VSR REPORT

ALLOY ENGINEERING
Berea, OH
November 2015

Alloy Engineering (AE) is a full-scale fab and machine shop, specializing in fabrication of exotic and high-temperature alloys. In this project, a series of ten polished austenitic stainless plates were rolled and seam welded, forming tubes that were ~ 78” long, 28” OD, and having 1/2” wall thickness.

During earlier production efforts, after “rounding” the tubes to within the required +/- 1/16” tolerance required prior to machining, these tubes in the past had been transported to a local provider of X-ray inspection services. Upon return, the tube ends would then be machined to allow assembly of end-caps, which, once assembled, would form a container used in a high-temperature isostatic press operation. The containers would then be transported a few hundred miles away, where the press operation was performed.

The challenge AE faced was a change-in-shape that occurred during transport, both during the trip to X-ray, and later to the end-user / press operation facility. “Re-rounding” of the tubes was needed to correct the changes-in-shape at each stage, further adding to production costs.

AE approached Advanced VSR to test whether a proper application of the VSR Process could render these tubes dimensionally stable, thus minimizing “rounding” tasks, and resulting in a higher- quality product that would better satisfy customer requirements.

Report prepared by:

Bruce Klauba
Advanced VSR Technology
Philadelphia, PA

Alloy Engineering (AE) is a full-scale fab and machine shop, specializing in fabrication of exotic and high-temperature alloys. In this project, a series of ten polished austenitic stainless plates were rolled and seam welded, forming tubes that were ~ 78" long, 28" OD, and having 1/2" wall thickness.

The challenge AE faced was a change-in-shape that occurred during transport, both during the trip to X-ray, and later to the end-user / press operation facility. "Re-rounding" of the tubes was needed to correct the changes-in-shape at each stage, further adding to production costs.

AE approached Advanced VSR to test whether a proper application of the VSR Process could render these tubes dimensionally stable, thus minimizing "rounding" tasks, and resulting in a higher- quality product that would better satisfy customer requirements.

VSR SETUP

Figure 1: VSR Setup used to stress relieve tubes, one of which is mounted upon a fixtured setup shown in the foreground. A T-slotted fixture plate, ~ 45" X 26" X 5" and weighing ~ 850 lbs., has mounted upon it two "saddles", whose contact surface with the tube is a rolled steel plate, very slightly larger than the tube OD. A similar saddle is clamped down from above. The saddles were separated by only 10" so that the majority of the workpiece was free to respond to vibration in an unrestricted manner, thus revealing their resonance pattern and undergoing sufficient flexure, a key requirement of the VSR Process, to cause effective stress relief.

An Advanced VSR Model 7.5 System stress relieved the 11 parts shown in this report.

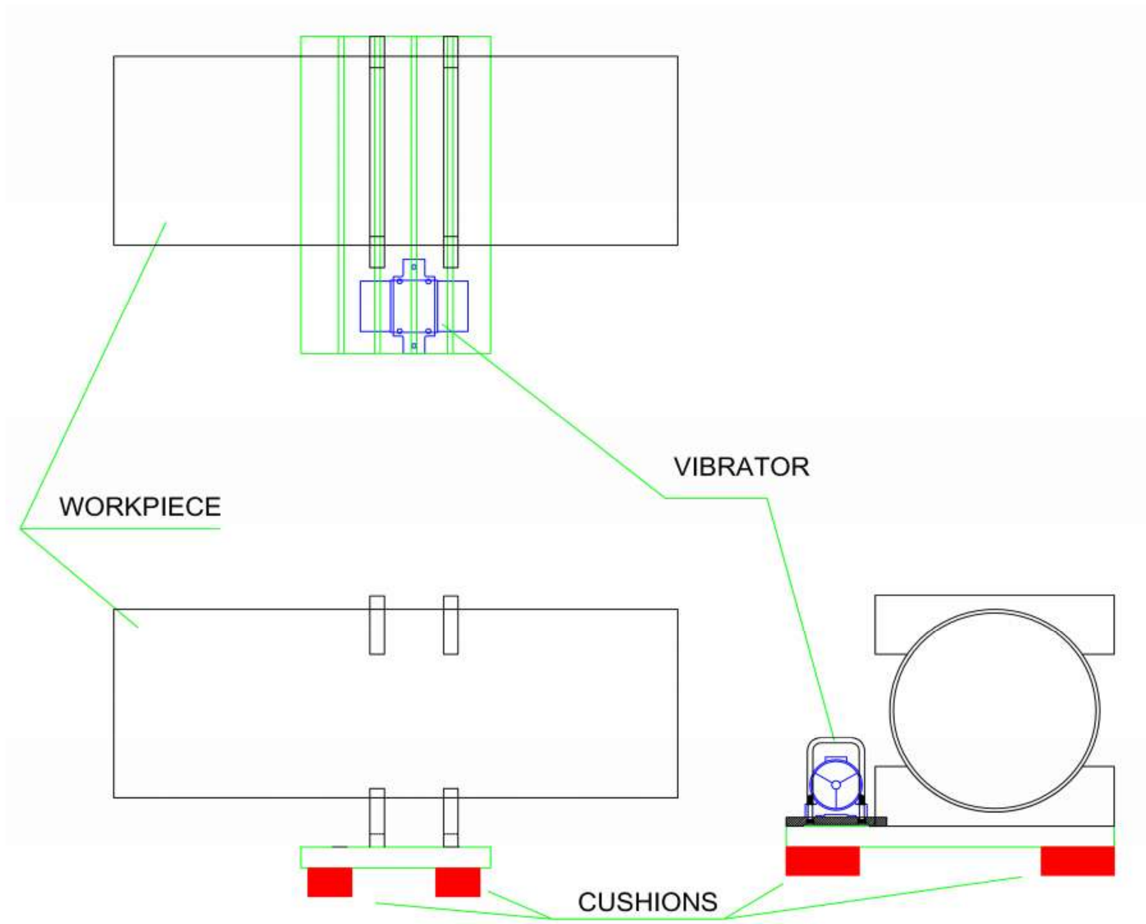

Figure 2: Drawing depiction of VSR Setup shows positions of fixture (green rectangle), vibrator, workpiece and cushions. Fasteners and accelerometer are not shown, for clarity.

Fixturing is often used to allow VSR Processing of workpieces that are too light, or are oddly-shaped / curved surfaced, which prevents setup directly upon cushions and clamping of the vibrator directly to the workpiece. However, the fixture design also must achieve two goals that, if not properly balanced in consideration, can interfere with one-another:

- Forming a mechanical pathway thru the tooling / clamping, for vibration to enter the workpiece efficiently, with minimal loss or noise (during vibration) due to insufficient “fit”.
- Minimizing of the damping of the workpiece, so as to allow the resonance behavior of the workpiece to be depicted during VSR scans.

Although some adjustment of the setup was required, and the saddles were less rigid or dimensionally accurate than the original, recommended design (which was to have the saddles made from aluminum plate stock), the VSR Setup was successful in achieving these goals, although starting to suffer signs of “wear and tear” after 10 tubes were stress relieved.

The VSR Process uses resonant vibration to cause sufficient flexure of the work-piece, so to combine the dynamic load from resonant vibration with residual stresses trapped in the material, resulting in plastic flow. Several independent research works, including those of Hahn[1], Shankar[2], and Yang, Jung and Yancey[3], have proven that resonance frequency vibration is the most effective form of vibration to relieve stress.

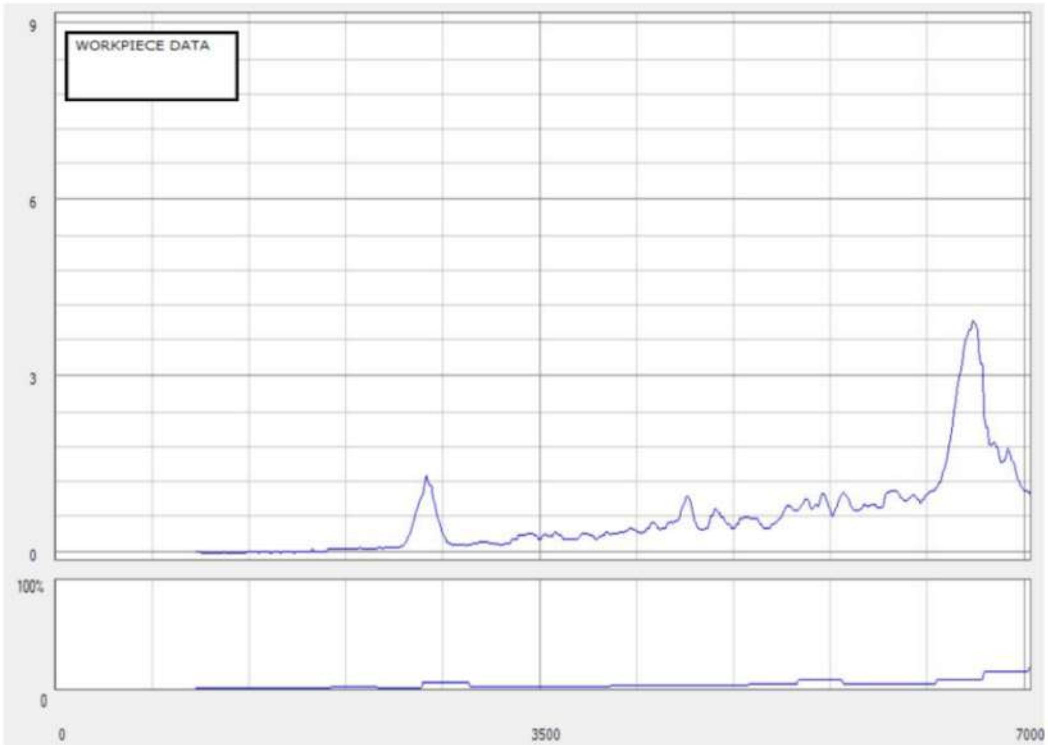

Figure 3: Workpiece 1, Quick Scan using 20% unbalance. This unbalance was found to be the correct setting to stress relieve all 10 tubes, based upon the completed VSR Treatment Chart data, Figures 5 thru 15. A Quick Scan (QS) of work-piece is done for calibration purposes. QS's use a scan rate of 50 RPM / second, and take less than two minutes to produce. VSR Treatment Charts consist of two plots:

- An upper plot of work-piece acceleration and a lower plot of vibrator input power, both of these plotted on a vertical axis vs. a common horizontal axis of vibrator RPM.
- Peaks in the upper plot are resonances of the work-piece.
- Peaks in the lower plot are resonances that cause increased, perhaps excessive, vibrator input power. One of the benefits of using a fixture is that peaks in power are kept to a minimum, if not eliminated.

