VSR Report

Argonne National Laboratory

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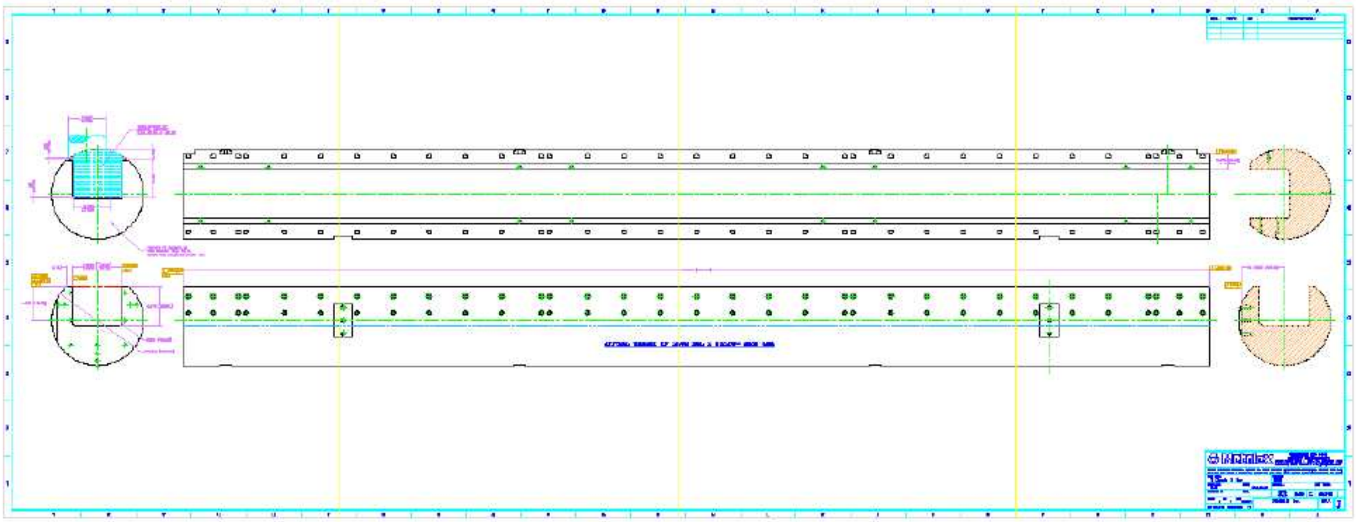
An ARGONNE NATIONAL LABORATORY research project required a very large and powerful electromagnet, which required a series of several dozen "Strong-backs" in the electromagnet's assembly. These forged components were to be made of pure titanium (for purposes of electromagnetic "transparency"), and have the following size and configuration requirements:

1. 144" L X 12" DIA
2. A slot, ≈ 6.6"w, x ≈ 6.5" deep, was to be cut full length, while maintaining flatness and parallelism dimensions of the slot's side and bottom surfaces within .001". This configuration would resemble a precision machine shaft with an extremely over-sized keyway cut full length, so that the center of the "shaft" was absent. See Figure 1.



The fact that these components were to be of pure titanium, rather than material commonly used for machine shafts, made the dimensional requirements even more challenging: Pure titanium behaves very similarly to austenitic stainless steel during machining; it is both relatively tough and gummy, and, therefore, easily develops machining stresses during rough machining. Further complicating the job was the extreme asymmetrical aspect of the machining. Almost all material to be removed was from one side of the component, so much so that the center is machined away. The possibility of distortion, in the forms of warping and twisting during the machining of more than 36% of the forging's material was considered likely, if not inevitable, by all machine shops that reviewed the drawings. Considering both the material and the dimensional tolerances, fulfilling requirements on a production of these components was considered a daunting task.

A clue as to the correct approach to resolve these issues was available: A prototype of these components had been made, and had shown excellent dimensional accuracy and stability throughout prototype testing by ARGONNE. This prototype had been vibratory stress relieved twice during manufacture: Once before rough machining, and again after rough machining.

