

VSR REPORT

MAG – IAS Hebron, KY Stress Relief Stabilization of 2 meter and 3 meter plates

UPDATE: There were 2 groups of 8 steel plates, one of which was VSR Processed, the other not. Both groups had been thermally stress relieved. Each group went into different machine tools, the VSR Processed plates being in a machine destined for GE, the other going to Russia. The GE machine performed almost perfectly when installed, and was quickly went into production. The Russian machine had significant dimensional error issues on-site, and, as of this writing, is not yet in production.

When MAG, previously known as Cincinnati Machine, had a collection of 8 thick steel plates that proved dimensionally unstable, distorting several thousandths of 1" during transport, they turned to Advanced VSR to use the VSR Process in an effort to stabilize them. Stress relieving of the plates resulted in additional distortion, in the range totaling 0.011" – 0.015", but also were able to be machined faster, by roughly 28% (36 vs. 50 hours).

These results, on their own, indicate that either a single stress relief is insufficient to render the near-net-shape plates suitably stable for final machining, or that the act of rough machining can generate sufficient stress to interfere with final machining results. These preliminary indications are NOT mutually exclusive; BOTH issues could work together, interfering with the effort to achieve target dimensional integrity. Inspection of the machine tools of which these plates are key components, on-site, could well allow firmer conclusions to be reached as to the best means of assuring these plates are the correct and proper shape for functionality.

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When MAG – IAS, LLC had a collection of 8 thick steel plates that proved dimensionally unstable, they turned to Advanced VSR to use the VSR Process in an effort to stabilize them. These plates had been thermally stress relieved and then machined. Changes in shape that took place during transport rendered them useless, using the intended design, so a modified design was developed, and the plates VSR Processed, with the hope of avoiding having the scrap the material. Dimensional tolerances over the 2 and 3 meter long (~ 80" and 120") lengths were in the range of +/- 0.001". The VSR Setup used to stabilize the plates is shown in Figure 1.

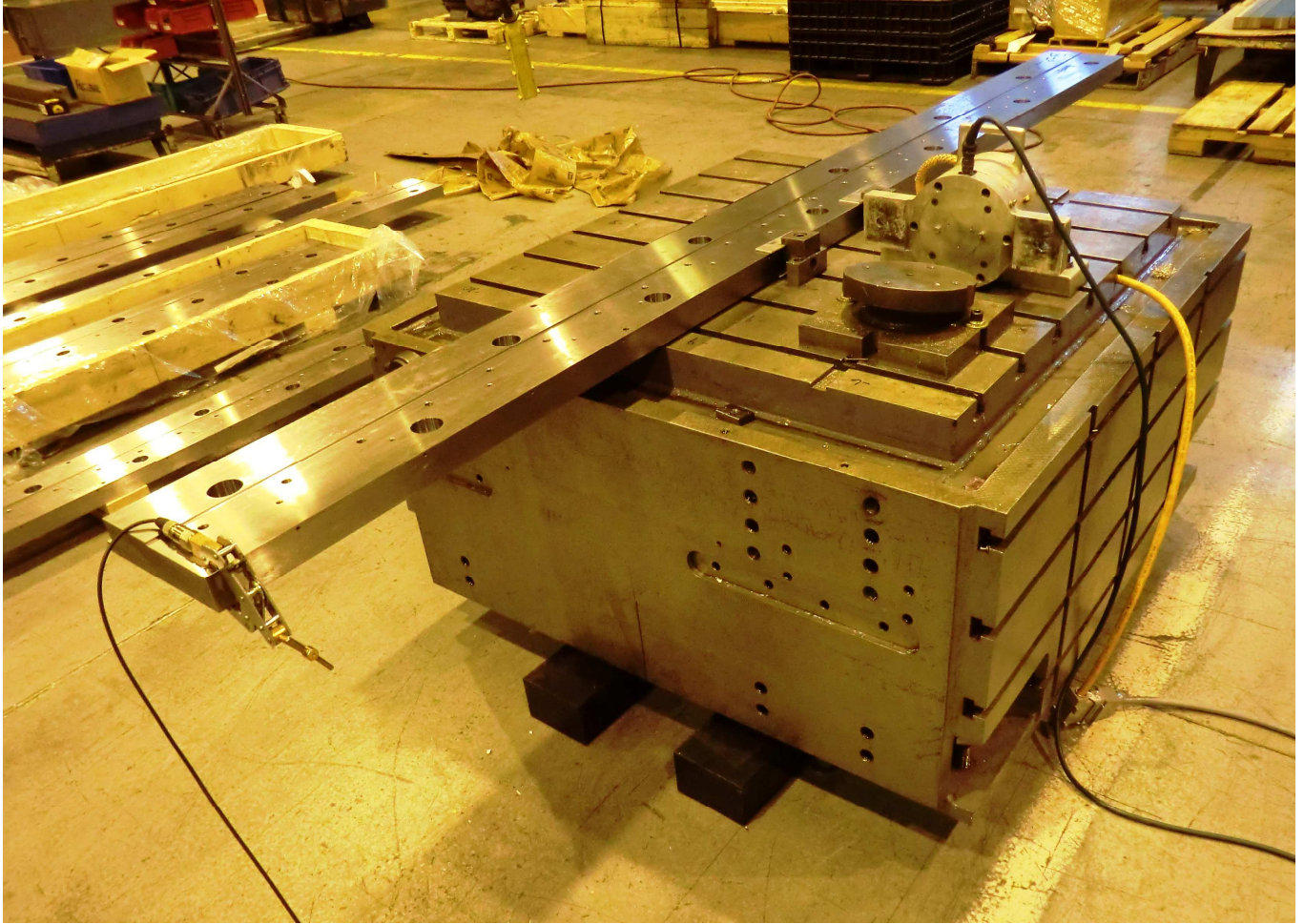


Figure 1: 3 meter long plate setup for VSR Treatment. A T-slotted fixture was mounted on four urethane load cushions, two of which are visible in the middle-foreground. The workpiece was shimmed above the T-slotted fixture using 1/8" CRS, ~ 2" X 3", at 3 locales coinciding with the clamping points: One near the center of the leftward side, the other two separated by two T slots. The fixture, shims and clamps thus acted as a medium thru which the vibration was transmitted. This arrangement minimized the damping of the workpiece, allowing the resonances of the workpiece to be available for the VSR Process. The 2.3 kW vibrator (which has both variable unbalance and speed) was bolted to the fixture, with its AOR (Axis of Rotation) parallel with the workpiece length, since lengthwise resonance was unlikely. Tooling in front of the vibrator was present on the fixture when provided, and was left in place, and made no contribution to the vibration data.

VSR SET UP

Each workpiece was clamped upon a T-slotted fixture, resting upon three shims, ~ 1/8" X 2" X 3", with the clamping centered on each shim. Three is the minimum number to determine a plane, and the location of the shims / clamps was far from the ends of the workpiece, thus minimizing damping of the workpiece. Minimizing damping maximizes the modes and intensity of resonance, and hence, flexure. Independent research has shown that flexure is a key criteria required to maximize the effectiveness of vibratory stress relief.¹²

The Vibrator was securely bolted at the mid-length of the top of the fixture, and oriented so that the Axis-of-Rotation (AOR) was aligned with the length of the workpiece. The resonances most likely to be excited would cause vertical deflection of the workpiece, with some possibility (achieved with the 3 m long plates) of "sideways" resonating. As is often the case, the probability of exciting a resonance generating length-wise amplitude was minimal, so the vibrator was aligned purposely so as to drive the workpiece in the most likely directions of resonating.

The Vibrator's unbalance was initially adjusted to 25% of the available 4.0 in-lbs of unbalance, i.e., 1.0 in-lbs.

An Accelerometer (a vibration sensor whose output is proportional to acceleration) was positioned on one corner of the workpiece, and oriented to be most sensitive to vertical amplitude during the smaller plate stress relief treatments. For the longer plates, the accelerometer was oriented to be sensitive to horizontal deflections, as shown in Fig 1.

Both science and experience have shown that acceleration (as opposed to velocity or deflection), is the best parameter to gauge vibration intensity at the height of resonance peaks, due to its proportionality to force, based on Newton's second law: $\mathbf{F} = \mathbf{ma}$ (where \mathbf{F} is force, \mathbf{m} is mass, and \mathbf{a} is acceleration).