Full-scale for acceleration for this chart = 9 g's; for RPM = 7 KRPM.

Re-scaling of acceleration or RPM can be done without compromise of vibration data integrity.

---

1 Dr. William Hahn, Vibratory Residual Stress Relief and Modifications in Materials to Conserve Resources and Prevent Pollution

2 Dr. S. Shankar, Vibratory Stress Relief of Mild Steel Weldments

3 Drs. Y. P. Yang, G. Jung, and R. Yancey, Finite Element Modeling Of Vibration Stress Relief After Welding

The accelerometer (a sensor whose output is proportional to acceleration) was placed on the end of the work-piece, adjacent to the weld-seam, and was oriented so as to be most sensitive to horizontal amplitude. The accelerometer clamp (if not the accelerometer) is visible in Figure 1, in the left mid-foreground. The parameter acceleration is used, as opposed to velocity or displacement, since it is the best parameter to monitor the dynamic load (force) induced in the work-piece, consistent with Newton's 2^{nd} Law: **F = ma** (Force is equal to mass X acceleration). Independent research has shown that load or pressure within the workpiece is the correct parameter to gauge the intensity of external excitation.

VSR Treatment

VSR Treatment is done by tuning upon the work-piece resonant peaks, and monitoring any changes in resonant response. Generally speaking, stress relieving causes two distinct changes in resonance pattern to take place:

1. An increase in the height of the resonance peak (typically the strongest response)
2. A shift of the resonance frequency in the direction of lower frequency (to the left on VSR Treatment charts)
3. A shift to the right of the resonance peak is typically an indication of a change-in-shape of the workpiece. Such changes were seen to take place as a result of VSR Treatment, but the changes were small, not taking the workpiece outside dimensional requirements.

After the Quick Scan is performed, a Pre-Treatment Scan (or Pre-Scan) is made. The Pre-Scan plots a high-resolution version of the data shown in the Quick Scan, and is used as a base-line: Quick Scans are fine for calibration, but often record the peaks shorter than they actually are, and also can miss very narrow peaks.

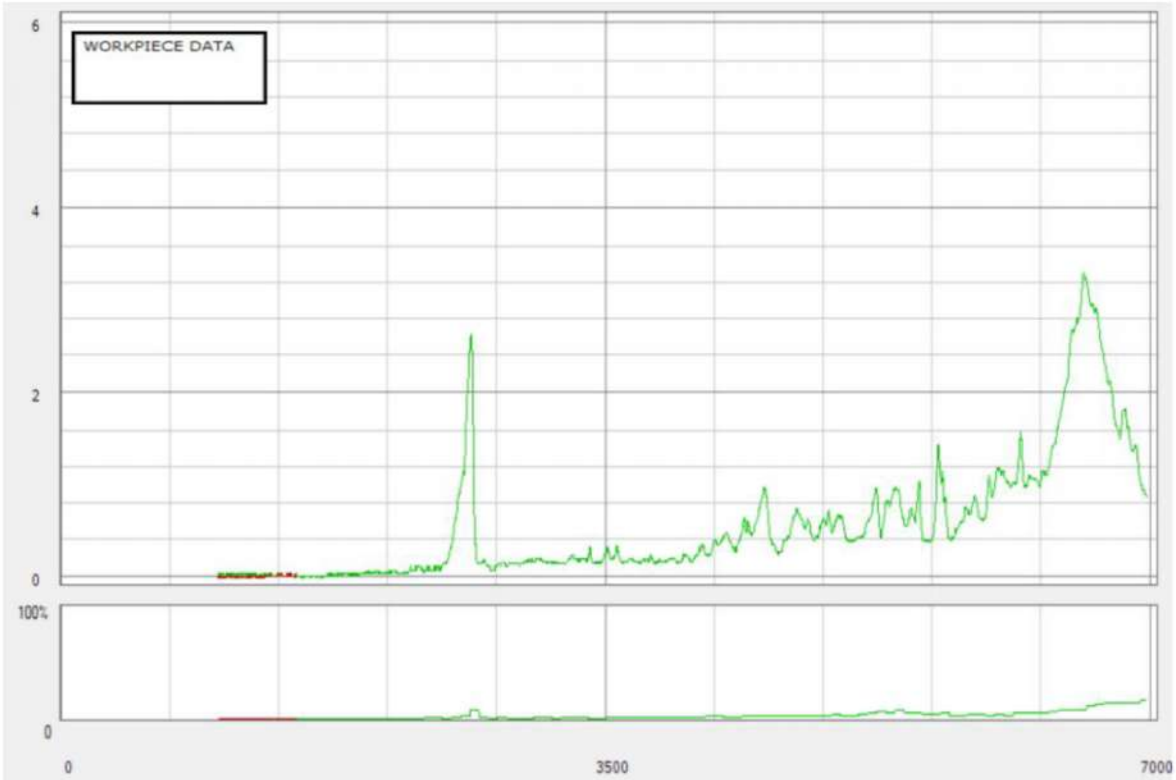

Figure 4: Workpiece 1, Pre-Treatment Scan / Baseline is a higher resolution version of the data shown in Quick Scan (Figure 3). This higher resolution is achieved by using a slower scan rate than the QS, in these cases the standard Pre- & Post-Treatment Scan rate of 10 RPM / sec. The VSR Technician uses the Pre-Scan data to tune the vibrator speed upon the resonances, and watch changes in resonance take place that accompany, and are indications of, stress relief. This chart shows two large resonances, one located at ~ 2600 RPM and is rather narrow. The other broader and higher in frequency is ~ at 6500 RPM.

These two peaks were seen during all the scans of the tubes, with minor variations in frequency. Although other peaks were dwelt upon and treated, these two peaks consistently were those that caused the changes in resonance pattern seen during these treatments, which were chiefly peak growth, with modest amount of peak shifting. At times the peak shifting was to the right, indicating a change in workpiece shape, although loosening of the fixtured setup complicated this response. In the event that further VSR Processing is performed on this project, improvements in the rigidity and clamping quality would be recommended.

Full-scales for this chart are 6 g's for acceleration and 7 KRPM for vibrator speed. The full-scale for vibrator input power (lower curve) is fixed at 1200 watts, the capacity of the vibrator.