In preparation for determining the procedures to be used to produce a production run of Strong-backs, a team of ARGONNE engineers and scientists received a VSR Technology Group presentation on the VSR Process and its technology. Based on this presentation, ARGONNE elected to specify the VSR Process to assure the dimensional accuracy and stability of these critical components. The procedure developed by ARGONNE was based upon the VSR-8000 System's Operating Manual, and the fixturing setup recommendations by VSR Technology Group.

Two machine shops, DIAL MACHINE, Rockford, IL, and METALEX MANUFACTURING, Cincinnati, OH, were awarded contracts to produce these components. METALEX had been using the VSR Process for more than 10 years; DIAL acquired a VSR-8000 System to fulfill this contract's requirements, although some of their staff had prior experience with the VSR Process while working at another Rockford, IL firm, INGERSOLL MACHINE TOOLS.

VSR SETUP

The recommended setup used to perform the VSR Process involved the use of a fixture. The fixture was several times the weight of the un-machined "blank", and the vibrator would be mounted on the fixture. Combined with a clamping system designed to both secure the workpiece and allow it to flex, this arrangement provides an efficient path through which the vibration can reach the workpiece and generate flexure, while minimizing the amplitude to which the vibrator itself would be subjected.

Fixtures are recommended in VSR Process applications involving workpieces that: (a) have no flat surfaces for clamping; (b) have a dominant length (L being >8X larger than width and height); (c) are light in weight. These titanium forgings meet the first two criteria, and were relatively light (which exacerbated the need for fixturing), when compared with many components that undergo the VSR Process, each weighs only 2419 lbs. (1100 kg) before machining, and 1548 lbs. (704 kg) after machining.

The setup required that the vibrator's AOR (Axis of Rotation) be aligned with the length of the workpiece. This would allow resonances of the workpiece, whether producing vertical or horizontal deflections to be both detected during Pre-Treatment Scans, and driven during VSR Treatment. Detecting and driving workpiece resonances – the most efficient method to generate workpiece flexure with sufficient force to cause stress relieving activity – is a key element of the VSR Process.

The workpiece was held to the fixture with a pair of V-blocks (designed and specified by the VSR Technology Group), and were positioned 5' from each end of the workpiece. This positioning, with 5' of overhang beyond each support/fixture point, allowed the flexure during resonance that is required to perform the VSR Process. This setup arrangement minimized the amplitude the vibrator experienced during Treatment, yet provided an efficient path for vibration to travel, through the fixture and clamping, and into the workpiece, without slippage.

An Accelerometer (a unidirectional acceleration sensor used to detect vibration amplitude during Treatment), was mounted on a clamping ring positioned at one end of the workpiece. The accelerometer was oriented so it would be most sensitive to radial vibration.

Acceleration is the best parameter to use to detect amplitude, and changes in amplitude, during vibratory stress relief, since it is proportional to force (Newton's 2nd Law: **F = ma** where "**F**" is force, "**m**" is mass, and "**a**" acceleration). The force from vibration the workpiece experiences in a relatively stress-free workpiece would only cause elastic loading to occur, but, in a workpiece with high levels of residual stresses, which are sufficiently large, can combine with these residual stresses (a form of "locked-up" force) to cause local plastic flow within the material. This is a key element of all forms of stress relieving, whether thermal, vibratory, "curing" (long term storage, most often used on castings), or unintentional, which can occur during transport (albeit, at the wrong time in the manufacturing process). In fact, changes in shape of precision-machined components during transport was the historic path which led to the discovery of Vibratory Stress Relief more than half a century ago.

The setup can be seen in **Figure 2**.

