	0.05707
3	–1	–1	+1	+1	+1	–1	+1	0.48964	0.53310	0.51137	0.04346
4	+1	–1	–1	+1	+1	+1	–1	0.47581	0.44001	0.45791	–0.03580
5	–1	+1	–1	–1	+1	+1	+1	0.60169	0.54341	0.57255	–0.05828
6	+1	–1	+1	–1	–1	+1	+1	0.51825	0.48901	0.50363	–0.02924
7	+1	+1	–1	+1	–1	–1	+1	0.55416	0.49921	0.52669	–0.05495
8	–1	–1	–1	–1	–1	–1	–1	0.51557	0.43531	0.47544	–0.08026
Avg. of +1	0.48673	0.49483	0.47377	0.47934	0.50013	0.48887	0.52856				
Avg. of –1	0.49519	0.48709	0.50815	0.50258	0.48179	0.49305	0.45336		s_d	0.05254	
Main Effect	–0.00846	0.00774	–0.03438	–0.02324	0.01834	–0.00418	0.07520		s_{rep}	0.03715	
| Main Effect |	0.00846	0.00774	0.03438	0.02324	0.01834	0.00418	0.07520		S_{effect}	0.01857	
Rank	5	6	2	3	4	7	1				

TABLE XXII.—FACTOR RANKINGS AND CALCULATED VALUES FOR EFFECTS ON STRAIN AT MARTENSITE FINISH TEMPERATURE, e_{Mf}, RESULTS

Statistical Significance of Effects—Example Calculations for e_{Mf} Results							
Factor ranking	**Factor**	**Effect**	**| Effect |**	**Student's *t*-value**	**| Student's *t*-value |**	**Two tailed *p-value*, (%)**	**Half-normal plotting values**
1	G	0.07520	0.07520	4.049	4.049	0.488	1.803
2	C	–0.03438	0.03438	–1.851	1.851	10.661	1.242
3	D	–0.02324	0.02324	–1.251	1.251	25.112	0.921
4	E	0.01834	0.01834	0.988	0.988	35.607	0.674
5	A	–0.00846	0.00846	–0.455	0.455	66.289	0.464
6	B	0.00774	0.00774	0.417	0.417	68.917	0.272
7	F	–0.00418	0.00418	–0.225	0.225	82.841	0.090

TABLE XXIII.—RUGGEDNESS EXAMPLE CALCULATIONS FOR STRAIN AT LOWER CYCLE TEMPERATURE, e_{LCT}, RESULTS

Ruggedness Example Calculations for e_{LCT} Results Assuming Uniaxial Pre-Strain Free Recovery (UPFR)											
Run Number	**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	0.49260	0.41370	0.45315	–0.07890
2	–1	+1	+1	+1	–1	+1	–1	0.37450	0.43630	0.40540	0.06180
3	–1	–1	+1	+1	+1	–1	+1	0.48100	0.52570	0.50335	0.04470
4	+1	–1	–1	+1	+1	+1	–1	0.46610	0.42380	0.44495	–0.04230
5	–1	+1	–1	–1	+1	+1	+1	0.59640	0.53970	0.56805	–0.05670
6	+1	–1	+1	–1	–1	+1	+1	0.50650	0.47660	0.49155	–0.02990
7	+1	+1	–1	+1	–1	–1	+1	0.54440	0.48820	0.51630	–0.05620
8	–1	–1	–1	–1	–1	–1	–1	0.50080	0.42100	0.46090	–0.07980
Avg. of +1	0.47649	0.48573	0.46336	0.46750	0.49238	0.47749	0.51981				
Avg. of –1	0.48443	0.47519	0.49755	0.49341	0.46854	0.48343	0.44110			s_d	0.05402
Main Effect	–0.00794	0.01054	–0.03419	–0.02591	0.02384	–0.00594	0.07871			s_{rep}	0.03820
| Main Effect |	0.00794	0.01054	0.03419	0.02591	0.02384	0.00594	0.07871			S_{effect}	0.01910
Rank	6	5	2	3	4	7	1				

