Dimensional Stability of 17-7 Stainless Steel Springs

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Introduction

The use of precision formed springs presents a challenge to the designer of fine mechanisms. The forming process by its nature introduces stress in excess of the yield stress of the material used, and relaxation after forming leaves substantial residual stress. Subsequent heat treatment must be limited to those processes which preserve the necessary high yield strength of the spring material. This limitation results in residual stress levels which have the potential to drive dimensional instability mechanisms. The present study was motivated by the observation that a group of 6 mm U-shaped 17-7 stainless steel springs had changed free state dimension after several years of storage. Fifty-three springs from this lot have been examined at the Center for Precision Metrology at the University of North Carolina at Charlotte in an attempt to determine the magnitude and nature of the underlying dimensional instability mechanism. While the initial dimensional instability of the springs is unknown, the level of continuing dimensional change in the springs provides a bound on the behavior at early times. Dimensional instability as well as temperature dependence of the instability mechanism have been observed in the springs.

OCMM Measurement

Spring dimensional measurements were carried out using an Optical CMM in the metrology lab of the UNCC Center for Precision Metrology. Through lighting illumination and an objective lens with magnification of 20 were used to analyze machine repeatability. To assess the repeatability of measurement independent of the actual spring geometry, a series of repeated measurements were made of a precision coated glass reference artifact with scales in the x- and y-directions. The distances between the scale lines were measured and used to evaluate short-term measurement repeatability. In each measurement, the scale was measured along +x (or +y) direction and then along –x (or –y) direction to reduce the effect of any backlash in the system. The average of the measurements in the two reverse directions is used as the result of a single measurement. The process was repeated several times and the standard deviation of 14 groups of measurements was 75 nm for the x-direction and 240 nm for the y-direction.

The long-term stability of the OCMM measurements was assessed by repeating the initial repeatability tests after six months had elapsed. The measurement instrument, measurement object, measurement procedures and data processing method were the same as those in the original tests. The standard deviation of 14 groups of measurements for this data was 77 nm for the x-direction and 250 nm for the y-direction. The result of this measurement series shows that both the value and uncertainty of measurements are essentially independent of the measurement date. No statistically significant linear drift was apparent.

To assess the underlying uncertainty of the spring measurement process, a series of experiments was carried out to assess the repeatability of the optical measurement of spring opening. The spring dimension was measured 30 times along both +x and –x directions. The entire cycle of steps, including removal and replacement of the spring from the machine was repeated 14 times. The test shows that the most repeatable measurement that characterizes the spring dimension is that of the median opening as determined from the average of the measurements in both +x and –x directions. The average of the standard deviation of the 30 measurements in each group is 53 nm. The standard deviation of 14 groups of measurements that were made over the period of a week is 192 nm, which is taken to be the estimate of the uncertainty for each spring dimension measurement.

Spring Data Summary

The dimensional stability of 53 springs has been analyzed for approximately sixteen months. The 53 springs were separated into two groups: untreated springs and temperature treated springs. 17 springs were subjected to heat treatments at several elevated temperatures or chilled to liquid nitrogen temperature. The remaining 36 springs were measured in an undisturbed state. It should be noted that the 36 undisturbed springs may not be representative of the entire lot because the 17 springs removed for thermal treatment typically had relatively large drift rates when compared to the rest of the lot. Springs that were thermally treated were heated or cooled at a maximum rate of 4° F per minute in order to avoid thermal stresses. The springs were heat treated in a vacuum oven with a custom digital temperature controller with cascaded thermocouple feedback loops. Temperature uncertainty is approximately 0.5° F for a range of 125° F to 400° F.

The average of the observed best-fit linear drift rates of the 36 untreated springs is 0.22 nm/day. The standard deviation of the best-fit drift rates is 1.22 nm/day, and the uncertainty of a single spring drift rate measurement is 0.38 nm/day. The average drift rate is statistically significant. 32 of the 36 springs have drift rates with larger magnitude than their drift rate uncertainties, which suggests that a large percentage of the springs may have significant drift rates. The standard deviation of the drift rates is significantly larger than the drift rate measurement uncertainty, which suggests there is a statistically significant distribution of the drift rates. A chi-square test verifies this hypothesis with greater than 99.99% certainty. The histogram data shown in Figure 1-1 (bin size is 0.5 nm/day) suggests that the lot of springs does not have a very normal distribution of drift rates. Three springs have high drift rates near 5 nm/day that prevent the measured distribution from tailing off like the Gaussian distribution. Also, a relatively large number of springs have drift rates of approximately 2 nm/day.