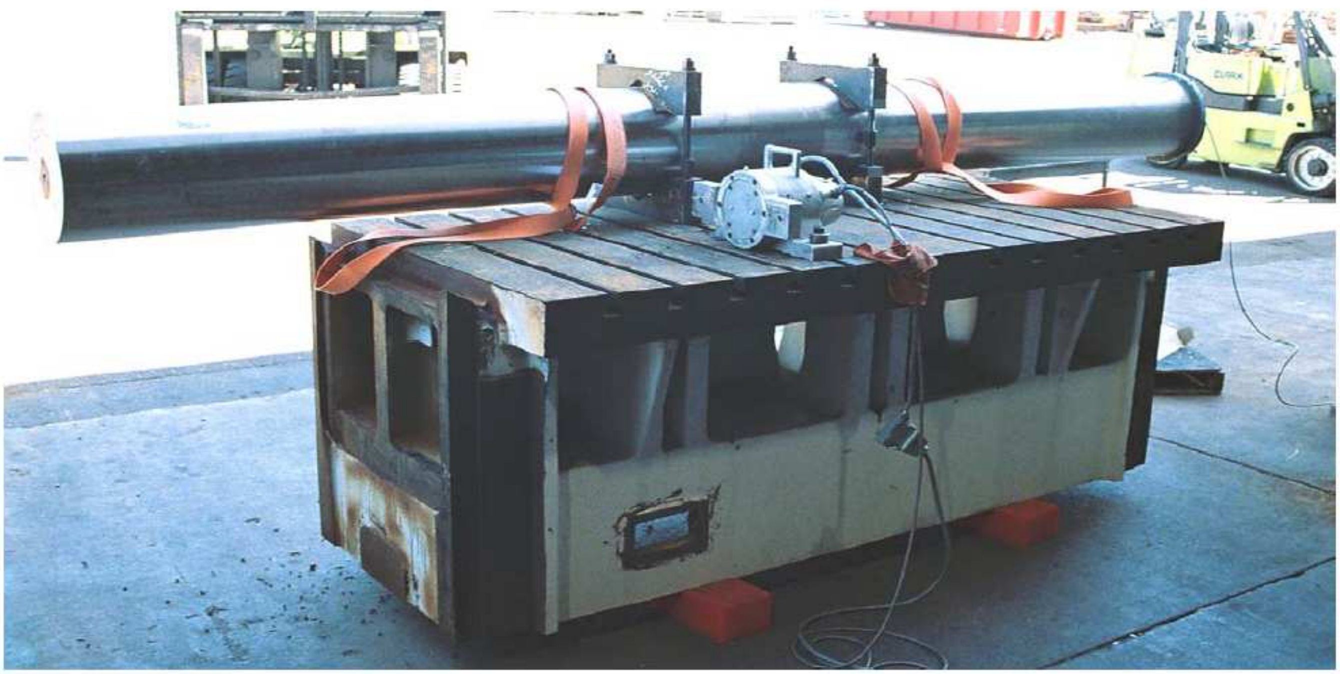


Figure 2: VSR Setup. Using a fixtured VSR setup maximizes both the achievable workpiece acceleration range and clarity of the vibration data, while minimizing vibrator power levels, making the setup more "user-friendly".

The 3.5 ton fixture, with T-slotted top plate, allowed easy installation of two V-blocks (centered on workpiece, 24" apart), and the vibrator. Two orange Isolation Load Cushions, a standard accessory of VSR Systems, can be seen in the foreground (circled), beneath the fixture; two additional load cushions are on the opposite side. The vibrator's AOR (Axis of Rotation) is aligned with the length of the workpiece, which allows both vertical and horizontal deflection of the workpiece. The Accelerometer is clamped to a slip-fit ring, affixed with set-screws, on the right end of the workpiece.

PRE-TREATMENT SCAN

The VSR System's BL8 Vibrator has adjustable unbalance from (0.2 – 4.0 in-lbs.), enabling resonating of a workpiece with the correct intensity to achieve stress relief. The standard practice is to use the vibrator's lowest unbalance setting, and an RPM range of 1000 RPM to 5000 RPM, and use the VSR System's QuickScan feature (scan rate: 50 RPM / second) to determine whether resonances are being achieved, and provide a rough estimate of their intensity. The initial unbalance setting (0.2 in-lbs.) could not sufficiently excite the workpiece, so the unbalance was incrementally increased to levels of 10% (0.4 in-lbs.), and then 15% (0.6 in-lbs.) unbalance. It was at 15% of maximum unbalance that the resonance pattern of the workpiece became apparent. (Later, based on peak growth that occurred during Treatment, this was determined to be the ideal setting for Treatment.)