TABLE XXIV.—FACTOR RANKINGS AND CALCULATED VALUES FOR EFFECTS ON STRAIN AT LOWER CYCLE TEMPERATURE, e_{LCT}, RESULTS

Statistical Significance of Effects—Example Calculations for e_{LCT} Results							
Factor ranking	**Factor**	**Effect**	**| Effect |**	**Student's *t*-value**	**| Student's *t*-value |**	**Two tailed *p-value*, (%)**	**Half-normal plotting values**
1	G	0.07871	0.07871	4.121	4.121	0.445	1.803
2	C	–0.03419	0.03419	–1.790	1.790	11.658	1.242
3	D	–0.02591	0.02591	–1.357	1.357	21.700	0.921
4	E	0.02384	0.02384	1.248	1.248	25.213	0.674
5	B	0.01054	0.01054	0.552	0.552	59.831	0.464
6	A	–0.00794	0.00794	–0.416	0.416	69.016	0.272
7	F	–0.00594	0.00594	–0.311	0.311	76.495	0.090

TABLE XXV.—RUGGEDNESS EXAMPLE CALCULATIONS FOR STRAIN AT UPPER CYCLE TEMPERATURE, e_{UCT}, RESULTS

Ruggedness Example Calculations for e_{UCT} Results Assuming Uniaxial Pre-Strain Free Recovery (UPFR)											
Run Number	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	0.37830	0.35290	0.36560	–0.02540
2	–1	+1	+1	+1	–1	+1	–1	0.42810	0.41210	0.42010	–0.01600
3	–1	–1	+1	+1	+1	–1	+1	0.32180	0.33860	0.33020	0.01680
4	+1	–1	–1	+1	+1	+1	–1	0.44620	0.46280	0.45450	0.01660
5	–1	+1	–1	–1	+1	+1	+1	0.31530	0.31380	0.31455	–0.00150
6	+1	–1	+1	–1	–1	+1	+1	0.32440	0.29550	0.30995	–0.02890
7	+1	+1	–1	+1	–1	–1	+1	0.36310	0.37500	0.36905	0.01190
8	–1	–1	–1	–1	–1	–1	–1	0.44490	0.37810	0.41150	–0.06680
Avg. of +1	0.37478	0.36733	0.35646	0.39346	0.36621	0.37478	0.33094				
Avg. of –1	0.36909	0.37654	0.38740	0.35040	0.37765	0.36909	0.41293	s_d		0.02882	
Main Effect	0.00569	–0.00921	–0.03094	0.04306	–0.01144	0.00569	–0.08199	s_{rep}		0.02038	
| Main Effect |	0.00569	0.00921	0.03094	0.04306	0.01144	0.00569	0.08199	S_{effect}		0.01019	
Rank	6	5	3	2	4	7	1				

TABLE XXVI.—FACTOR RANKINGS AND CALCULATED VALUES FOR EFFECTS ON STRAIN AT UPPER CYCLE TEMPERATURE, e_{UCT}, RESULTS

Statistical Significance of Effects—Example Calculations for e_{UCT} Results							
Factor ranking	Factor	Effect	| Effect |	Student's *t*-value	| Student's *t*-value |	Two tailed *p-value*, (%)	Half-normal plotting values
1	G	–0.08199	0.08199	–8.048	8.048	0.009	1.803
2	D	0.04306	0.04306	4.227	4.227	0.390	1.242
3	C	–0.03094	0.03094	–3.037	3.037	1.893	0.921
4	E	–0.01144	0.01144	–1.123	1.123	29.860	0.674
5	B	–0.00921	0.00921	–0.904	0.904	39.590	0.464
6	A	0.00569	0.00569	0.558	0.558	59.406	0.272
7	F	0.00569	0.00569	0.558	0.558	59.406	0.090

TABLE XXVII.—RUGGEDNESS EXAMPLE CALCULATIONS FOR COOLING TRANSFORMATION STRAIN, e_{ct}, RESULTS

Ruggedness Example Calculations for e_{ct} Results Assuming Uniaxial Pre-Strain Free Recovery (UPFR)											
Run Number	**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	0.21454	0.16312	0.18883	–0.05142
2	–1	+1	+1	+1	–1	+1	–1	0.09524	0.17391	0.13458	0.07867
3	–1	–1	+1	+1	+1	–1	+1	0.29469	0.31922	0.30696	0.02453
4	+1	–1	–1	+1	+1	+1	–1	0.15637	0.10660	0.13149	–0.04977
5	–1	+1	–1	–1	+1	+1	+1	0.37773	0.31801	0.34787	–0.05972
6	+1	–1	+1	–1	–1	+1	+1	0.28832	0.28975	0.28904	0.00143
7	+1	+1	–1	+1	–1	–1	+1	0.31570	0.25620	0.28595	–0.05950
8	–1	–1	–1	–1	–1	–1	–1	0.16072	0.14894	0.15483	–0.01178
Avg. of +1	0.22383	0.23931	0.22985	0.21474	0.24379	0.22574	0.30745				
Avg. of –1	0.23606	0.22058	0.23003	0.24514	0.21610	0.23414	0.15243		s_d	0.04946	
Main Effect	–0.01223	0.01873	–0.00018	–0.03040	0.02769	–0.00840	0.15502		s_{rep}	0.03497	
| Main Effect |	0.01223	0.01873	0.00018	0.03040	0.02769	0.00840	0.15502		S_{effect}	0.01749	
Rank	5	4	7	2	3	6	1				