¹ [Y. P. Yang, G. Jang and R. Yancey, ASM: Trends in Welding Research 2005, Advanced VSR Technical Library](#)

² [W. F. Hahn, Vibratory Residual Stress Relief and Modifications in Metals to Conserve Resources and Prevent Pollution, Alfred University, CEER, Advanced VSR Technical Library](#)

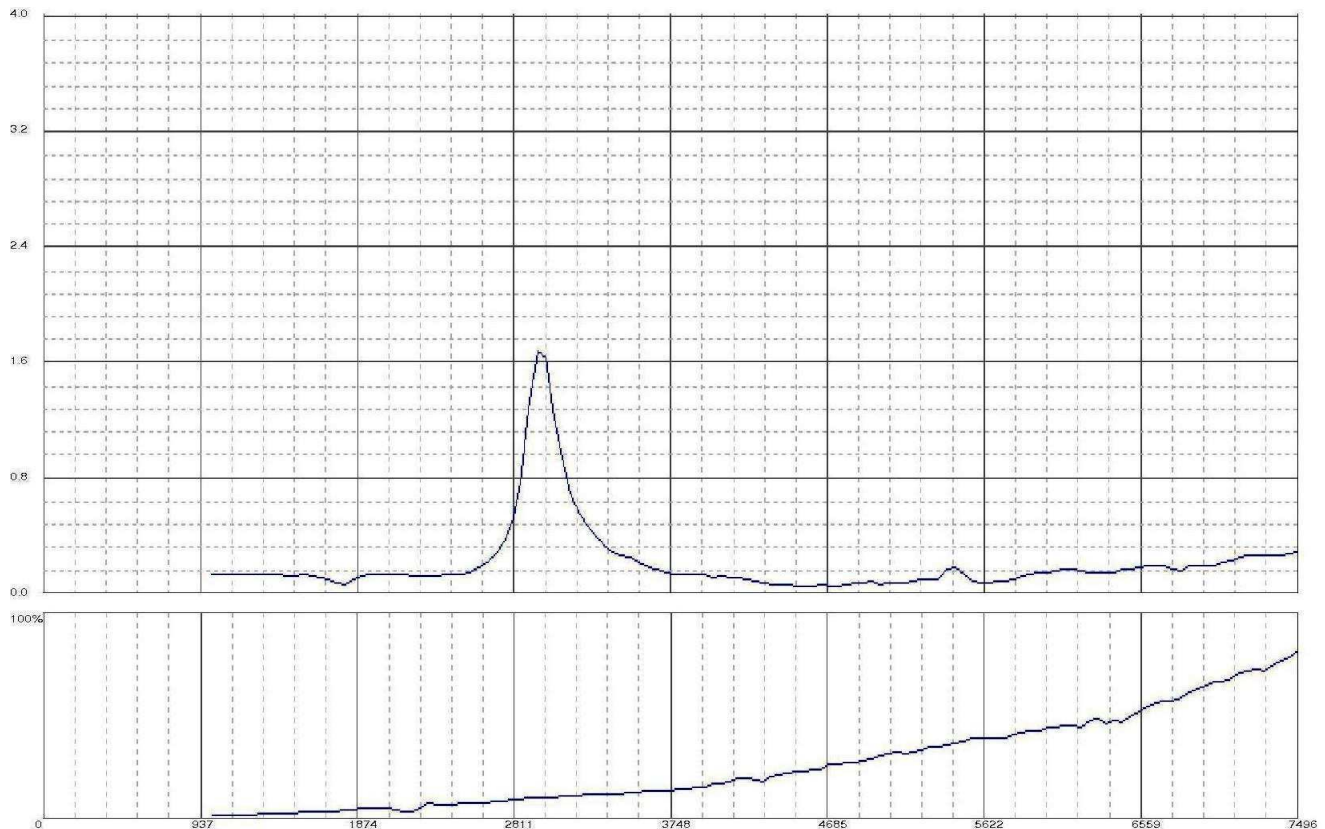


Figure 2: Workpiece 1, Quick Scan. VSR charts have two sets of data: An upper workpiece acceleration curve, calibrated in g's and a lower vibrator input power curve (with fixed full-scale [FS], with 100% = 2.2 kW), both these data sets plotted vertically vs. a horizontal axis = the vibrator speed, calibrated in RPM. Peaks in the upper curve are resonances of the workpiece, while peaks in the lower curve (which did not occur during this project) represent a resonance that causes increased, perhaps excessive, vibrator amplitude.

A Quick Scan (all of which are recorded in blue “ink”) is used to allow calibration, documenting that at least one resonance is achieved, rescaling the acceleration scale if required (adjustable FS from 1 – 50 g's), and verifying that nothing is loose or loosening. Quick Scans are made at a rate of 50 RPM / sec, which is 5 times faster than what is normally used for Pre- or Post-Treatment Scans, the trade-off being time vs. resolution. Quick Scans can “lop-off” or miss the full height or other detail of a resonance, so they are used for calibration only.

RPM FS = 7500 RPM
 ACC FS = 4 g's
 UNBALANCE = 1.0 in-lbs.
 POWER FS = 2.2 kW (fixed)
 SCAN RATE = 50 RPM / SEC\

VSR TREATMENT

After the initial setup, a Quick Scan (Figure 2) was performed, which showed only one significant resonance peak at ~ 2800 RPM. A Pre-Treatment Scan, which is performed using a scan rate 5 times slower revealed no additional significant additional peaks, even thou the scan went out to 7500 RPM (system max = 8 KRPM).

Peaks in the upper curve are resonance peaks of the workpiece. If a peak occurs in the power curve, it indicates that a peak in load upon the Vibrator has also occurred. In the Chart above, the full-scale of the acceleration (adjustable from 1g thru 50g) was set at 6g. Adjustments can be made to either the acc or speed scales after a scan has been performed, even displaying data (such as a tall peak that was originally off-scale) one of many "user-friendly" aspects of the VSR-8000 System.

Full-scale for the power is preset permanently at the power capacity of the BL8 Vibrator's motor: 100% = 2.2 kW.

Pre-Treatment Scans are recorded in **green** since the workpiece is "**green**" (freshly welded or cast).

Treatment is done by tuning on and dwelling upon the peaks identified in the Pre-Treatment Scan. The VSR-8000 System has very tight speed regulation ($\pm 0.02\%$). The Vibrator can be tuned in increments of 1-RPM. This enables the Vibrator to be tuned directly on the resonance peaks, so that maximum flexure, and thus the maximum stress relief using vibration, can take place.