The VSR System was then switched to the Pre-Treatment Scan mode. The System scanned thru the operator-selected 1000 RPM to 5000 RPM range at the operator adjustable rate of 10 RPM/second, and recorded the initial resonance pattern of the workpiece. DIAL MACHINE's VSR-8000 Console can be seen in **Figure 3**, and the Pre-Treatment Scan displayed on the Console's touch-screen PC can be seen in **Figure 4**. Green is used to record the Pre-Treatment Scan data, since the workpiece is (borrowing the common foundry term used to describe fresh castings) "green".

The instrumentation that produces the vibration data is very accurate and precise:

- The RPM data uses a digital stream of data from the vibrator's 600 pulse / revolution resolver. This data has a margin of error of < 0.003 %.
- The acceleration data is generated by an industrial accelerometer whose AC output is sent thru an instrumentation-grade amplifier, which is linear within 0.5% over its range of 1g – 50g full scale.

Figure 3: VSR-8000 Console. The console features an industrial grade, touch-screen PC which displays all pertinent vibration data, and includes several process controls. The pushbuttons (to the right of the PC screen) control vibrator start / stop, automatic/manual scanning, and vibrator RPM increase / decrease pushbuttons.

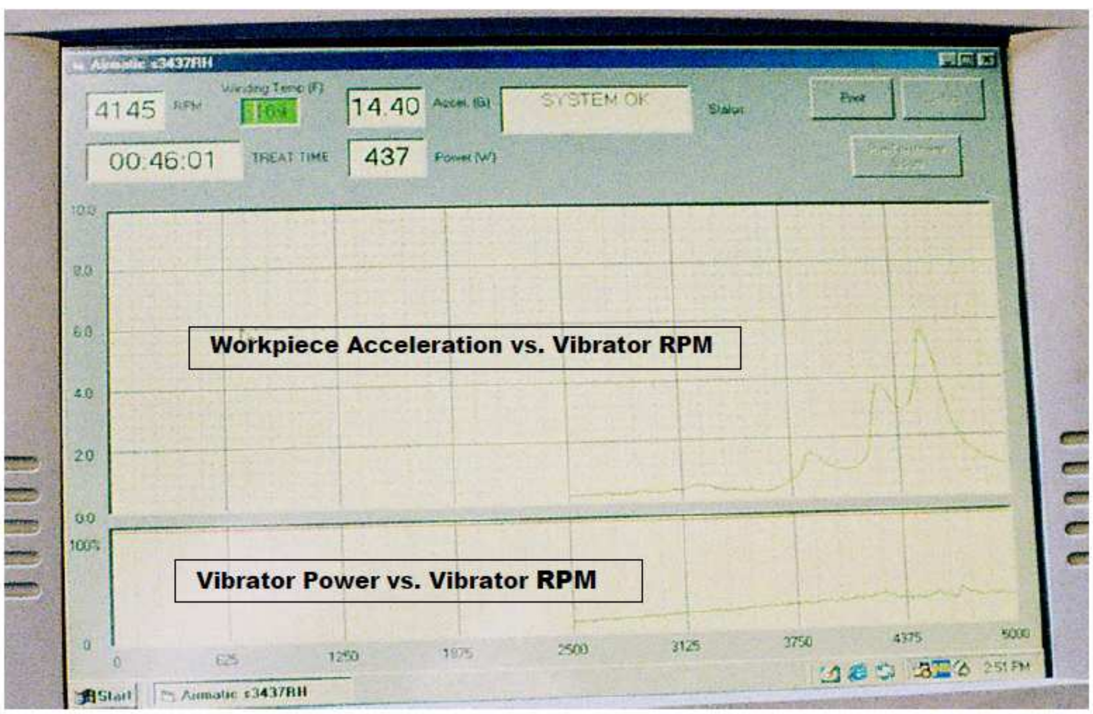


Figure 4: VSR Pre-Treatment Scan displays two plots: The top display plots the workpiece acceleration; the bottom vibrator power, both are plotted vertically vs. the common horizontal axis of vibrator RPM. Pre-Treatment scans are recorded in green, since the workpiece is "green", ie, freshly manufactured and prone to be full of stresses.