TABLE XXVIII.—FACTOR RANKINGS AND CALCULATED VALUES FOR EFFECTS ON COOLING TRANSFORMATION STRAIN, e_{ct}, RESULTS

Statistical Significance of Effects—Example Calculations for e_{ct} Results							
Factor ranking	**Factor**	**Effect**	**| Effect |**	**Student's *t*-value**	**| Student's *t*-value |**	**Two tailed *p-value*, (%)**	**Half-normal plotting values**
1	G	0.15502	0.15502	8.865	8.865	0.005	1.803
2	D	–0.03040	0.03040	–1.738	1.738	12.578	1.242
3	E	0.02769	0.02769	1.583	1.583	15.744	0.921
4	B	0.01873	0.01873	1.071	1.071	31.970	0.674
5	A	–0.01223	0.01223	–0.700	0.700	50.652	0.464
6	F	–0.00840	0.00840	–0.480	0.480	64.586	0.272
7	C	–0.00018	0.00018	–0.011	0.011	99.153	0.090

TABLE XXIX.—RUGGEDNESS EXAMPLE CALCULATIONS FOR HEATING TRANSFORMATION STRAIN, e_{ht}, RESULTS

Ruggedness Example Calculations for e_{ht} Results Assuming Uniaxial Pre-Strain Free Recovery (UPFR)											
Run Number	**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	1.07770	1.06012	1.06891	–0.01758
2	–1	+1	+1	+1	–1	+1	–1	0.94756	1.07252	1.01004	0.12496
3	–1	–1	+1	+1	+1	–1	+1	1.14575	1.12850	1.13713	–0.01725
4	+1	–1	–1	+1	+1	+1	–1	1.03980	1.01719	1.02850	–0.02261
5	–1	+1	–1	–1	+1	+1	+1	1.16715	1.13772	1.15244	–0.02943
6	+1	–1	+1	–1	–1	+1	+1	1.09439	1.10355	1.09897	0.00916
7	+1	+1	–1	+1	–1	–1	+1	1.10989	1.05367	1.08178	–0.05622
8	–1	–1	–1	–1	–1	–1	–1	0.98163	1.03089	1.00626	0.04926
Avg. of +1	1.06954	1.07829	1.07876	1.06436	1.09674	1.07249	1.11758				
Avg. of –1	1.07647	1.06771	1.06724	1.08164	1.04926	1.07352	1.02843	s_d		0.05740	
Main Effect	–0.00693	0.01058	0.01152	–0.01728	0.04748	–0.00103	0.08915	s_{rep}		0.04059	
| Main Effect |	0.00693	0.01058	0.01152	0.01728	0.04748	0.00103	0.08915	S_{effect}		0.02030	
Rank	6	5	4	3	2	7	1				

TABLE XXX.—FACTOR RANKINGS AND CALCULATED VALUES FOR EFFECTS ON HEATING TRANSFORMATION STRAIN, e_{ht}, RESULTS

Statistical Significance of Effects—Example Calculations for e_{ht} Results							
Factor ranking	**Factor**	**Effect**	**| Effect |**	**Student's *t*-value**	**| Student's *t*-value |**	**Two tailed *p-value*, (%)**	**Half-normal plotting values**
1	G	0.08915	0.08915	4.393	4.393	0.318	1.803
2	E	0.04748	0.04748	2.339	2.339	5.192	1.242
3	D	–0.01728	0.01728	–0.852	0.852	42.240	0.921
4	C	0.01152	0.01152	0.568	0.568	58.778	0.674
5	B	0.01058	0.01058	0.521	0.521	61.844	0.464
6	A	–0.00693	0.00693	–0.341	0.341	74.311	0.272
7	F	–0.00103	0.00103	–0.051	0.051	96.075	0.090