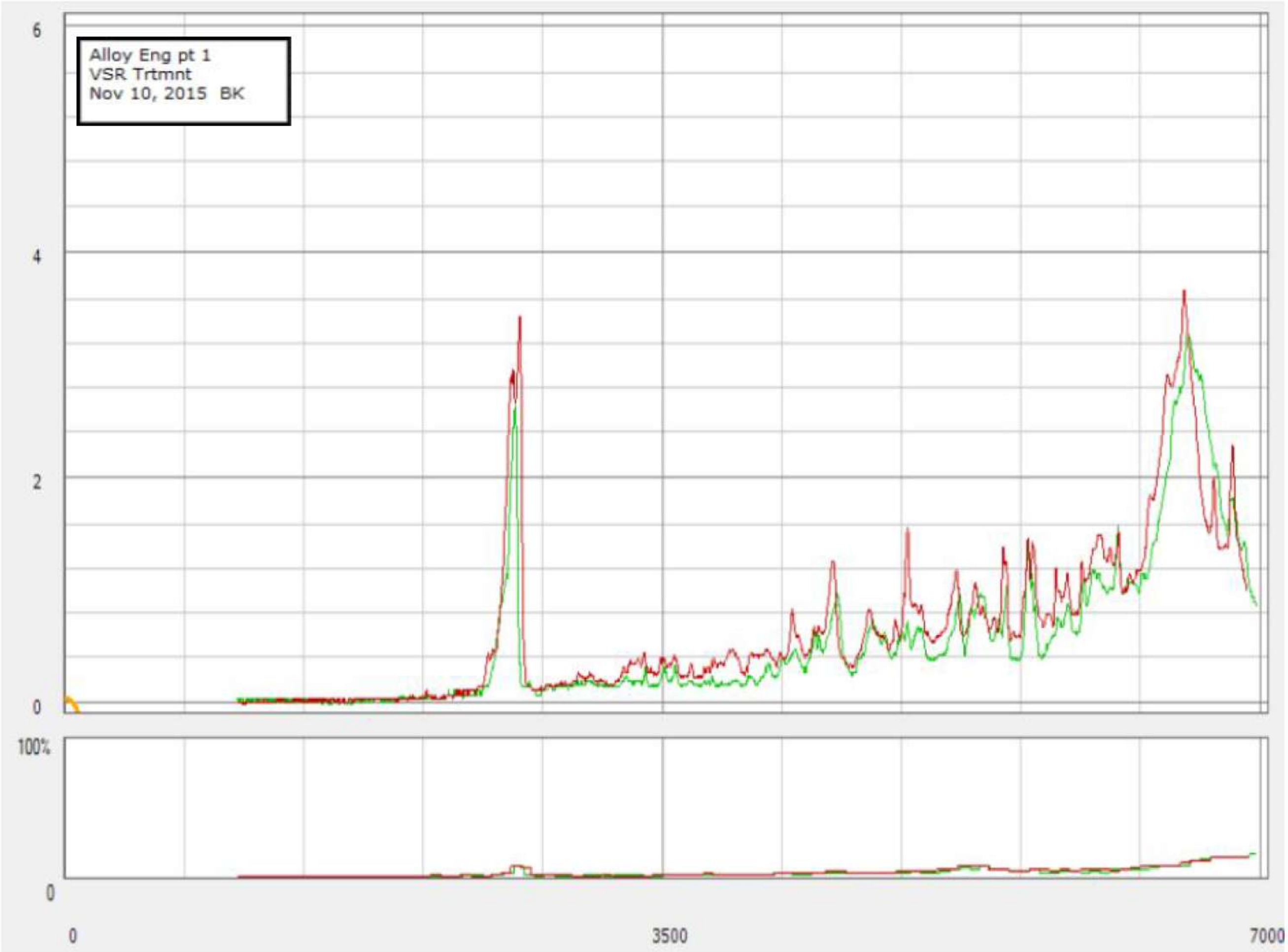

Figure 5: VSR Treatment of Workpiece 1 shows peak growth as being the chief response. The red, Post-Treatment scan is done in red, and superimposed upon the green, Pre-Scan data. Peak height increases were ~ 30%. Treatment time on each peak was approximately 15 minutes.

Full-scales for this chart are 6 g's for acceleration and 7 KRPM for vibrator speed.

Although many of the peaks shown in this and other vibration data are narrow (are small in the X-axis, as compared with the Y-axis), this posed no difficulties, since the Model 7.5 VSR Console and VS9 Vibrator supply speed regulation of less than 0.1 %, and the vibrator can be tuned during treatment in increments of 6 RPM. The VS9 Vibrator has a max speed of 9000 RPM and adjustable unbalance over a range of 0.1 – 2.0 in-lbs.

With this level of control, and VSR 5.3.1 software, the operators were able to perform the VSR Process upon these 11 workpieces in roughly 15 working hours.

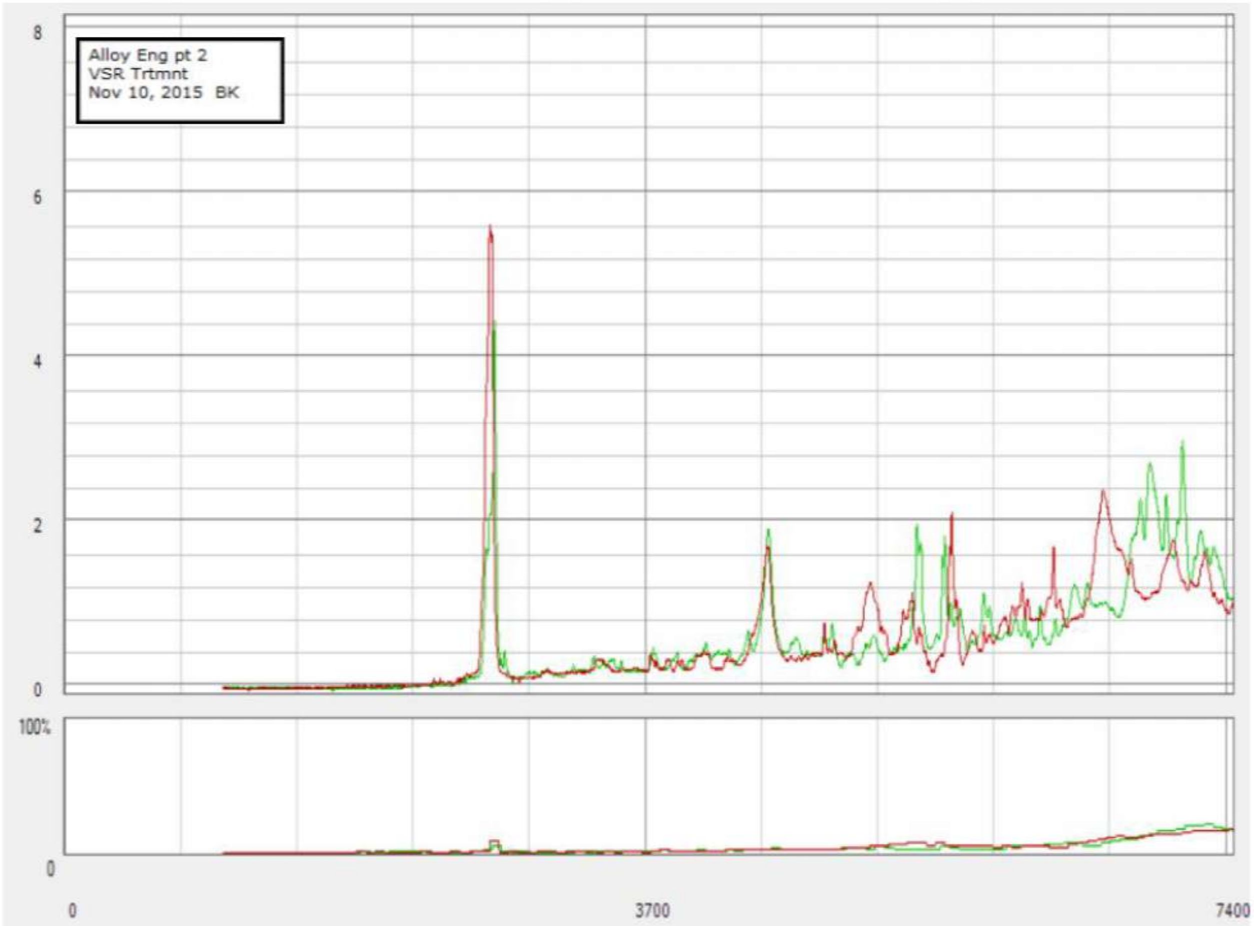

Figure 6: VSR Treatment of Workpiece 2 shows peak growth of the peak at ~ 2600 RPM as being the chief response, while peak shifting of the higher frequency peak at ~ 6500 RPM, took place. 2600 RPM peak height increase was ~ 35%. Treatment time on each peak was approximately 10 - 15 minutes, so the total treatment time was ~ one hour.

As other tubes were stress relieved, it became increasing clear that some of the peak shifting, and at times, peak disappearance, was likely due to loosening of the fixturing during treatment. Compensation for this loosening was done by re-tightening the nuts holding the upper saddles down. However, some “buggering” of the threads, esp of the hex nuts, started preventing such re-tightening. This is one area where improvement in the fixturing would be recommended, by using heat-treated, rather than all-thread rod, and milling-clamp grade nuts, instead of standard, Grade 5 nuts.

Full-scales for this chart are 8 g's for acceleration and 7 KRPM for vibrator speed.