Peaks in the upper curve are workpiece resonances that will be tuned upon to perform Treatment. Peaks that occur in the lower curve correspond to vibrator speeds that cause excessive vibrator amplitude, which require changes to either vibrator unbalance or position. (The displayed power curve shows only mild peaks requiring no action or change to the setup. This is common to setups that employ a fixture, and is one of the "user-friendly" benefits of using a fixtured VSR Setup.)

The real time workpiece acceleration, vibrator speed, and vibrator power are also displayed digitally, as is vibrator motor temperature.

VSR Treatment

VSR Treatment was performed by tuning the vibrator speed, which can be tuned in increments as small as one (1) RPM, upon the resonance peaks discovered and displayed on the Pre-Treatment Scan. As stress relief occurs, the peaks will:

- Grow, quickly at first, when the workpiece is full of stress, with the growth later slowing down, and then ceasing, resulting in a higher, stable peak.

- Shift to the left (direction of lower RPM).

Both of these changes are consistent with a lowering of the rigidity of the workpiece, which is one of the consequences of effective stress relief, regardless of method. At times a shift of a resonance peak to the right occurs, which is evidence of a change in shape of the workpiece.

The first peak, located ≈ 3900 RPM (the left-most peak of the three seen on the Pre-Treatment Scan in **Figure 4**), grew slightly, and shifted to the left during a course of 10 minutes. The second peak, located at ≈ 4200 RPM grew very quickly, increasing from 4.0g to over 6.0g within the first 2 minutes of Treatment. It continued to grow, and was more than 14g at the time the Pre-Treatment Scan photo was taken (shown by the real-time digital display at the top of the screen), which required an additional 12 minutes to reach its maximum; mild shifting occurred with the peak frequency decreasing from 4200 to 4145 RPM.

The third peak had already increased from 5.5g to 8.0g when it was tuned upon. This is a common occurrence during the Treatment: Treatment of a peak that shows a large response can cause a response on other peaks. However, the third peak had also shifted to the right approximately 100 RPM, indicating the workpiece had changed shape. When the third peak was tuned upon, it continued to grow, eventually stabilizing at 16.5g at the end of the Treatment. This response indicates the workpiece would have distorted during machining.

POST-TREATMENT SCAN

An automated Post-Treatment Scan was then performed. It is automatically recorded in red and superimposed over the Pre-Treatment Scan. This allows the Pre-Scan to function as a base-line from which to gauge VSR Treatment progress. This is shown in **Figure 5**.

The difference between the green and red curves indicated a strong response to the Treatment: All the forgings were supposedly fully annealed by the supplier before being delivered to machine shops. Whether this was not done, not done properly, or the annealing did not render the workpiece dimensionally stable is open to speculation.

One of the advantages of the VSR-8000 System's display software is the ability to recalibrate Chart data (prior to it being archived). Note that the some of the acceleration data went off-scale vertically during the Post-Treatment Scan. By touching the SETUP window (the virtual button is in the upper right corner of the screen, see **Figure 5**), the operator was able to shrink the acceleration chart data vertically, so that full-scale was now 14g, instead of 10g. The image of the completed VSR Treatment Chart, showing all vibration, is shown in **Figure 6**.