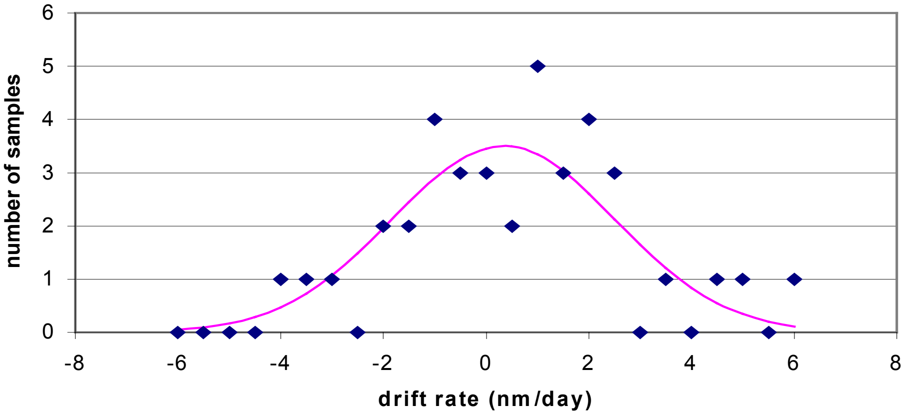

Figure 1-1: Untreated spring drift rate distribution with overlayed Gaussian distribution with standard deviation equal to that estimated from the population of samples

Of the 17 thermally treated springs, 15 springs were subjected to heat treatments at elevated temperatures to test the correlation of spring opening and drift rate to thermal cycling. It should be noted that the springs used for the heat treatment tests were chosen because of their relatively large drift rates and should not be viewed as a random sample from the lot. The statistics of the fitted linear drift rates of the 15 heat treated springs, prior to and after treatment, were:

average drift rate, nm/day:	Prior: 1.87 ±0.72	After: 0.11 ±0.36
standard deviation of drift rate, nm/day:	Prior: 2.78	After: 1.40
drift rate measurement uncertainty, nm/day:	Prior: 1.49	After: 0.60

The larger uncertainty in the initial drift rate of the treated springs (compared to the untreated springs) is attributable to the lower measurement time and the associated smaller number of data points used to estimate the slope through the spring drift data.

The average drift rate decreased from a statistically significant amount prior to treatment to a statistically insignificant value after treatment, suggesting that the heat treatments help to relieve stress or cause some other change in the springs to reduce their average drift rate. Since the measurement uncertainty of the post-treatment drift rates is larger than the standard deviation of the drift rates, it is unclear whether the heat treatments reduced the variability of the drift rates about the mean.

Figure 1-2 shows the change in spring opening versus the initial drift rate for three temperature treatments. Linear trend lines are plotted with the measured points to show correlation of the change in opening with initial drift rate. A spring treated at 93.3 °C (200 °F) with the change in opening of approximately 5 microns appears to be an outlier from the other points and was not used to fit the linear trend line. The slopes of the linear fit lines suggest that the higher the heat treatment temperature, the greater the sensitivity of the change in opening to initial drift rate. Additional tests and data at intermediate heat treatment temperatures could help to verify this theory.