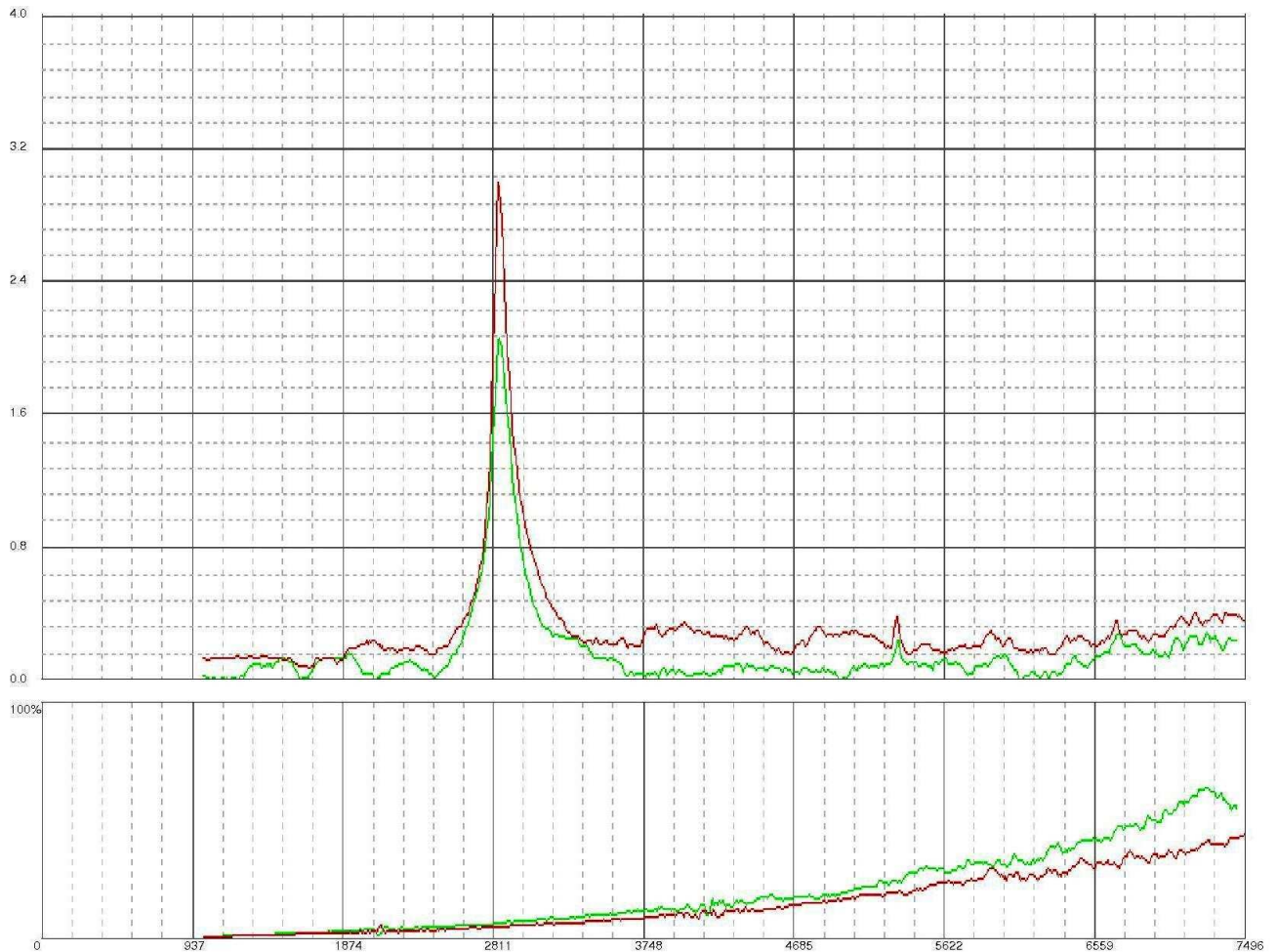


Figure 3: Workpiece 1, 1st VSR Treatment. After the QS was made, a Pre-Treatment Scan (Pre-Scan) was made and recorded in green. With only the green Pre-Scan, the operator then chooses which peak(s) to tune upon and dwell. The real-time amplitude is displayed by a cursor (not shown) and the digital displays on the VSR OS. These are used to monitor the progress of the VSR Treatment. Dwelling upon a peak takes place until stability is reached, whatever form the changes might be. Chiefly, peak changes are peak growth. Peak shifting (most often to the left), but also peak shrinkage and shifting to the right can occur. When able to be verified, these latter changes normally indicate a change in workpiece shape / dimensions.

After the changes in the resonance at ~ 2800 RPM (which chiefly involved peak growth of ~ 46%) stabilized, a Post-Treatment Scan or Post-Scan was made, recorded in red, superimposed on the baseline / Pre-Scan.

RPM FS = 7500 RPM
 ACC FS = 4 g's
 UNBALANCE = 1.0 in-lbs.
 POWER FS = 2.2 kW (fixed)
 SCAN RATE = 10 RPM / SEC



Figure 4: MX-8000 VSR Console. Touch-screen computer displays VSR Chart Data, digital data (RPM, power, and acceleration). Chart data is saved by printing in Adobe/pdf format. Low voltage connections are on left (2 USB Ports, Accelerometer, and Vibrator resolver / tachometer), and higher voltage connections on right (power in, motor). With vibrator speed regulation of $\sim 0.02\%$ and acceleration display error less than 0.5% of full-scale, the console's instrumentation provides more than adequate (on the order of one order of magnitude) accuracy to depict than changes seen during these VSR Treatments.

After tuning on the 2800-RPM peak, peak growth was noted within two minutes. The remaining increase, amounting to growth of $\sim 46\%$, took an additional 25 minutes to achieve, at which point the peak height remained stable. A Post-Treatment Scan (which is recorded in red) was performed, documenting the changes that had taken place during treatment.

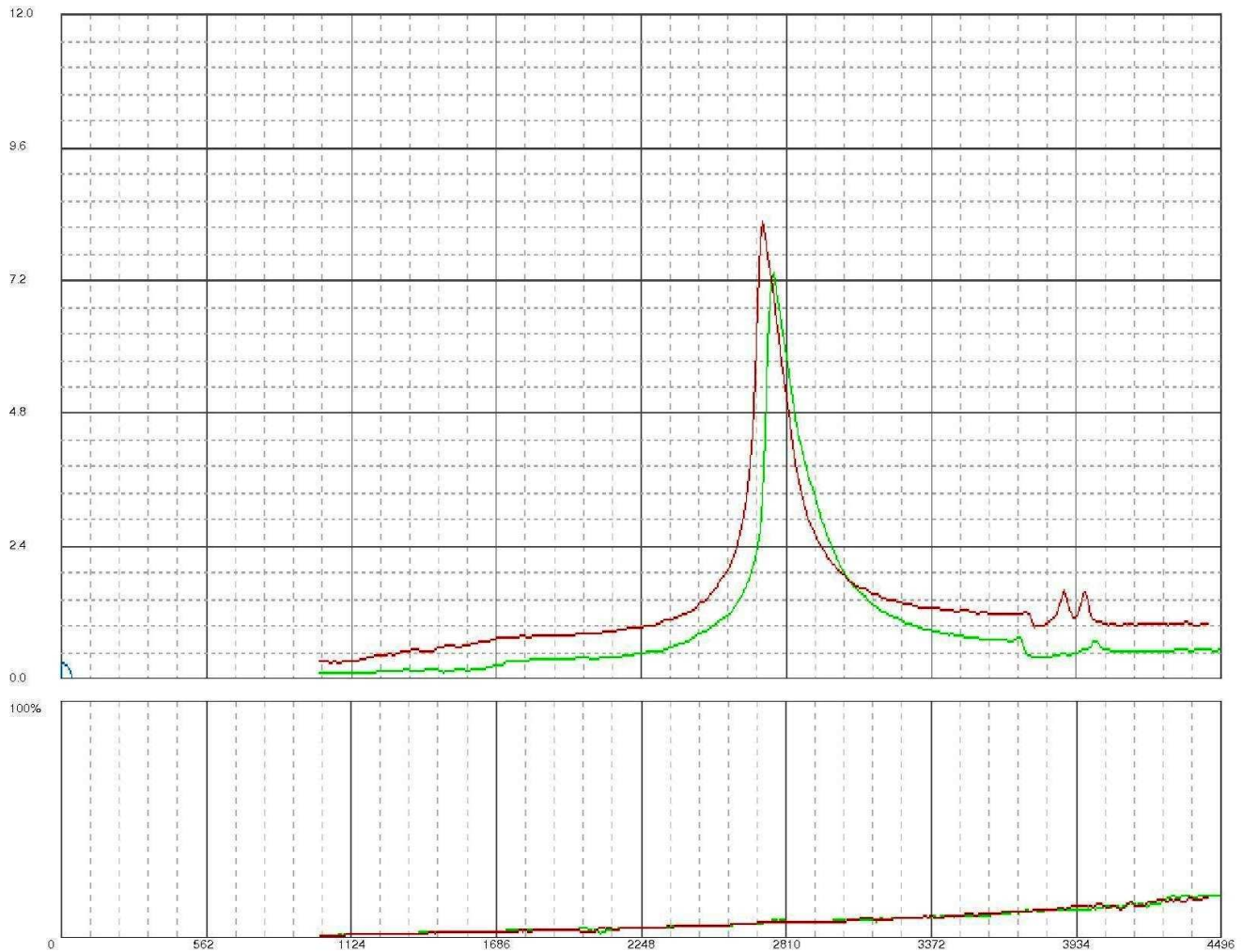


Figure 5: 2nd VSR Treatment Chart. To verify that the 1st treatment was sufficient, not only in treatment time but intensity, a 2nd treatment was performed at ~ 3X higher unbalance: 80% or 3.2 in-lbs. Some additional change took place (~ 13 % growth and ~ 1%, or 30 RPM peak shifting to the left), over a period of 15 minutes. 5 additional minutes yielded no further change, at which point a Post-Scan was performed.

Based upon this response, the remaining 2 meter long plates were treated using first the 80% unbalance setting (results shown in Fig. 7), followed by the 25% (Fig. 8).

RPM FS = 4500 RPM
 ACC FS = 12 g's
 UNBALANCE = 3.2 in-lbs.
 POWER FS = 2.2 kW (fixed)
 SCAN RATE = 10 RPM / SEC