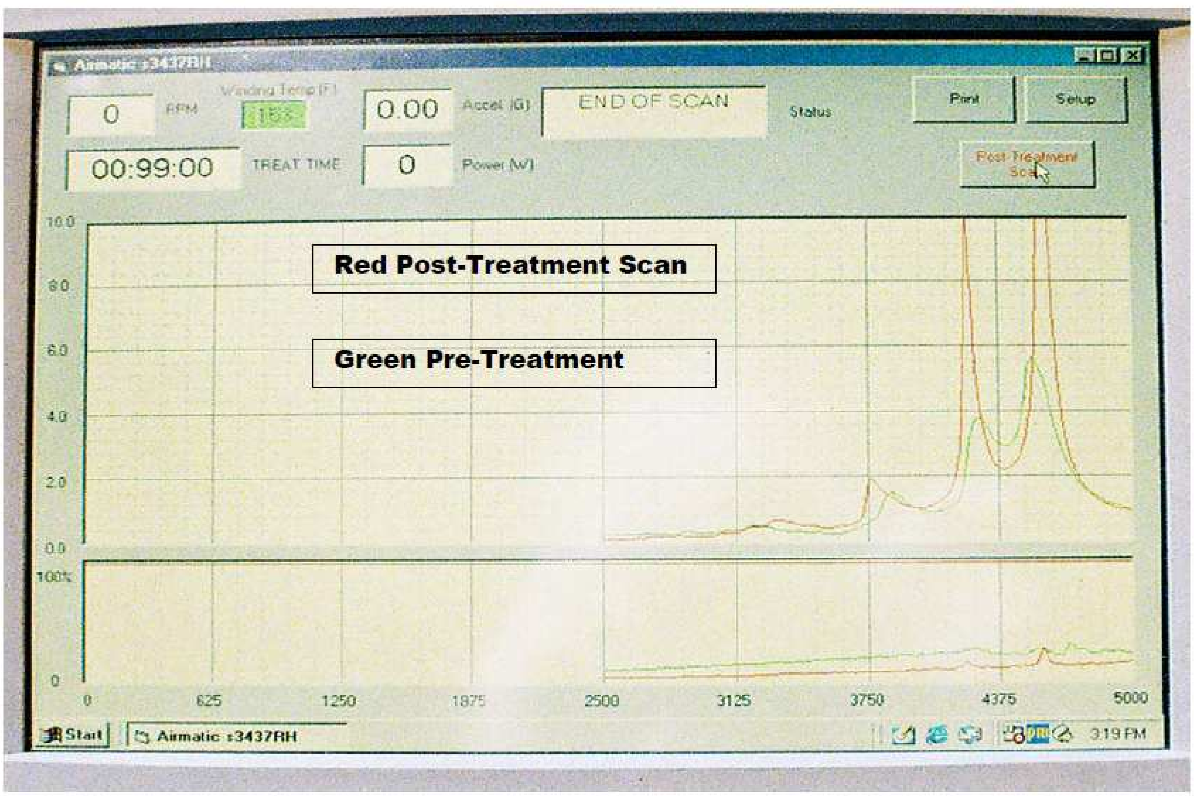


FIGURE 5: Completed VSR Treatment Chart. This was made by performing a Post-Treatment Scan, which was automatically recorded in red and superimposed over the Pre-Treatment Scan. The Pre-Scan data functions as a base-line, documenting the changes in the resonance pattern that took place during Treatment. This display shows a strong response (so much, the peaks grew off-scale), indicating that the workpiece underwent extensive stress relief.

Conversely, without Treatment this workpiece would have displayed extensive dimensional instability during machining: uneven surface finish, excessive cutter noise and chatter, faster tool wear, and extensive distortion while in-fixture, or upon release from the machining setup.