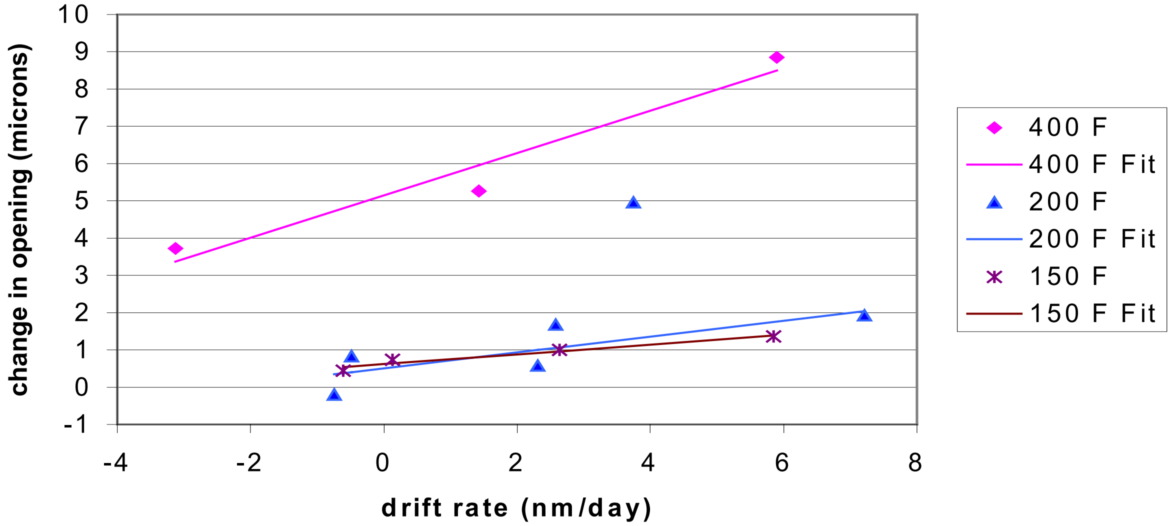

Figure 1-2: Change in spring opening versus initial drift rate for the springs heat treated at 150, 200, and 400 °F, with associated linear fits

Of the 17 heat treated springs, 6 were heat treated a second time. Three springs reheated to 204.4 °C (400 °F) showed no significant change in opening, in contrast to the change detected after the first heat treatment (average of 5.95 ± 1.24 μm). This may suggest that the first treatment relieved most or all of the unstable residual stress in the springs.

Three springs reheated to 93.3 °C (200° F for 12 hours) showed significant changes to both heat treatments. Statistics prior to and after the second treatment were:

average drift rate:	Prior: 0.05 ± 3.24 nm/day	After: 0.52 ± 0.66 nm/day
standard deviation of drift rate:	Prior: 5.61 nm/day	After: 1.14 nm/day
drift rate uncertainty:	Prior: 6.92 nm/day	After: 2.26 nm/day
average change in opening:	Prior: 1.78 ± 1.60 μm	After: 0.24 ± 0.28 μm

The average drift rates before and after treatment were both statistically insignificant, so a possible conclusion is that the heat treatment did not change the average drift rate. The same can be said of the standard deviation of the drift rates since both, before and after treatment, were statistically insignificant (ie. less than measurement uncertainty). The average change in spring opening was much lower for the second treatment than for the first treatment, which may suggest that the first treatment removed a significant amount of residual stress, but did not fully relieve the spring material.

To test for possible room temperature phase transition from residual metastable states, two springs were subjected to cryogenic temperatures by submersion (within a package insulated to limit cooling rate) into liquid nitrogen. The average drift rate of the two springs increased from 1.01 ± 1.59 nm/day to 4.12 ± 1.50 nm/day, which suggests that cryogenically treating the springs caused increased drift rates.

The activation energy associated with a simple creep mechanism has been estimated from the slope of a plot of the logarithm of creep rate versus inverse absolute. Figure 1-3 shows the three points, based on the average logarithmic creep rate caused by the heat treatments described above, used for fitting a line. The slope of this fitted line is –1435 K^{-1}, which gives an activation energy of 0.12 eV. Performing additional heat treatments at intermediate temperatures could help verify both the applicability of the simple activation energy model as well as the activation energy of the process.

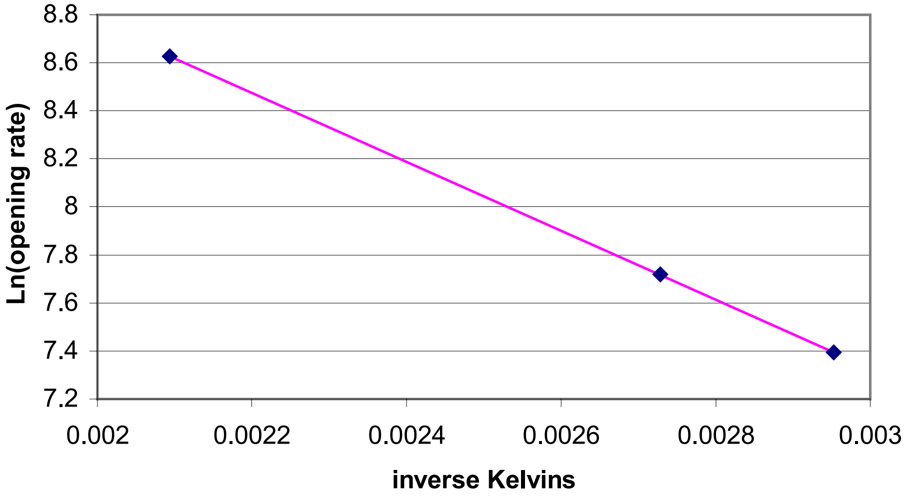

Figure 1-3: Average logarithmic creep rate from heat treatment versus inverse absolute temperature