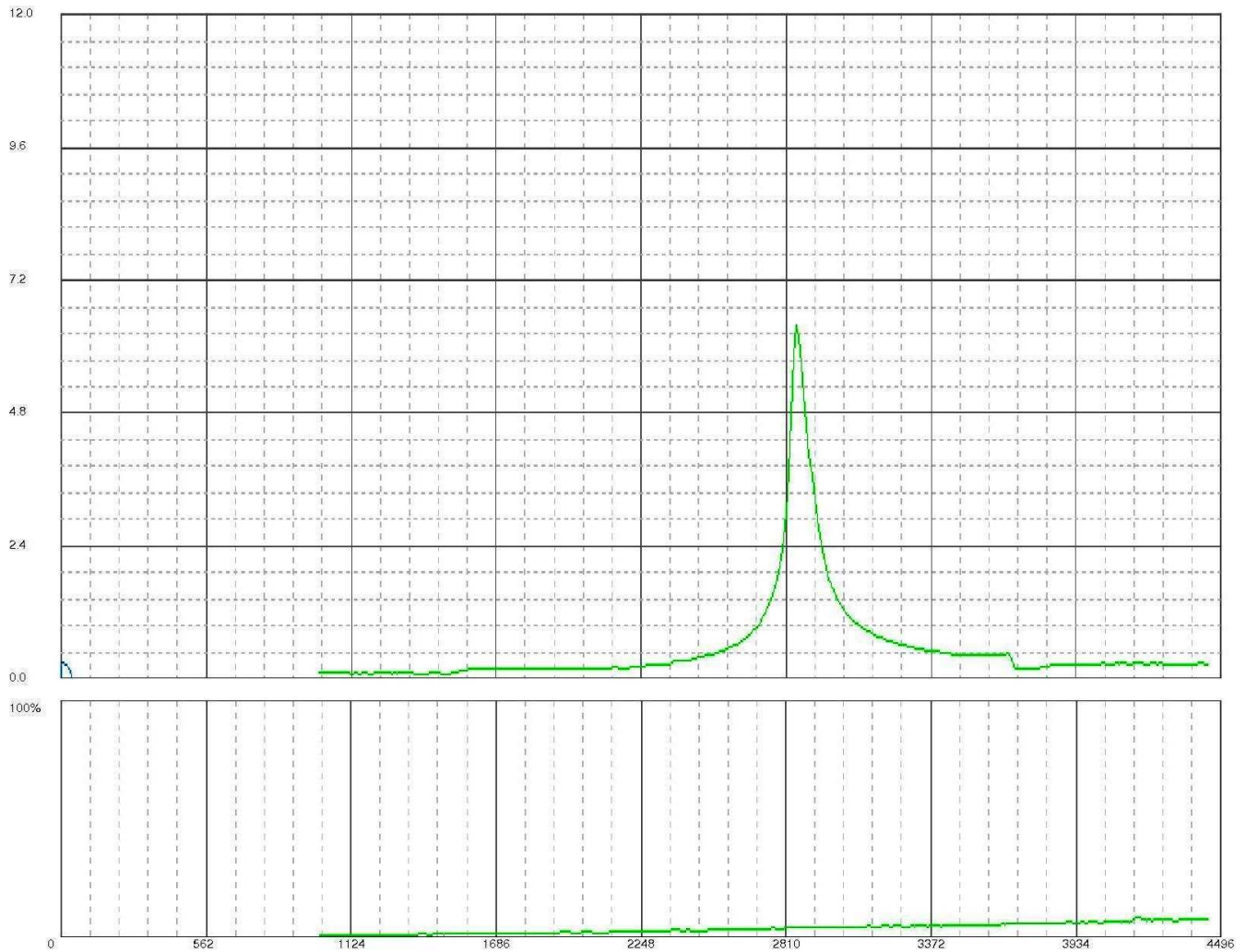


Figure 6: Workpiece 2 Pre-Scan. Using the same setup as used to generate Figure 5's data, the Pre-Scan shows a similar resonance peak slightly above 2800 RPM. This is the baseline data the VSR Operator sees at the beginning of a treatment, from which is gauged treatment progress.

RPM FS = 4500 RPM
ACC FS = 12 g's
UNBALANCE = 3.2 in-lbs.
POWER FS = 2.2 kW (fixed)
SCAN RATE = 10 RPM / SEC

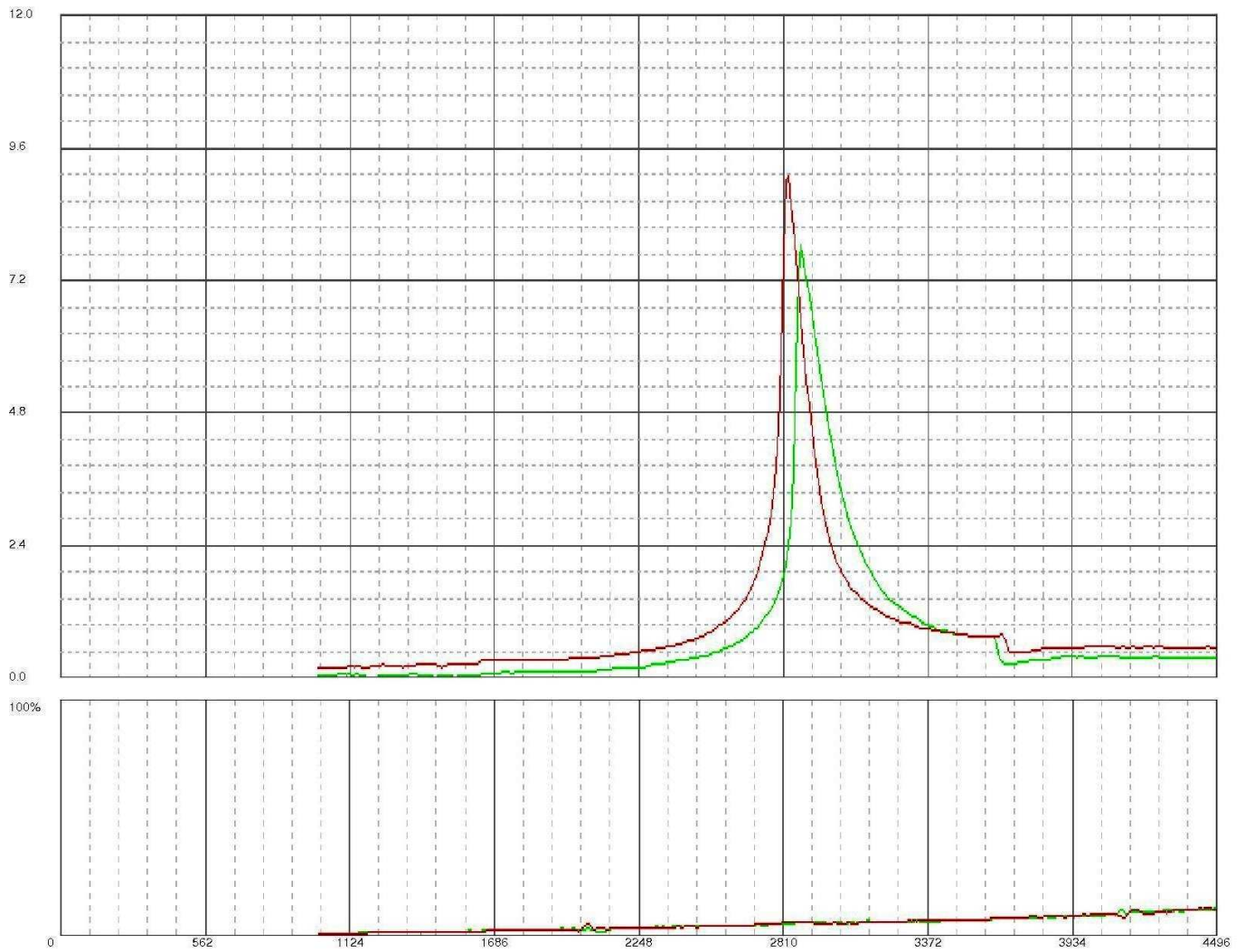


Figure 7: Workpiece 2 treatment shows peak growth from 7.7 to 9.1 g's, or ~ 18%, and peak shift leftwards from 2890 to 2820 RPM, or ~ 2.5%.

RPM FS = 4500 RPM
ACC FS = 12 g's
UNBALANCE = 3.2 in-lbs.
POWER FS = 2.2 kW (fixed)
SCAN RATE = 10 RPM / SEC