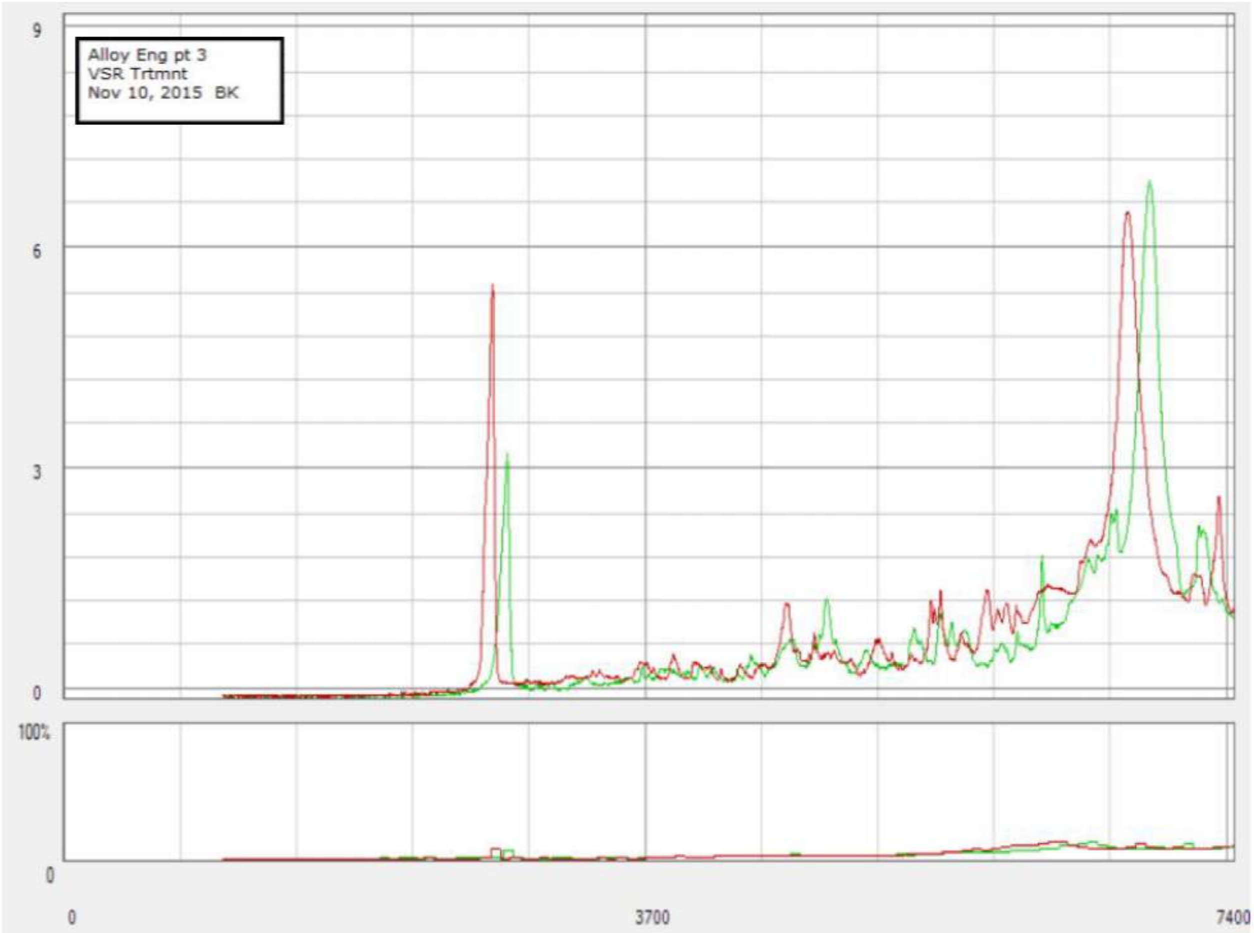

Figure 7: VSR Treatment of Workpiece 3 was performed with more attention paid to maintenance of clamping quality: Hex nuts on top of the upper saddle were periodically checked and maintained at reasonably constant torque. This effort resulted in one of the clearest set of VSR Treatment data seen up to this point, showing almost doubling of the peak height of the lower frequency peak, and clear shifting of the higher frequency peak, of roughly 140 RPM to the left. Peak height remained very much the same, but it is worth noting that variations in vibrator speed cause variations in vibrator force output proportional to the square of the RPM difference. E.g.: a reduction of 140 RPM from 6850, ~ 2 % drop will result in a reduction of ~ 4 % of the force output of the vibrator, which is very close to the peak reduction shown.

Treatment times were again, roughly 15 minutes per peak.

Full-scales for this chart are 9 g's for acceleration and 7.4 KRPM for vibrator speed.

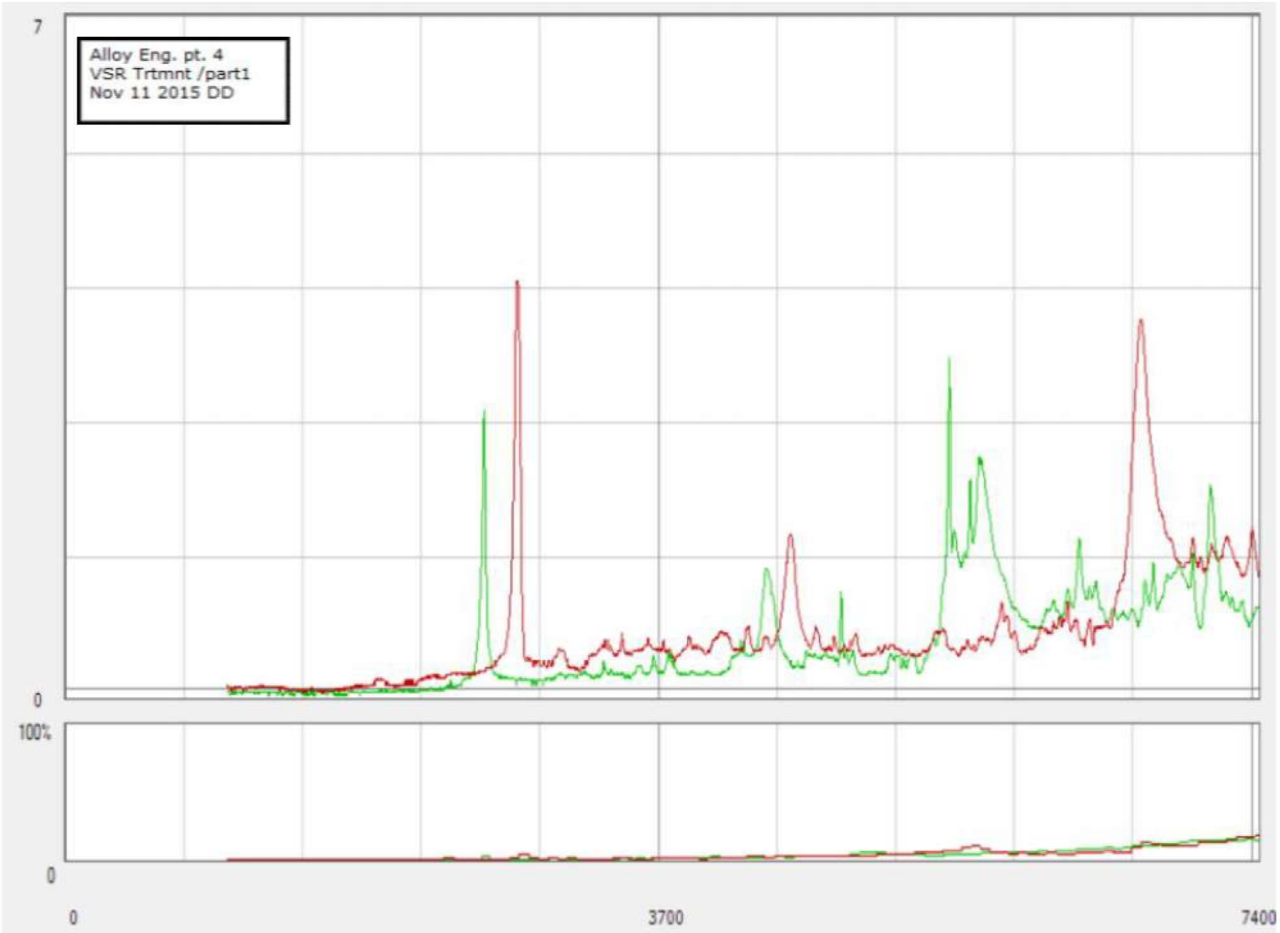

Figure 8: Workpiece 4, partial VSR Treatment (clamps loosened, re-tightened and new Post data plotted, shown in next figure). Loosening of the clamps became such a problem during this treatment, that a premature Post-Scan was done to document the progress-to-date, and a second treatment performed using fresh vibration data (shown in Figure 9).

Full-scales for this chart are 7 g's for acceleration and 7.4 KRPM for vibrator speed.

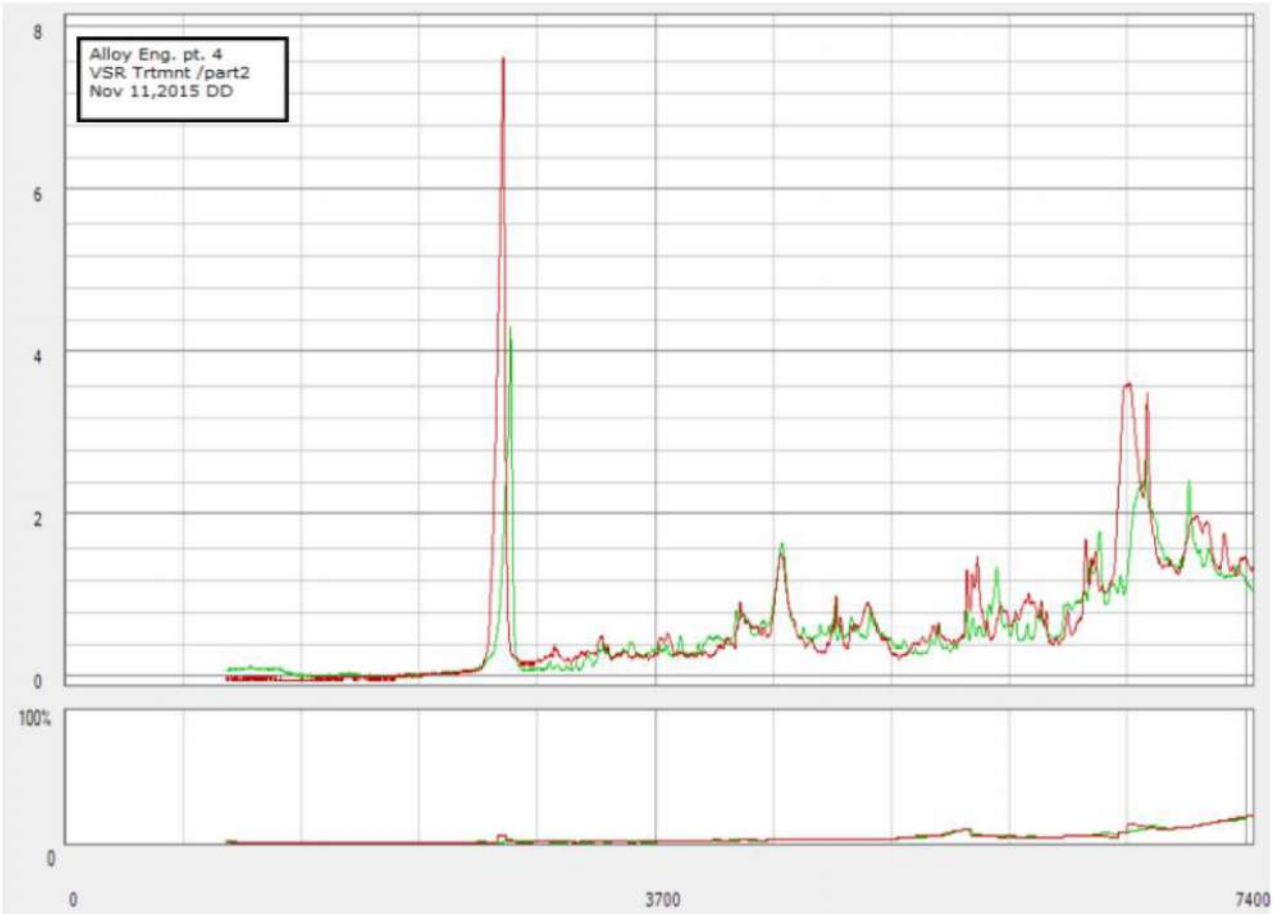

Figure 9: Workpiece 4, 2nd portion of VSR Treatment started and depicted in Figure 8. After re-establishing clamping tightness, this treatment resulted in the large peak growth of the lower frequency peak, doubling in size, accompanied by mild, leftward shifting. Some splitting of the upper frequency peak, resulting in two individual peaks, can be seen.