TABLE XXXI.—RUGGEDNESS EXAMPLE CALCULATIONS FOR STRESS AT MAXIMUM STRAIN DURING PRE-STRAINING, S_i, RESULTS

Ruggedness Example Calculations for S_i Results Assuming Uniaxial Pre-Strain Free Recovery (UPFR)											
Run Number	**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	148.371	150.495	149.433	2.124
2	–1	+1	+1	+1	–1	+1	–1	158.762	160.598	159.680	1.836
3	–1	–1	+1	+1	+1	–1	+1	148.682	149.741	149.211	1.059
4	+1	–1	–1	+1	+1	+1	–1	154.932	143.138	149.035	–11.794
5	–1	+1	–1	–1	+1	+1	+1	149.386	148.880	149.133	–0.506
6	+1	–1	+1	–1	–1	+1	+1	153.612	156.066	154.839	2.454
7	+1	+1	–1	+1	–1	–1	+1	155.828	152.267	154.048	–3.561
8	–1	–1	–1	–1	–1	–1	–1	157.642	156.574	157.108	–1.068
Avg. of +1	151.839	153.073	153.291	152.994	149.203	153.172	151.808				
Avg. of –1	153.783	152.548	152.331	152.628	156.419	152.450	153.814		s_d	4.73611	
Main Effect	–1.9443	0.5253	0.9602	0.3655	–7.2155	0.7217	–2.0065		s_{rep}	3.34893	
| Main Effect |	1.9443	0.5253	0.9602	0.3655	7.2155	0.7217	2.0065		S_{effect}	1.67447	
Rank	3	6	4	7	1	5	2				

TABLE XXXII.—FACTOR RANKINGS AND CALCULATED VALUES FOR EFFECTS ON STRESS AT MAXIMUM STRAIN DURING PRE-STRAINING, S_i, RESULTS

Statistical Significance of Effects—Example Calculations for S_i Results							
Factor ranking	**Factor**	**Effect**	**| Effect |**	**Student's *t*-value**	**| Student's *t*-value |**	**Two tailed *p-value*, (%)**	**Half-normal plotting values**
1	E	–7.2155	7.2155	–4.309	4.309	0.353	1.803
2	G	–2.0065	2.0065	–1.198	1.198	26.980	1.242
3	A	–1.9443	1.9443	–1.161	1.161	28.365	0.921
4	C	0.9602	0.9602	0.573	0.573	58.430	0.674
5	F	0.7217	0.7217	0.431	0.431	67.943	0.464
6	B	0.5253	0.5253	0.314	0.314	76.289	0.272
7	D	0.3655	0.3655	0.218	0.218	83.342	0.090

TABLE XXXIII.—RUGGEDNESS EXAMPLE CALCULATIONS FOR INITIAL LOADING STRAIN AT *LCT*, e_0, RESULTS

Ruggedness Example Calculations for e_0 Results Assuming Uniaxial Pre-Strain Free Recovery (UPFR)											
Run Number	**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	0.00078	0.00030	0.00054	–0.00048
2	–1	+1	+1	+1	–1	+1	–1	0.00110	0.00240	0.00175	0.00130
3	–1	–1	+1	+1	+1	–1	+1	–0.00100	0.00010	–0.00045	0.00110
4	+1	–1	–1	+1	+1	+1	–1	–0.00090	–0.00030	–0.00060	0.00060
5	–1	+1	–1	–1	+1	+1	+1	–0.00130	0.00230	0.00050	0.00360
6	+1	–1	+1	–1	–1	+1	+1	–0.00120	–0.00020	–0.00070	0.00100
7	+1	+1	–1	+1	–1	–1	+1	–0.00010	–0.00050	–0.00030	–0.00040
8	–1	–1	–1	–1	–1	–1	–1	0.00050	0.00000	0.00025	–0.00050
Avg. of +1	–0.00027	0.00062	0.00029	0.00010	0.00000	0.00024	–0.00024				
Avg. of –1	0.00051	–0.00038	–0.00004	0.00015	0.00025	0.00001	0.00049	s_d	0.00136		
Main Effect	–0.00078	0.00100	0.00032	–0.00005	–0.00025	0.00023	–0.00072	s_{rep}	0.00096		
| Main Effect |	0.00078	0.00100	0.00032	0.00005	0.00025	0.00023	0.00072	S_{effect}	0.00048		
Rank	2	1	4	7	5	6	3				