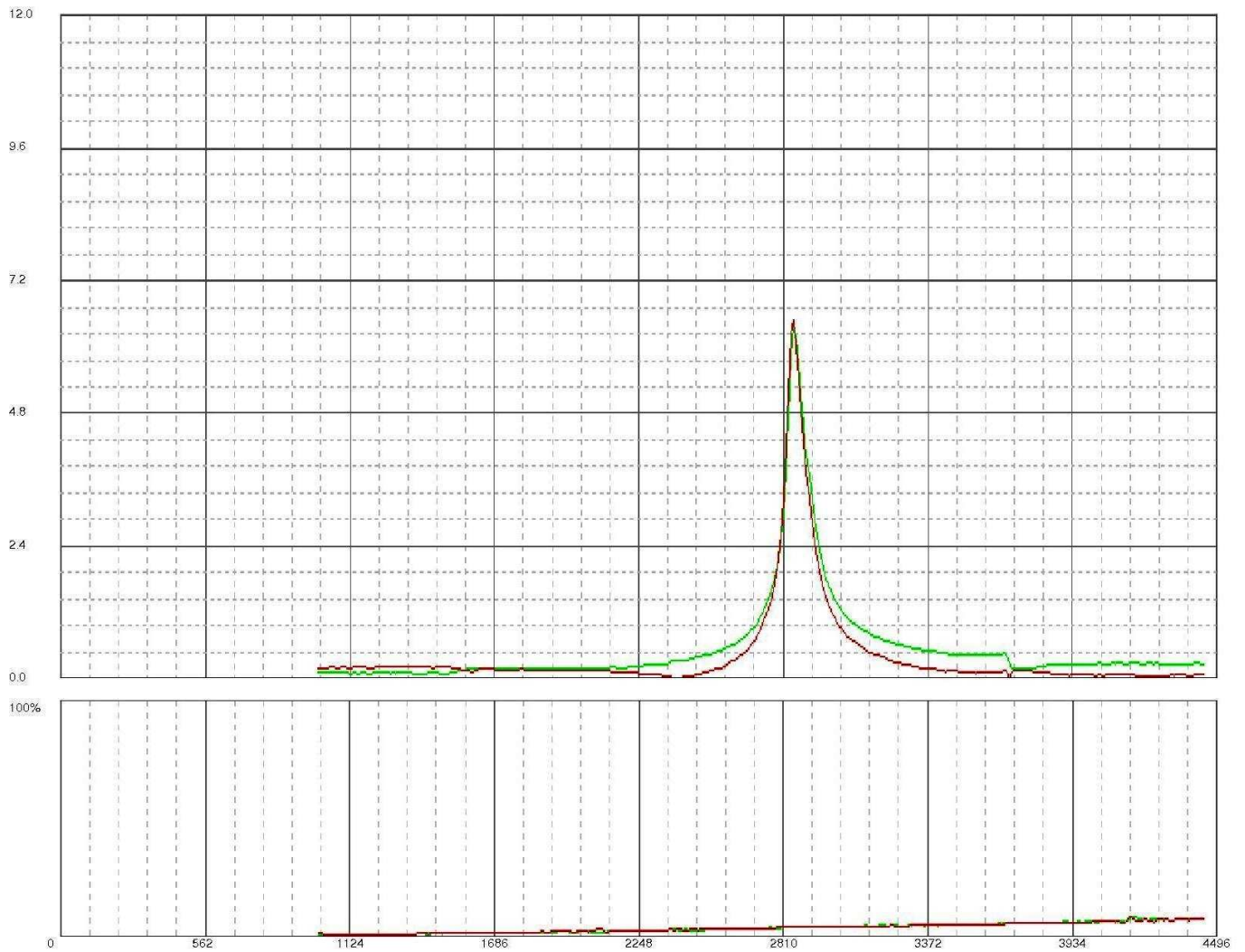


Figure 8: 2nd treatment of workpiece 2 at 25% unbalance yielded very little change, indicating the viability of using the 80% unbalance setting (shown in Fig. 7).

RPM FS = 4500 RPM
ACC FS = 12 g's
UNBALANCE = 1.0 in-lbs.
POWER FS = 2.2 kW (fixed)
SCAN RATE = 10 RPM / SEC

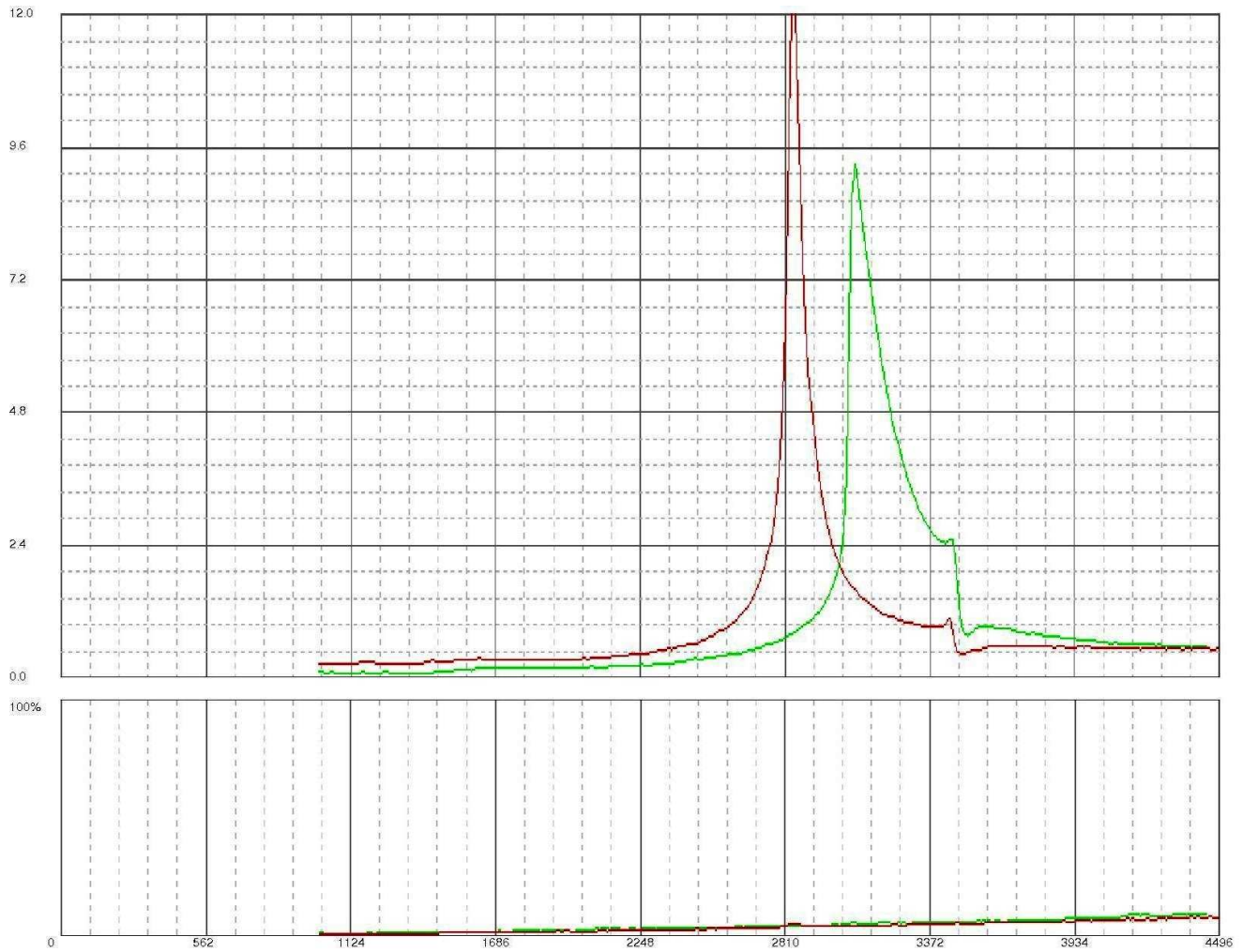


Figure 9: Workpiece 3 treatment using 80% unbalance yielded similar peak growth, but larger peak shifting.

RPM FS = 4500 RPM
ACC FS = 12 g's
UNBALANCE = 3.2 in-lbs.
POWER FS = 2.2 kW (fixed)
SCAN RATE = 10 RPM / SEC

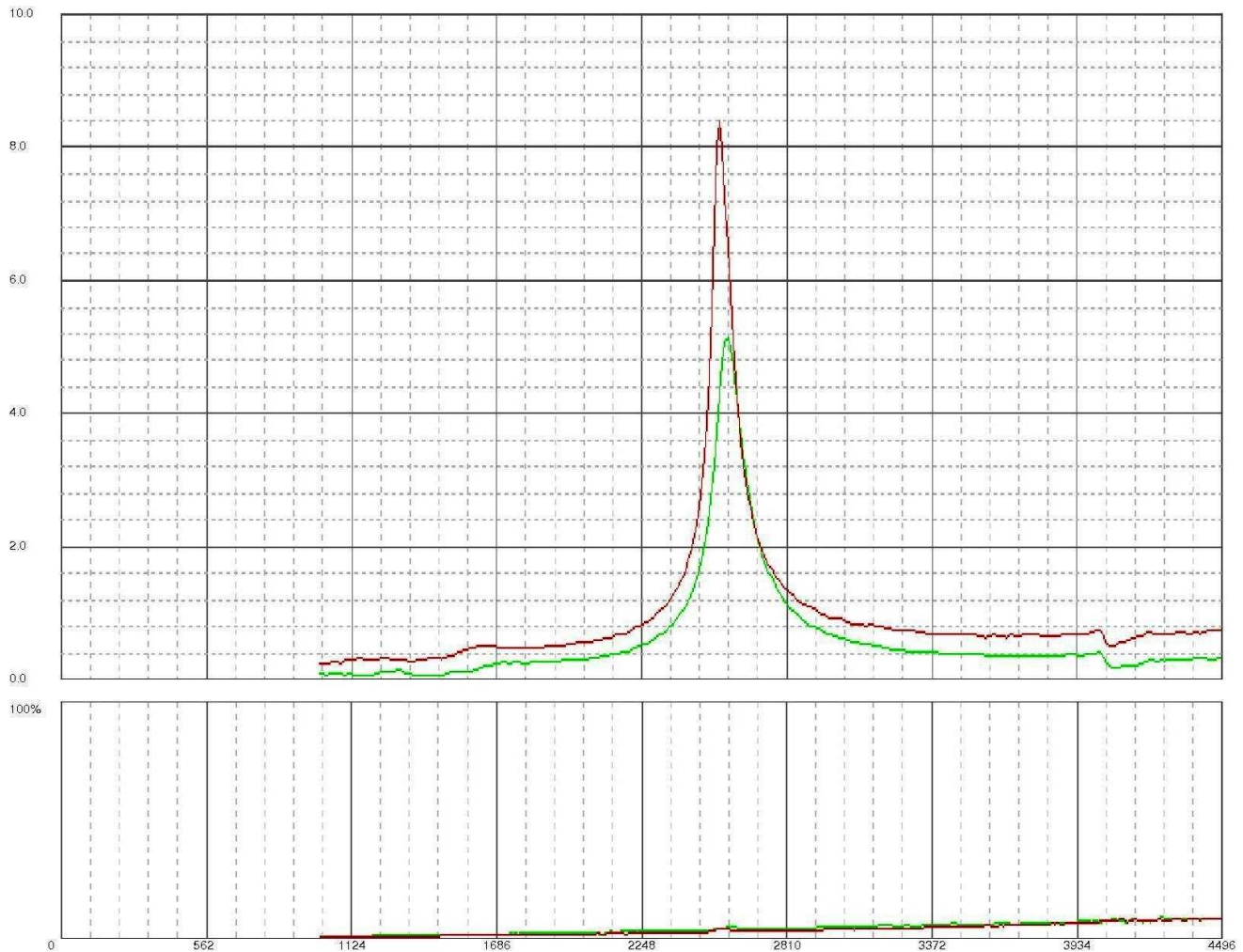


Figure 10: Workpiece 4 treatment using 80% unbalance yielded similar peak growth, but nominal peak shifting.