Again, some of these less-than-classic changes in resonance pattern can be attributed to changes in fixturing / clamping quality. It should be noted that, even with high-quality tooling, such data can sometimes occur.

Full-scales for this chart are 8 g's for acceleration and 7.4 KRPM for vibrator speed.

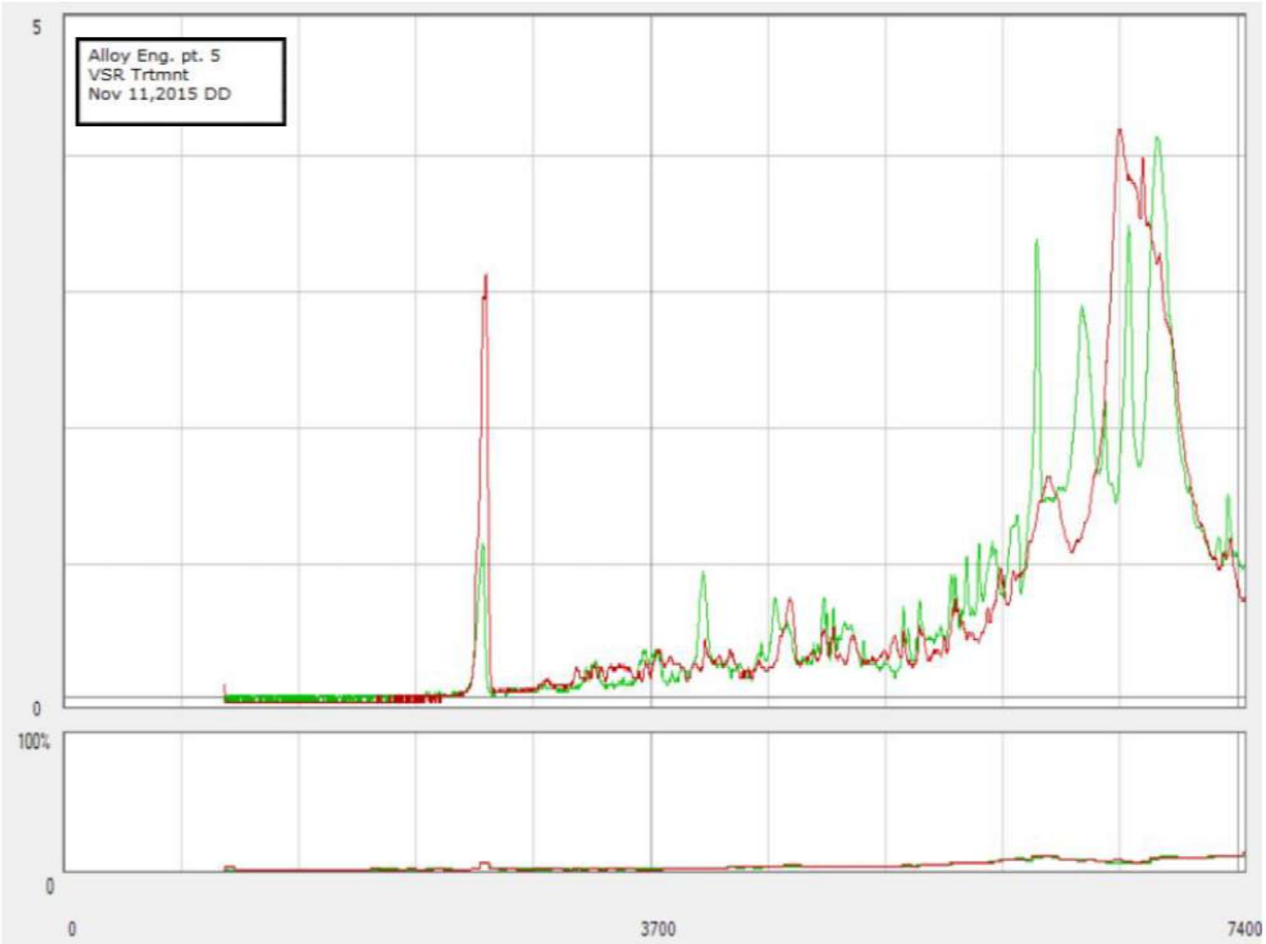

Figure 10: Workpiece 5 treatment data showed a lower frequency peak that more than tripled in height during stress relief. Results at upper frequencies were more complex, with some evidence of peaks combining, resulting in one broader, larger peak where originally there had been two.

This indicates that the stress pattern in the tube was likely causing the overall dynamic rigidity in one direction (orthogonal to the tube center-line) to be greater than the other (likely ~ 90 degrees apart). As stress relief occurred, these dynamic rigidity vectors became more equal, resulting in one larger, broader peak.

Full-scales for this chart are 5 g's for acceleration and 7.4 KRPM for vibrator speed.

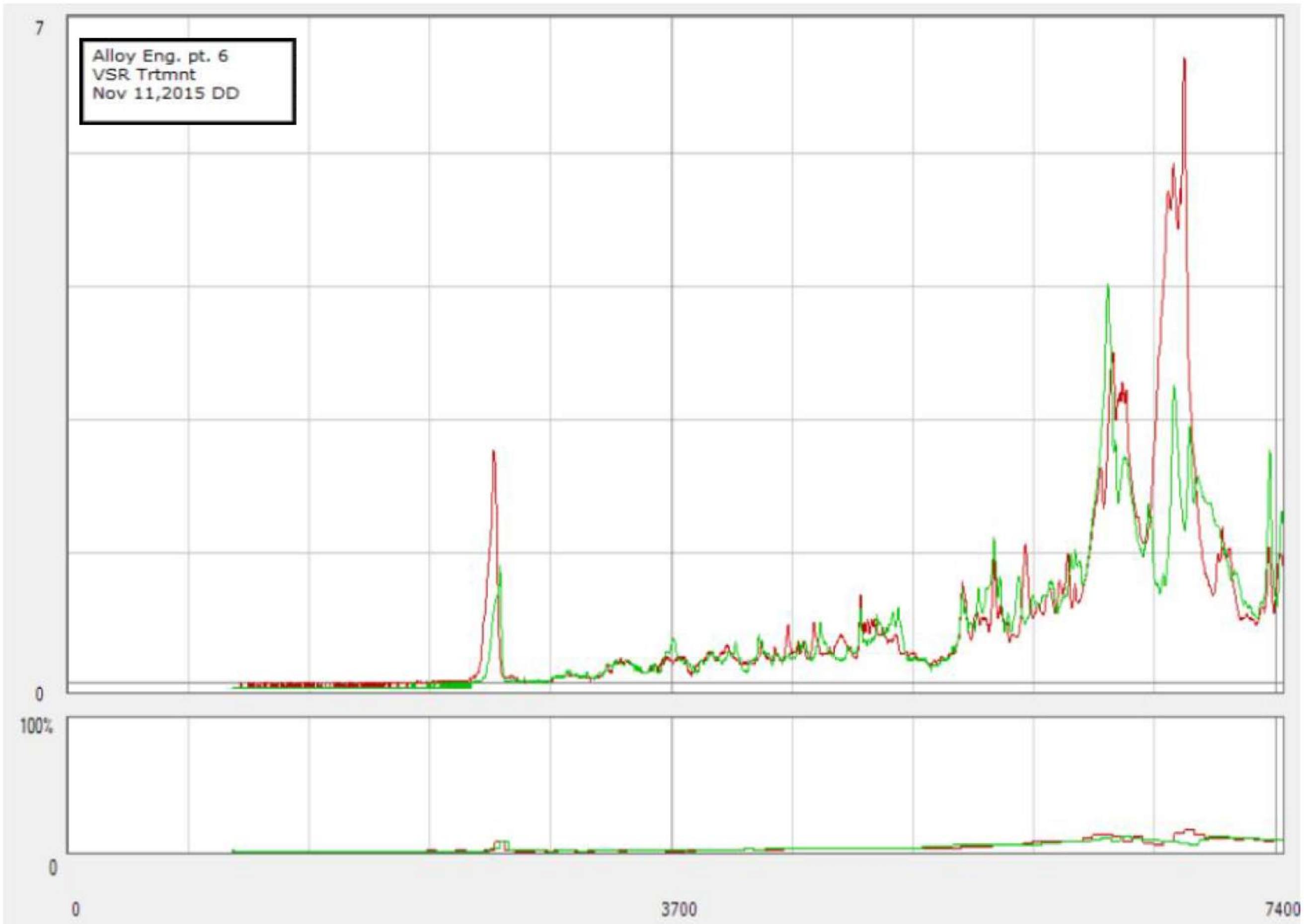

Figure 11: Workpiece 6 VSR Treatment shows again a doubling of the lower frequency peak height, albeit shorter than others, and changes in the upper frequencies that indicate both stress relief and some change-in-shape.