TABLE XXXIV.—FACTOR RANKINGS AND CALCULATED VALUES FOR EFFECTS ON INITIAL LOADING STRAIN AT *LCT*, e_0, RESULTS

Statistical Significance of Effects—Example Calculations for e_0 Results							
Factor ranking	**Factor**	**Effect**	**| Effect |**	**Student's *t*-value**	**| Student's *t*-value |**	**Two tailed *p-value*, (%)**	**Half-normal plotting values**
1	B	0.00100	0.00100	2.068	2.068	7.740	1.803
2	A	–0.00078	0.00078	–1.612	1.612	15.096	1.242
3	G	–0.00072	0.00072	–1.498	1.498	17.777	0.921
4	C	0.00032	0.00032	0.669	0.669	52.510	0.674
5	E	–0.00025	0.00025	–0.524	0.524	61.674	0.464
6	F	0.00023	0.00023	0.472	0.472	65.147	0.272
7	D	–0.00005	0.00005	–0.098	0.098	92.430	0.090

TABLE XXXV.—RUGGEDNESS EXAMPLE CALCULATIONS FOR MAXIMUM LOADING STRAIN, e_i, RESULTS

Ruggedness Example Calculations for e_i Results Assuming Uniaxial Pre-Strain Free Recovery (UPFR)											
Run Number	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	2.00500	2.00450	2.00475	–0.00050
2	–1	+1	+1	+1	–1	+1	–1	2.00090	2.00110	2.00100	0.00020
3	–1	–1	+1	+1	+1	–1	+1	1.99960	1.99960	1.99960	0.00000
4	+1	–1	–1	+1	+1	+1	–1	2.00330	1.99890	2.00110	–0.00440
5	–1	+1	–1	–1	+1	+1	+1	1.99880	2.00350	2.00115	0.00470
6	+1	–1	+1	–1	–1	+1	+1	2.00470	2.00310	2.00390	–0.00160
7	+1	+1	–1	+1	–1	–1	+1	2.00580	2.00520	2.00550	–0.00060
8	–1	–1	–1	–1	–1	–1	–1	2.00820	2.00030	2.00425	–0.00790
Avg. of +1	2.00381	2.00310	2.00231	2.00180	2.00165	2.00179	2.00254				
Avg. of –1	2.00150	2.00221	2.00300	2.00351	2.00366	2.00353	2.00278			s_d	0.00367
Main Effect	0.00231	0.00089	–0.00069	–0.00171	–0.00201	–0.00174	–0.00024			s_{rep}	0.00260
| Main Effect |	0.00231	0.00089	0.00069	0.00171	0.00201	0.00174	0.00024			S_{effect}	0.00130
Rank	1	5	6	4	2	3	7				

TABLE XXXVI.—FACTOR RANKINGS AND CALCULATED VALUES FOR EFFECTS ON MAXIMUM LOADING STRAIN, e_i, RESULTS

Statistical Significance of Effects—Example Calculations for e_i Results							
Factor ranking	Factor	Effect	| Effect |	Student's *t*-value	| Student's *t*-value |	Two tailed *p-value*, (%)	Half-normal plotting values
1	A	0.00231	0.00231	1.782	1.782	11.797	1.803
2	E	–0.00201	0.00201	–1.551	1.551	16.491	1.242
3	F	–0.00174	0.00174	–1.339	1.339	22.248	0.921
4	D	–0.00171	0.00171	–1.320	1.320	22.850	0.674
5	B	0.00089	0.00089	0.684	0.684	51.606	0.464
6	C	–0.00069	0.00069	–0.530	0.530	61.267	0.272
7	G	–0.00024	0.00024	–0.183	0.183	85.998	0.090