RPM FS = 4500 RPM
ACC FS = 10 g's
UNBALANCE = 3.2 in-lbs.
POWER FS = 2.2 kW (fixed)
SCAN RATE = 10 RPM / SEC

Setup used for the 3 meter long plates was similar in clamping to fixture, but different in both vibrator unbalance and accelerometer orientation. Two peaks were discovered at very different RPM ranges: A high-frequency peak at ~ 6000 RPM, and low-frequency peaks in the range of 1200 – 1500 RPM. Furthermore, these resonances caused deflection in different directions: The 6 KRPM peak caused amplitude chiefly horizontally (side-to-side), while the low-frequency peaks were chiefly vertical. It was during one of the high-frequency peak treatments that the photo shown in Fig. 1 was taken.

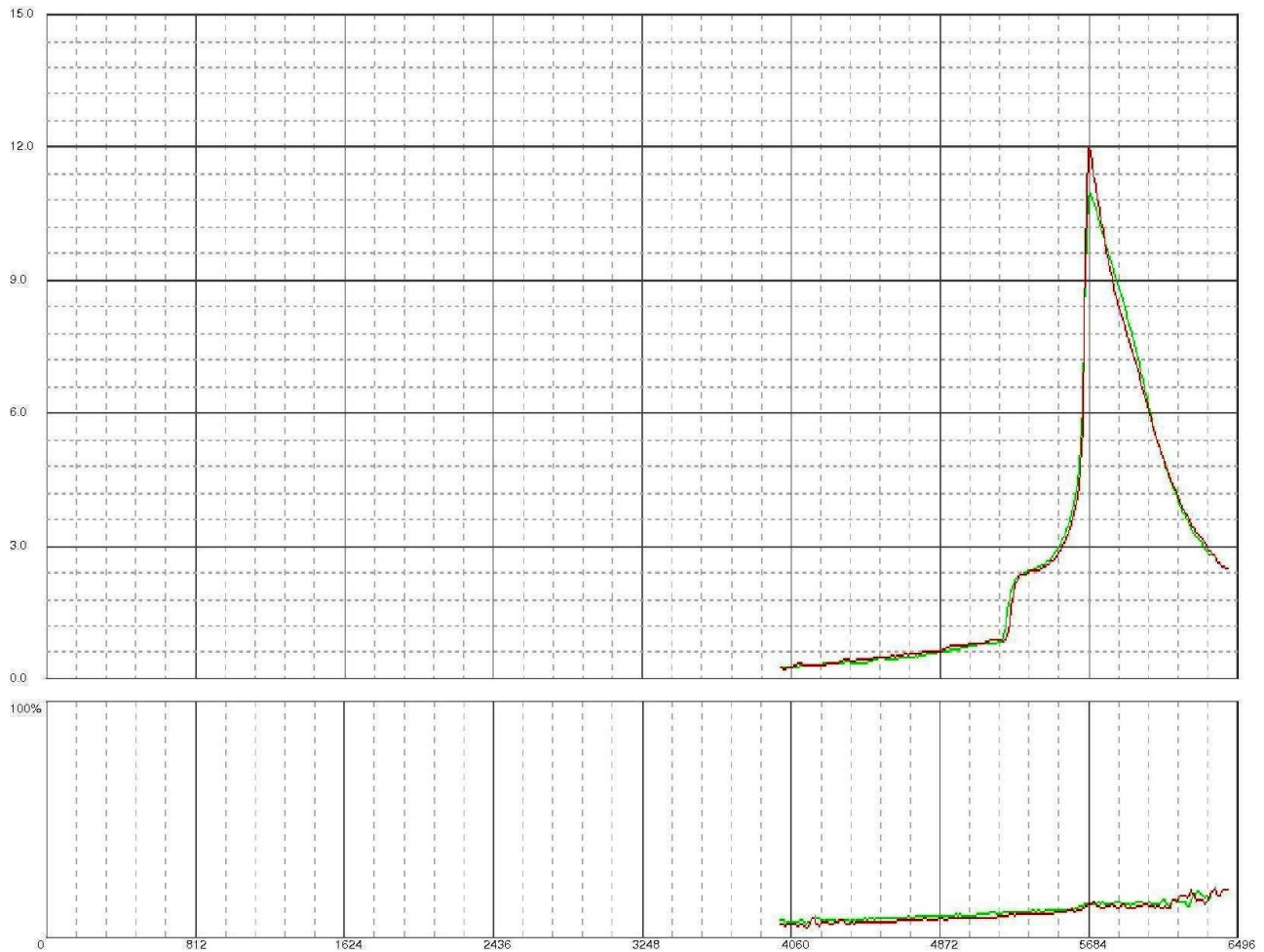


Figure 11: Workpiece 5 treatment using 50% unbalance yielded peak growth, from 10.6 – 12.0 g's, but very little peak shifting. At this unbalance, the low-frequency peaks shown in Fig. 12 were very nominal / un-distinct, so an increase to 100% unbalance was used.

RPM FS = 6500 RPM
ACC FS = 15 g's
UNBALANCE = 2.0 in-lbs.
POWER FS = 2.2 kW (fixed)
SCAN RATE = 10 RPM / SEC