Full-scales for this chart are 7 g's for acceleration and 7.4 KRPM for vibrator speed.

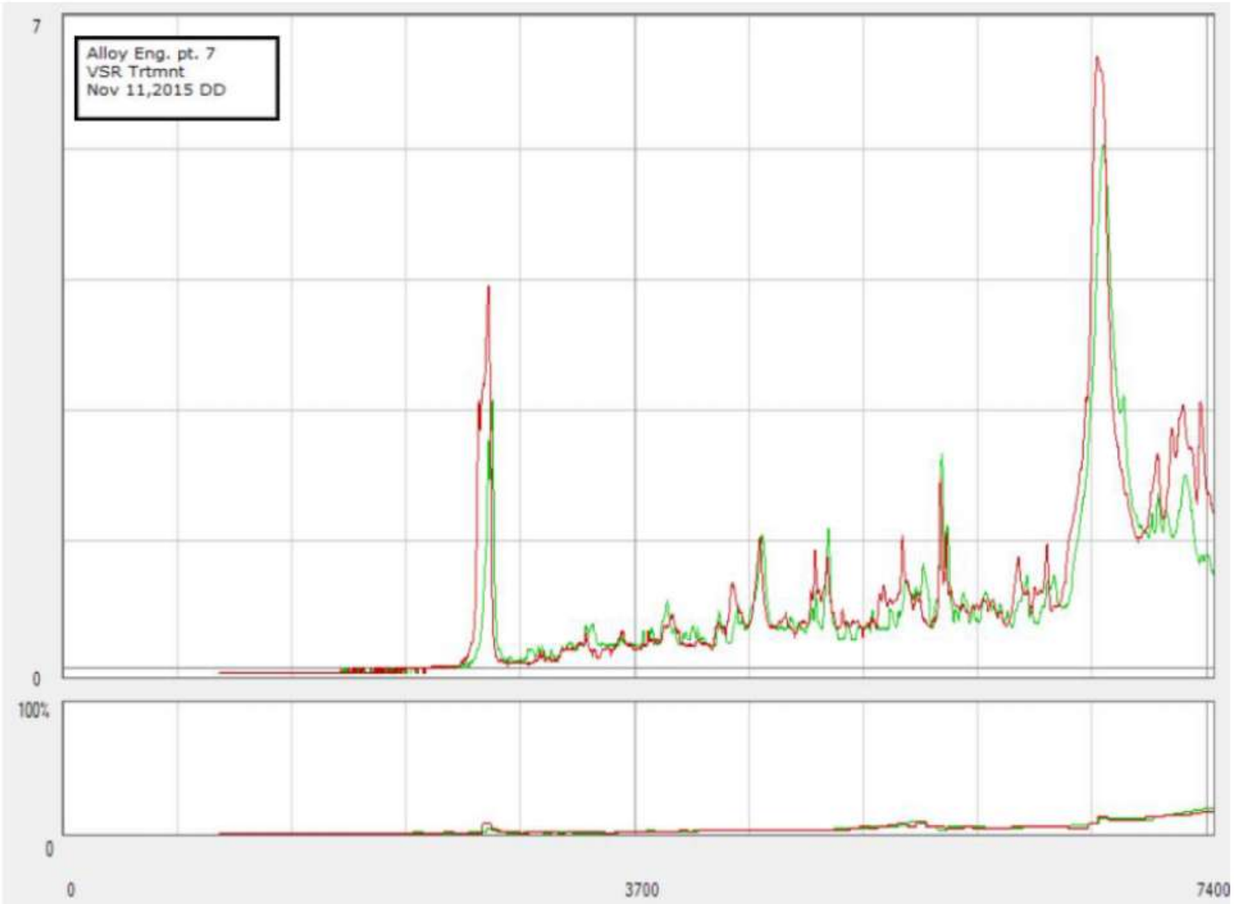

Figure 12: Workpiece 7 VSR Treatment shows basic peak growth for both the lower and higher frequencied peaks.

Full-scales for this chart are 7 g's for acceleration and 7.4 KRPM for vibrator speed.

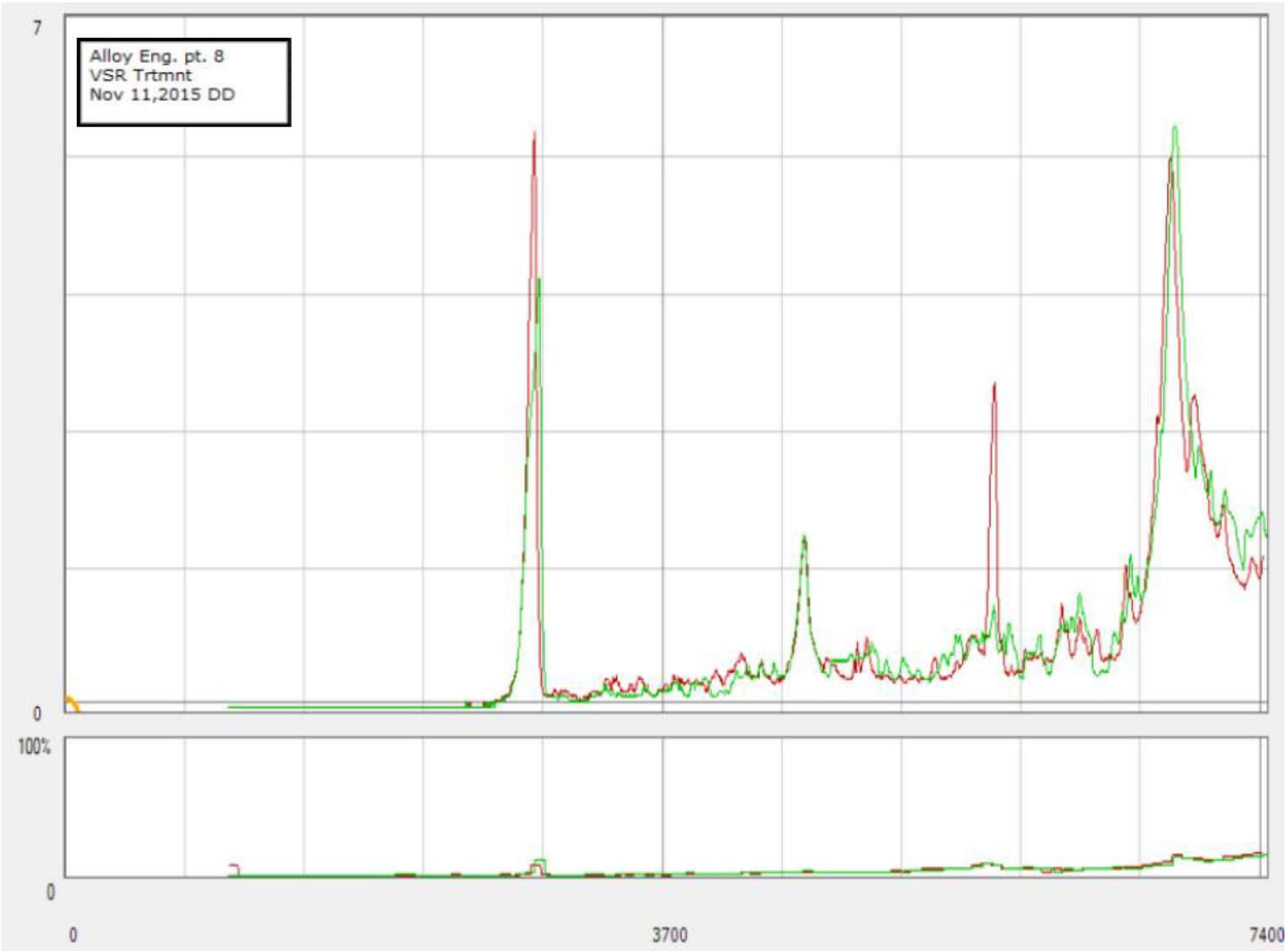

Figure 13: Workpiece 8 VSR Treatment shows peak growth for the low frequency peak, and a previously unseen peak participant, greatly increasing in size.

Full-scales for this chart are 7 g's for acceleration and 7.4 KRPM for vibrator speed.