TABLE XXXVII.—RUGGEDNESS EXAMPLE CALCULATIONS FOR UNLOADED STRAIN, e_u, RESULTS

Ruggedness Example Calculations for e_u Results Assuming Uniaxial Pre-Strain Free Recovery (UPFR)											
Run Number	**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	1.51650	1.46980	1.49315	–0.04670
2	–1	+1	+1	+1	–1	+1	–1	1.42340	1.51190	1.46765	0.08850
3	–1	–1	+1	+1	+1	–1	+1	1.50200	1.49820	1.50010	–0.00380
4	+1	–1	–1	+1	+1	+1	–1	1.50350	1.48740	1.49545	–0.01610
5	–1	+1	–1	–1	+1	+1	+1	1.54230	1.51620	1.52925	–0.02610
6	+1	–1	+1	–1	–1	+1	+1	1.48490	1.45510	1.47000	–0.02980
7	+1	+1	–1	+1	–1	–1	+1	1.51300	1.47280	1.49290	–0.04020
8	–1	–1	–1	–1	–1	–1	–1	1.51050	1.46990	1.49020	–0.04060
Avg. of +1	1.48788	1.49574	1.48273	1.48903	1.50449	1.49059	1.49806				
Avg. of –1	1.49680	1.48894	1.50195	1.49565	1.48019	1.49409	1.48661			s_d	0.04387
Main Effect	–0.00892	0.00680	–0.01923	–0.00663	0.02430	–0.00350	0.01145			s_{rep}	0.03102
| Main Effect |	0.00892	0.00680	0.01923	0.00663	0.02430	0.00350	0.01145			S_{effect}	0.01551
Rank	4	5	2	6	1	7	3				

TABLE XXXVIII.—FACTOR RANKINGS AND CALCULATED VALUES FOR EFFECTS ON UNLOADED STRAIN, e_u, RESULTS

Statistical Significance of Effects—Example Calculations for e_u Results							
Factor ranking	**Factor**	**Effect**	**| Effect |**	**Student's *t*-value**	**| Student's *t*-value |**	**Two tailed *p-value*, (%)**	**Half-normal plotting values**
1	E	0.02430	0.02430	1.567	1.567	16.118	1.803
2	C	–0.01923	0.01923	–1.239	1.239	25.512	1.242
3	G	0.01145	0.01145	0.738	0.738	48.441	0.921
4	A	–0.00892	0.00892	–0.575	0.575	58.304	0.674
5	B	0.00680	0.00680	0.438	0.438	67.431	0.464
6	D	–0.00663	0.00663	–0.427	0.427	68.212	0.272
7	F	–0.00350	0.00350	–0.226	0.226	82.792	0.090

TABLE XXXIX.—RUGGEDNESS EXAMPLE CALCULATIONS FOR RECOVERY STRAIN, e_{rec}, RESULTS

Ruggedness Example Calculations for e_{rec} Results Assuming Uniaxial Pre-Strain Free Recovery (UPFR)											
Run Number	**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	1.03040	1.05610	1.04325	0.02570
2	–1	+1	+1	+1	–1	+1	–1	1.04840	1.07560	1.06200	0.02720
3	–1	–1	+1	+1	+1	–1	+1	1.01970	0.97320	0.99645	–0.04650
4	+1	–1	–1	+1	+1	+1	–1	1.03740	1.06860	1.05300	0.03120
5	–1	+1	–1	–1	+1	+1	+1	0.94590	0.98130	0.96360	0.03540
6	+1	–1	+1	–1	–1	+1	+1	0.97840	0.97880	0.97860	0.00040
7	+1	+1	–1	+1	–1	–1	+1	0.96860	0.98480	0.97670	0.01620
8	–1	–1	–1	–1	–1	–1	–1	1.00970	1.04890	1.02930	0.03920
Avg. of +1	1.01289	1.01139	1.02008	1.02204	1.01408	1.01430	0.97884				
Avg. of –1	1.01284	1.01434	1.00565	1.00369	1.01165	1.01143	1.04689		s_d	0.02807	
Main Effect	0.00005	–0.00295	0.01442	0.01835	0.00243	0.00287	–0.06805		s_{rep}	0.01985	
| Main Effect |	0.00005	0.00295	0.01442	0.01835	0.00243	0.00287	0.06805		S_{effect}	0.00992	
Rank	7	4	3	2	6	5	1				

TABLE XL.—FACTOR RANKINGS AND CALCULATED VALUES FOR EFFECTS ON RECOVERY STRAIN, e_{rec}, RESULTS

Statistical Significance of Effects—Example Calculations for e_{rec} Results							
Factor ranking	**Factor**	**Effect**	**| Effect |**	**Student's *t*-value**	**| Student's *t*-value |**	**Two tailed *p-value*, (%)**	**Half-normal plotting values**
1	G	–0.06805	0.06805	–6.857	6.857	0.024	1.803
2	D	0.01835	0.01835	1.849	1.849	10.690	1.242
3	C	0.01442	0.01442	1.454	1.454	18.937	0.921
4	B	–0.00295	0.00295	–0.297	0.297	77.489	0.674
5	F	0.00287	0.00287	0.290	0.290	78.043	0.464
6	E	0.00243	0.00243	0.244	0.244	81.395	0.272
7	A	0.00005	0.00005	0.005	0.005	99.612	0.090

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