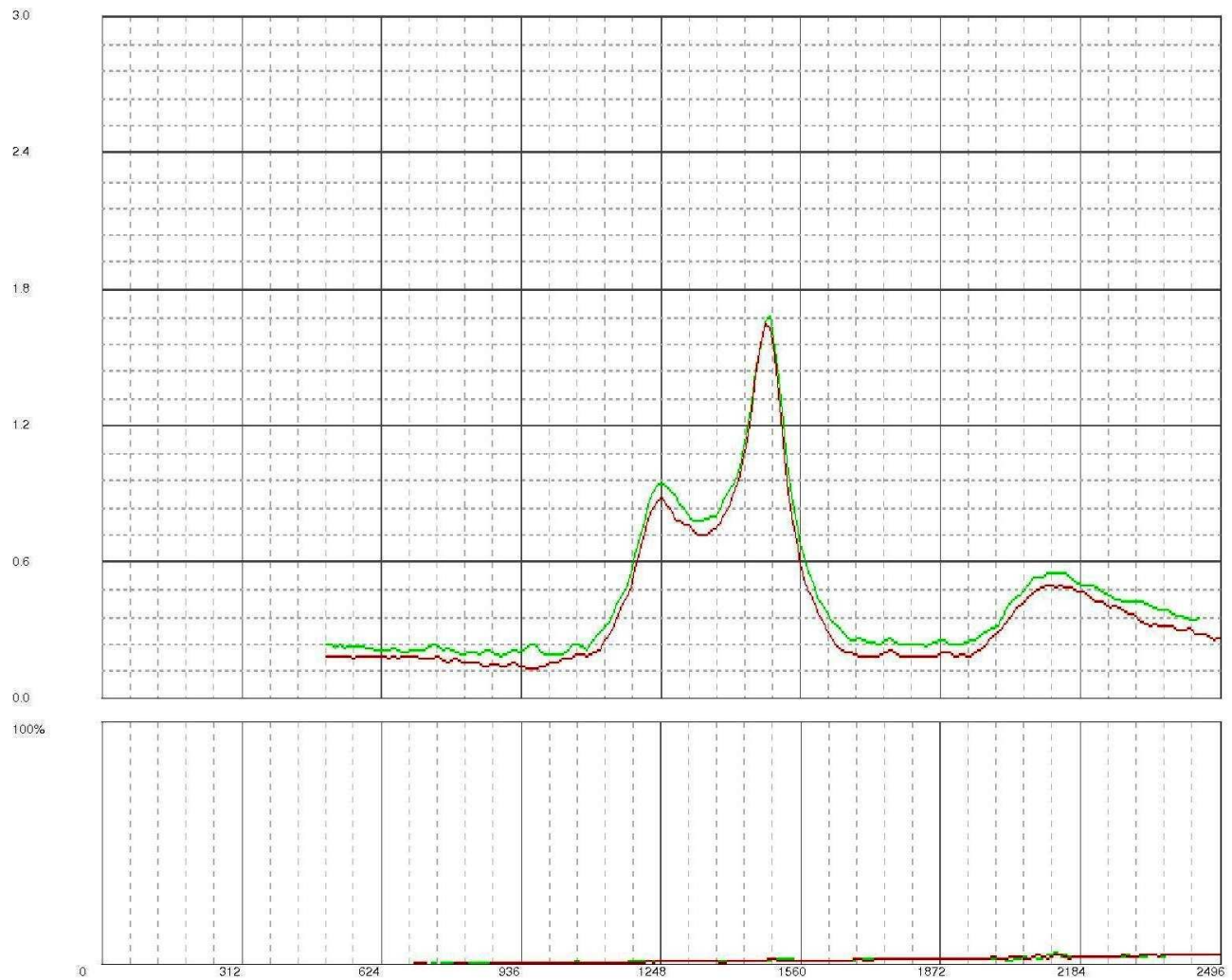


Figure 12: Workpiece 5 treatment using 100% unbalance yielded almost no change, either in the form of peak growth or shifting.

RPM FS = 2500 RPM
ACC FS = 3 g's
UNBALANCE = 4.0 in-lbs.
POWER FS = 2.2 kW (fixed)
SCAN RATE = 10 RPM / SEC

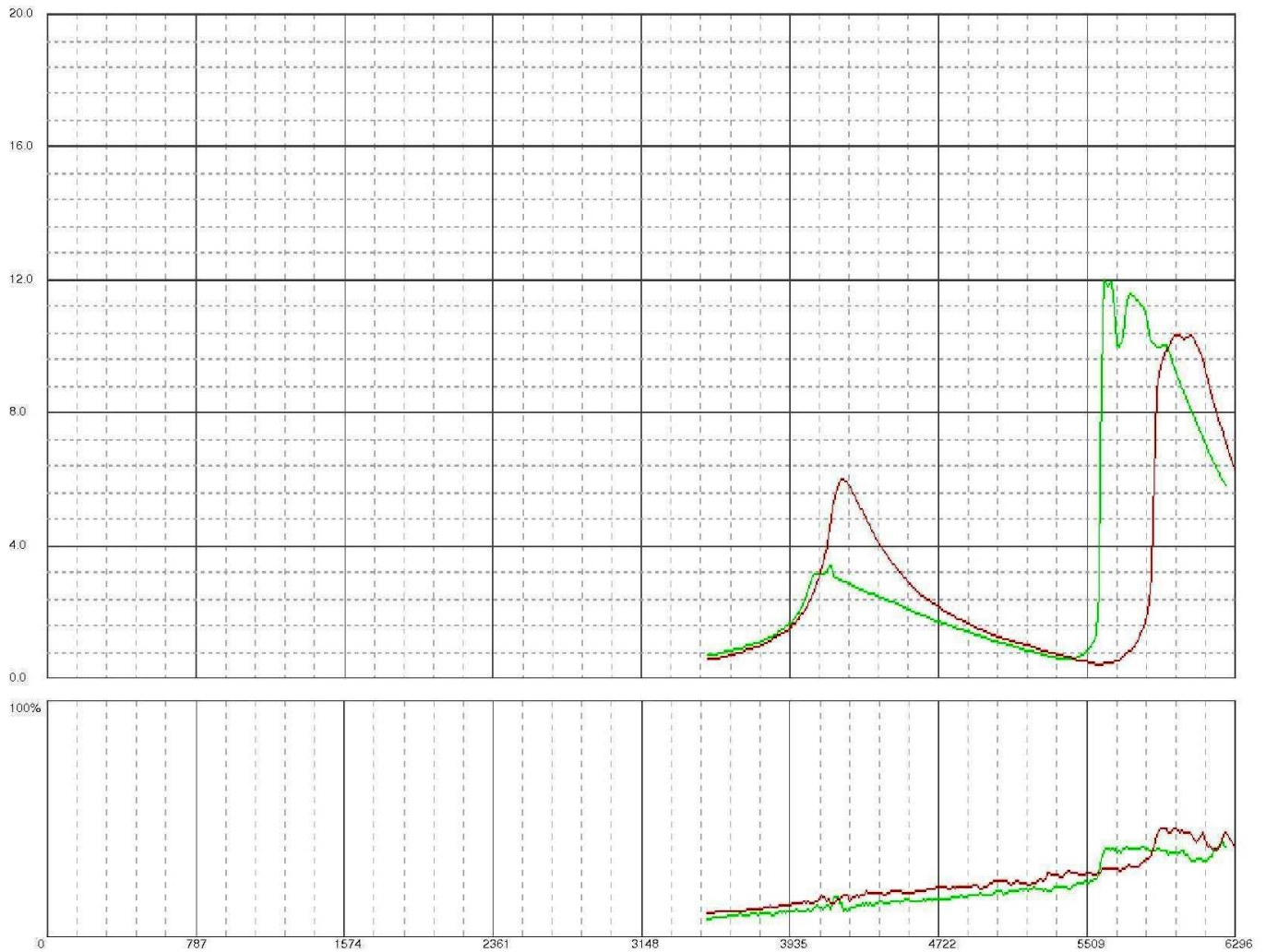


Figure 13: Workpiece 6 treatment using 50% unbalance yielded two peaks, one of which grew and shifted slightly to the right at ~ 4200 RPM, the other reducing slightly and shifting further to the right. These changes are most commonly seen when changes in workpiece shape / dimensions take place. See pages for further discussion.

RPM FS = 6300 RPM
ACC FS = 20 g's
UNBALANCE = 2.0 in-lbs.
POWER FS = 2.2 kW (fixed)
SCAN RATE = 10 RPM / SEC

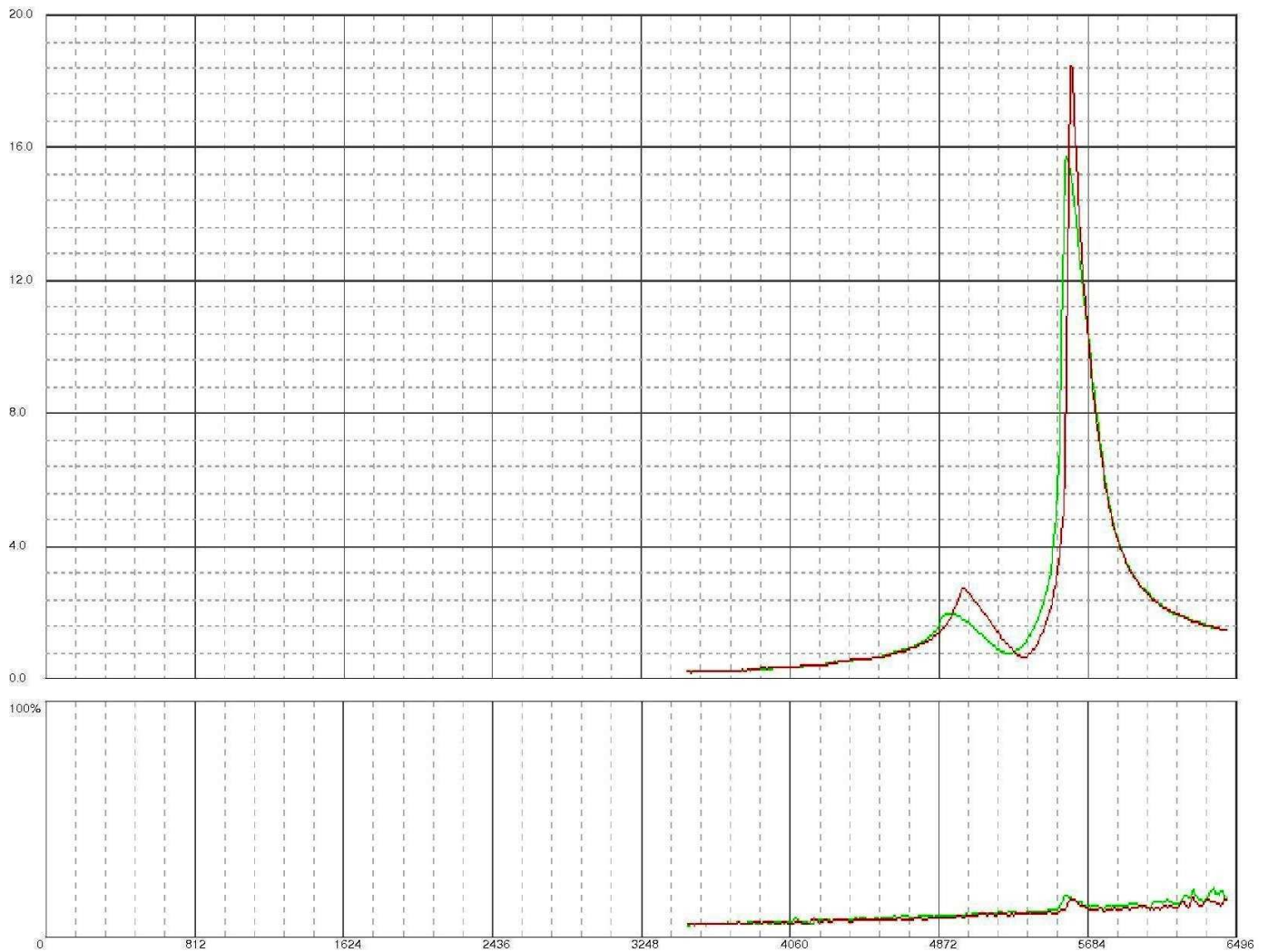


Figure 14: Workpiece 7 treatment using 50% unbalance yielded peak growth, with modest peak shifting to the right. Again, the peak shifting to the right is often accompanied by a change in shape of the workpiece.