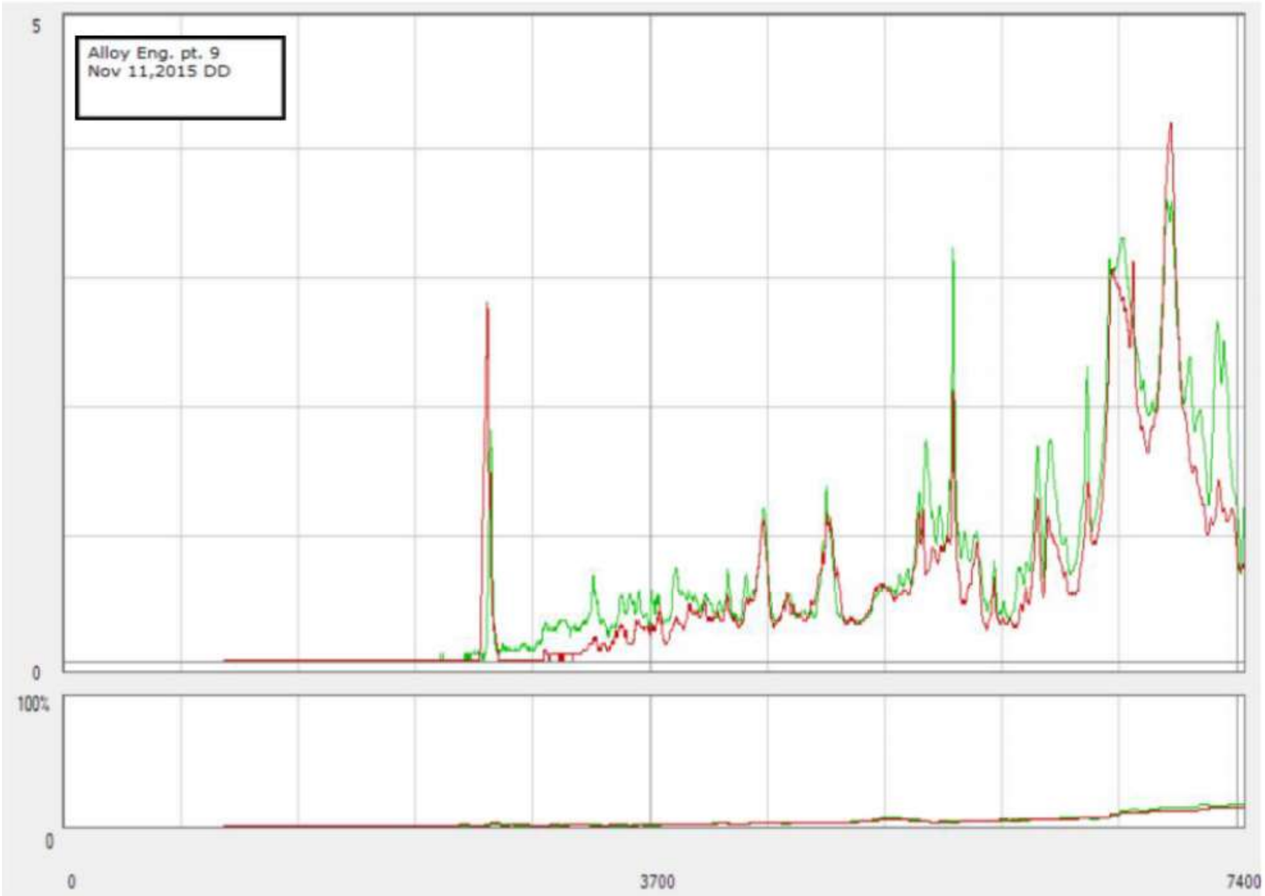

Figure 14: Workpiece 9 VSR Treatment shows evidence of peak growth, but also some spurious data responses that are best explained as tooling degradation: By this time, tightening of some of the nuts on the upper saddle was complicated by having them freeze in position on the all-thread rod, and increasingly momentary ringing of the all-thread rod against the workpiece was witnessed.

Full-scales for this chart are 5 g's for acceleration and 7.4 KRPM for vibrator speed.

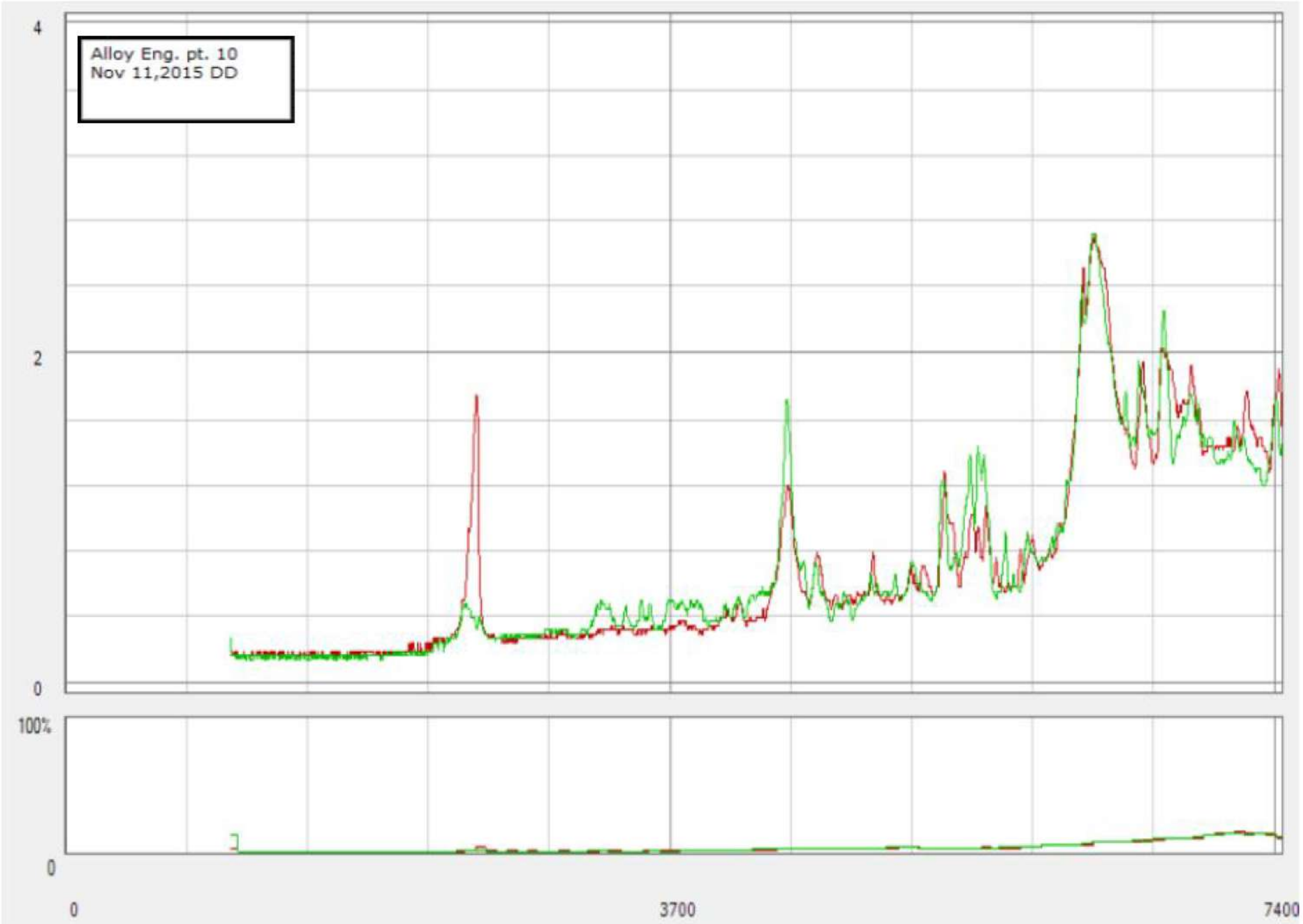

Figure 15: Workpiece 10 VSR Treatment shows clear evidence of peak large growth of the lower frequency peak, but little additional change.

Full-scales for this chart are 4 g's for acceleration and 7.4 KRPM for vibrator speed.

Figure 16: VSR Setup used for stress relief of Alloy 800 fan. Rotary devices that are “live” often will undergo sufficient change-in-shape in early operation to cause change in dynamic balance.   This can cause a previously dynamically balanced component to go out-of-balance, almost certainly shortening, at times catastrophically, component life. The purpose of performing a stress relief upon such a part is to prevent such changes-in-shape that cause out-of-balance events to occur.

Figure 16: Another view of the fan VSR Setup shows more detail of the T-slotted base plate.

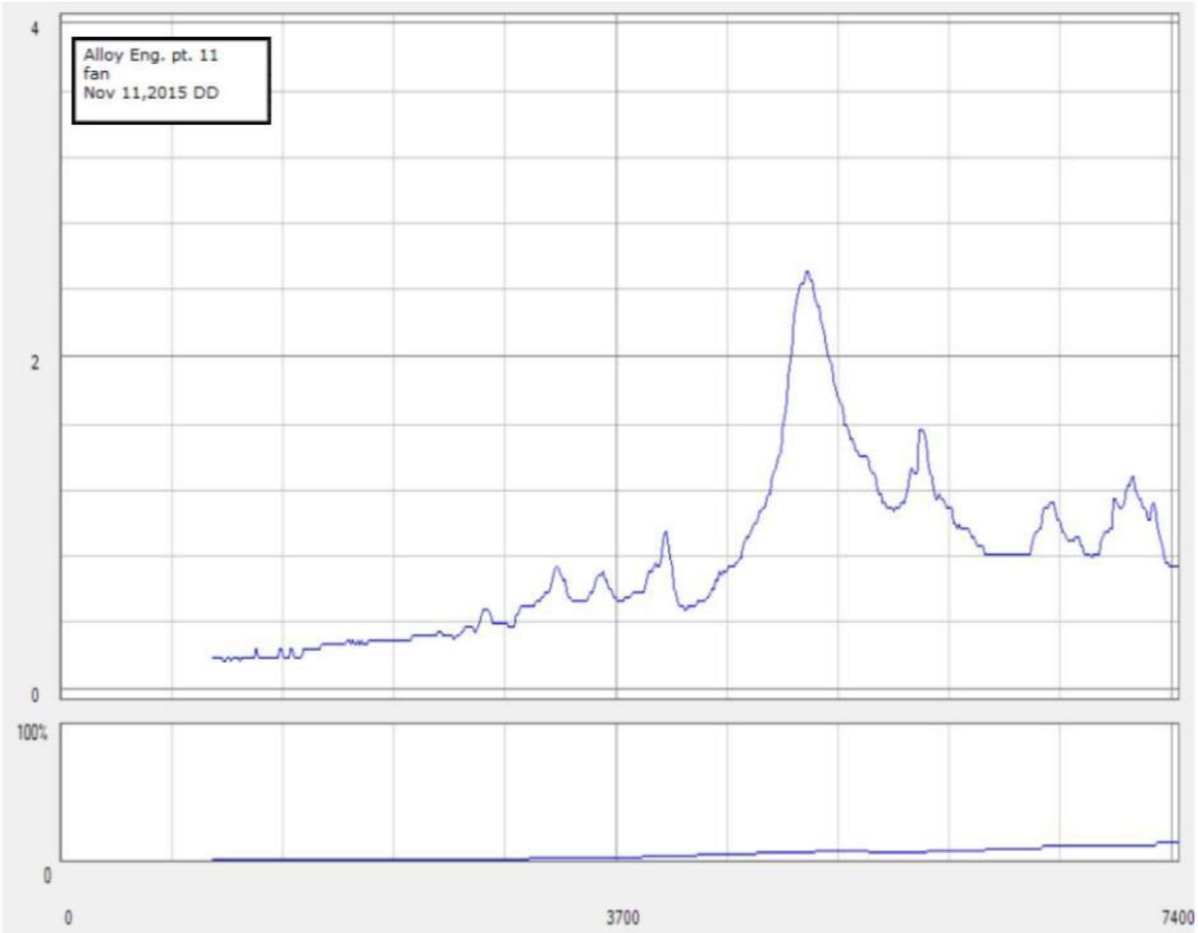

Figure 17: Workpiece 11 was the fan, which was first setup using 20% unbalance, but this was found to be insufficient, and so was increased to 40% of the max. See Figure 18.