RPM FS = 6500 RPM
ACC FS = 20 g's
UNBALANCE = 2.0 in-lbs.
POWER FS = 2.2 kW (fixed)
SCAN RATE = 10 RPM / SEC

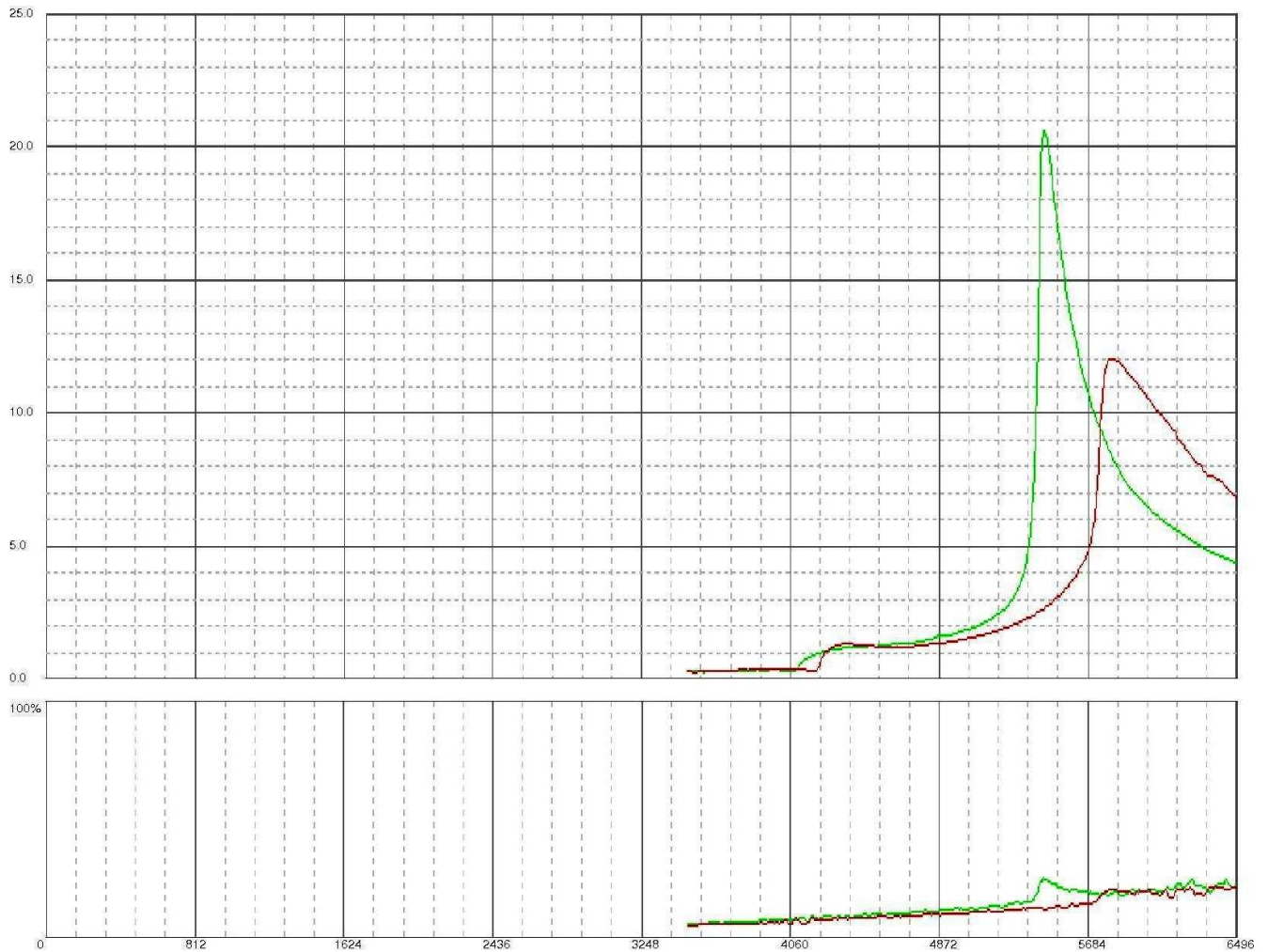


Figure 15: Workpiece 8 treatment using 50% unbalance yielded a single peak, which reduced and shifted to the right. This type of response is most commonly seen when a change in workpiece shape occurs.

RPM FS = 6500 RPM
ACC FS = 25 g's
UNBALANCE = 2.0 in-lbs.
POWER FS = 2.2 kW (fixed)
SCAN RATE = 10 RPM / SEC

DISCUSSION / WHAT DOES SUCCESS LOOK LIKE ?

Although a number of the changes in resonance pattern were classical (peak growth, peak shift to the left) for VSR Treatments, several peaks shifted to the right, shrank, or a combination of both. These later changes experience has shown usually indicate that the workpiece itself has changed shape. Simple structures, with minimal “cross-membering”, i.e., lack of stiffening members in the construction orthogonal to a dominant length, a condition common to long shafts or plate stock, are more prone, due to the nominal stiffness orthogonal to the workpiece length, to distortion machining, stress relieving (whether thermal, vibratory or accidental / unintentional, e.g. during transport).

Historically, distortion followed by improved dimensional stability, after transport, has been “discovered” hundreds of times. The most famous example likely is the purposeful transport of welded structures during WWII by German shops, since heat-treating facilities were an early focus of intense bombing. The term “fahrtbehandlung”, meaning literally “travel-treatment”, traditionally used to describe the relaxing benefit a traveler enjoys, was used to describe the practice. Indeed, it was just such “fahrtbehandlung” that resulted in distorted plates, unfortunately AFTER final machining, that was the chief impetus of MAG to pursue using the VSR Process on these plates.

Just as during fahrtbehandlung, some distortion can take place in a workpiece during stress relieving. With thermal, this can be due to unequal cooling or gravitational sagging (since the structure has $\sim \frac{1}{2}$ its strength during soak, in the furnace), but also due to a lowering of the potential energy associated with the stress relief, per se. Similarly, the VSR Process can result in such distortion, but only due to the last reason: Not the first two.

Thus, any machining plan following a stress relief treatment should take into account the possibility of change in workpiece dimensions. A new “map” of the workpiece, post stress relief, which might require thicker shims during workpiece fixturing / clamping, would be no great surprise. Indeed, it would be prudent to consider such distortion inevitable, since some of the change (all of it, during the VSR Process), is due to a lowering of the force fields within the structure to a level that minimizes the threat that untreated stresses would hold over target dimensional goals.

One of the more common outcomes of successful stress relief, and reported often by VSR Users, is a change in the behavior of the workpieces: They behave almost like perfect springs, in that loading within the elastic range, followed by load-removal, results in the workpiece returning back to “zero”.

So, although a bit “out-of-shape”, such parts are easier to machine to final form, and are likely to maintain their dimensional integrity. This likely accounts for the reduced time (~ 30%) to achieve final machining of the VSR Processed plates.

Similar experience took place by Ingersoll Machine Tool with an 18 m long gantry. Although never seeing the inside of a furnace (two VSR Treatments were performed, before and after rough machining) this gantry’s weighs were straight within ± 0.002 ” over the full ~ 700” length. Identical gantries that were later produced, but were thermally processed, required corrective measures to achieve the same accuracy. This is true, despite having passed inspection prior to leaving the factory: They were found to be out-of-tolerance on-site. The effects of “fahrtbehandlung” again manifested.

CONCLUSION

Based upon the response of the plates shown on the VSR Charts, this collection of eight plates should exhibit improved dimensional stability. The chart responses indicate that some, perhaps all the plates were “live”, and it is likely that some changed shape during treatment, but it is much preferred that such distortion take place prior to final machining, whose function is not only to produce a refined surface finish, but to address such variances in dimensions, so that not only accurate, but stable precision metal components are produced.