Full-scales for this chart are 4 g's for acceleration and 7.4 KRPM for vibrator speed.

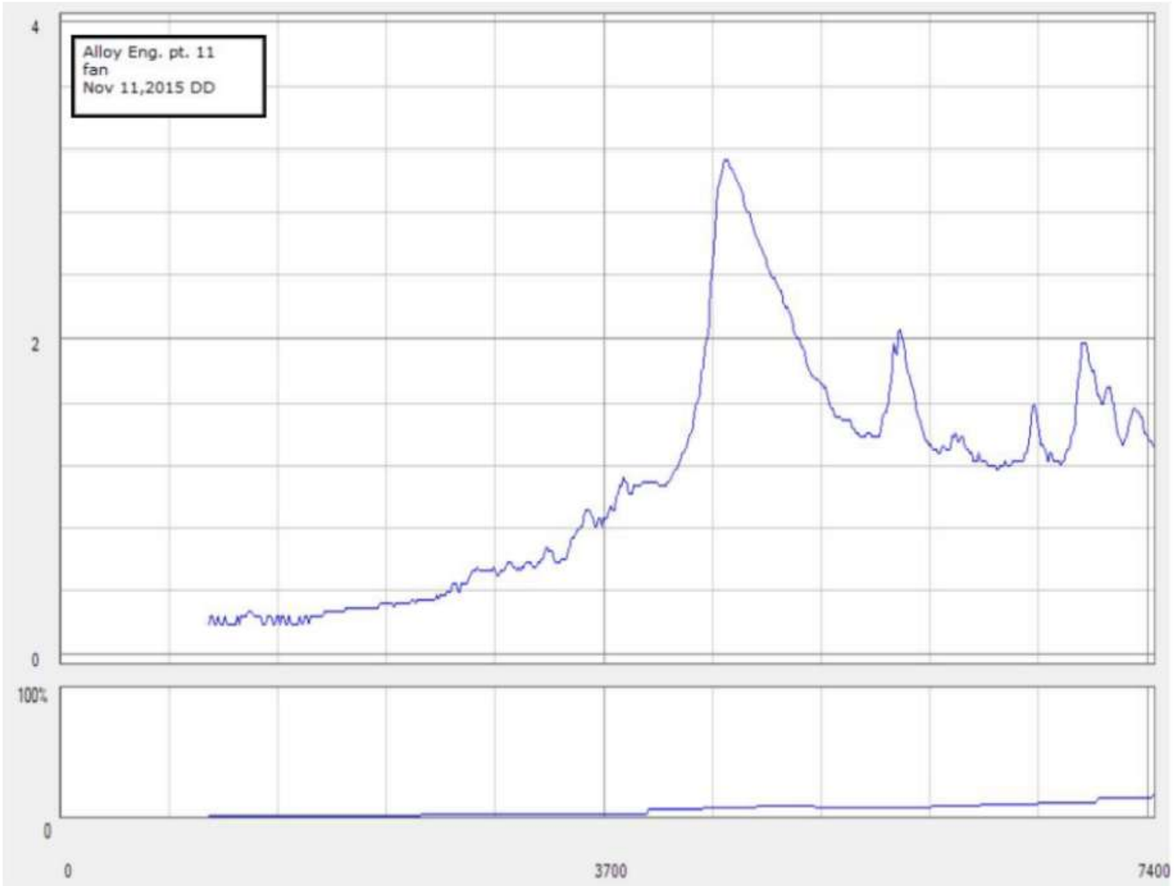

Figure 18: After increasing the vibrator unbalance to 40% (which is a task that takes roughly two minutes), a clear increase in the peak heights can be seen. The large peak in Figure 17 was ~ 2.4 g's, here it is 3 g's, a number that we often consider the minimum required to begin the VSR Process.

Full-scales for this chart are 4 g's for acceleration and 7.4 KRPM for vibrator speed.

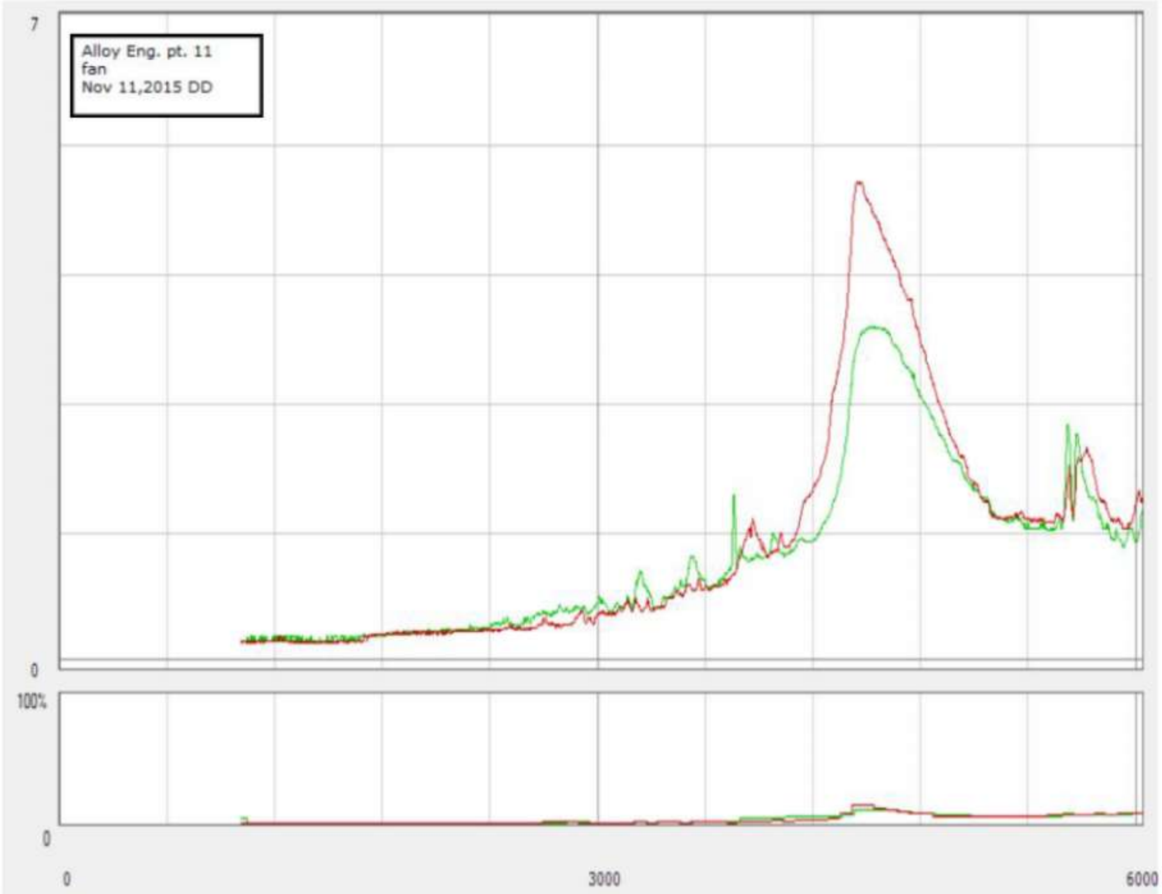

Figure 19: Fan VSR Treatment. Large peak grew from ~ 3.6 g's to 5.3 g's in a period of roughly 20 minutes.

RPM full-scale reduced, since there was little or no meaningful data beyond 6 KRPM
Full-scales for this chart are 7 g's for acceleration and 6 KRPM for vibrator speed.

CONCLUSIONS

Based upon the responses to VSR Treatments, even with less-than-ideal tooling, it is clear that the as-welded and rounded tubes were "live". Whether this "live-ness" is the chief reason for subsequent changes-in-shape that occur during transport remains to be seen. It is our opinion that repeatable shape data after the X-ray journeys will be a clear indication of success. To make this report comprehensive, it is recommended that such dimensional data be added to it, as it becomes available. The fan responded quite well to VSR Treatment, and so it should be expected that dynamic balance quality should be maintained, i.e., stable.

DIMENSIONAL RESULTS

Cylinder VSR P.6 is the only shell that went out of round after Vibration and X-ray were done. It went from 27 13/16" I.D. - 27 7/8" I.D. to 27 ¾" I.D. – 27 27/32" I.D.. All other cylinders stayed within 1/16" roundness, ranging from 27 13/16" I.D. to 27 7/8" I.D.