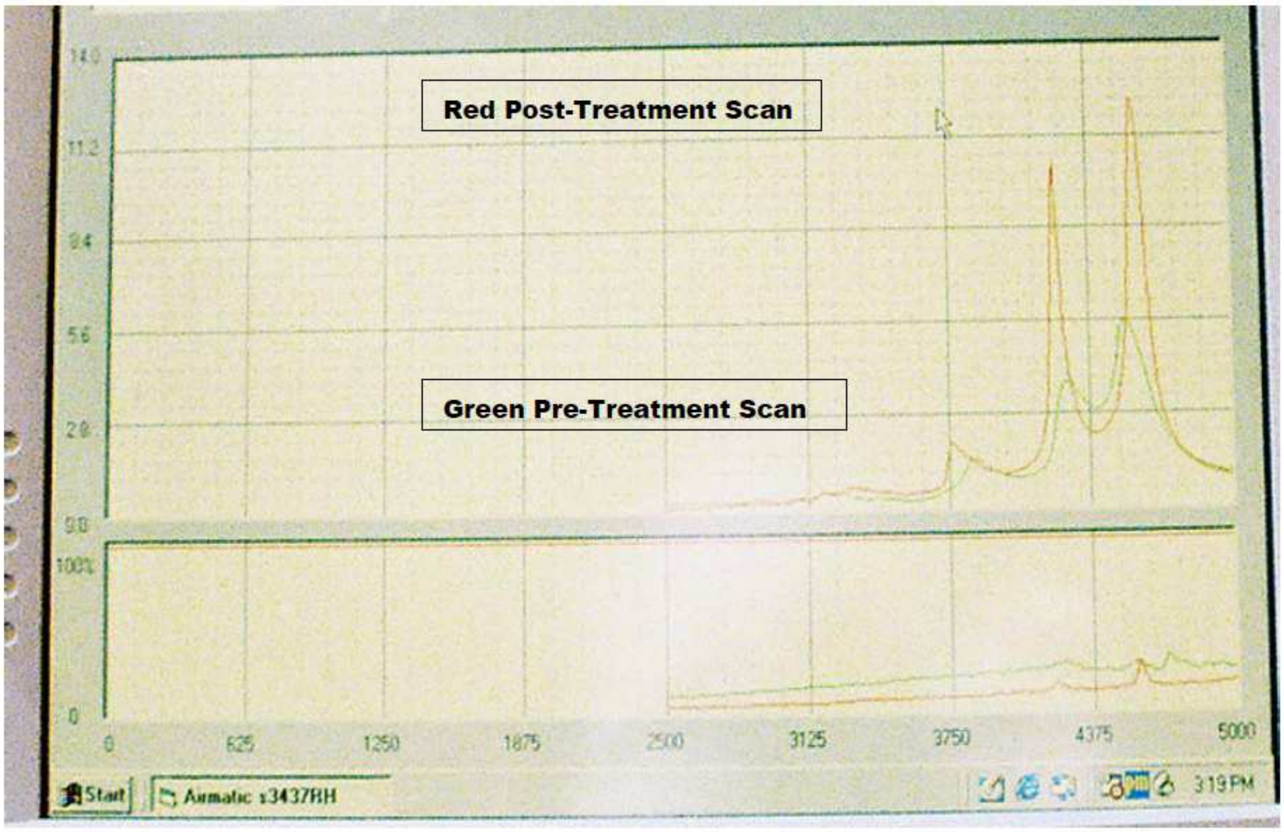


FIGURE 6: Recalibrated VSR Treatment Chart (acceleration full-scale changed from 10g to 14g) shows all the data, including recovered data that was off-scale in **Figure 5**. This ability to adjust the acceleration scale is helpful in both recovering off-scale data, or re-scaling data that had been recorded and displayed with too large a full scale (making its vertical range too short). The recalibration function is one of the many advantages of using a touch-screen PC together with the VSR-8000 System's software, as compared with other forms of instrumentation, eg, an XY-plotter.

This and other VSR Treatment Charts were archived and supplied to ARGONNE, documenting that required procedures in manufacturing these components was followed.

The VSR Process was used again to stress relieve these workpieces after rough machining. Stress relief after rough machining relieves two types of stresses:

- Machining stresses, which are likely to be significant based on the amount of stock removal, and the type of material.

- Stresses that had been "buried" in workpieces, but are brought close to the surface by extensive rough machining.

RESULTS

The two machine shops used the VSR Process on a total of 80 workpieces, each workpiece was stress relieved before and after rough machining. No rework was required during these production runs, with a small exception: One shop discovered voids during machining of the deep slot in two workpieces. A thorough NDT examination determined the defects to be only voids; no cracking had or was taking place. The voids were weld-repaired, an additional Treatment was performed, and machining was able to be completed without difficulty.

Such unwanted discoveries, eg, discovering voids in forgings or castings, detection of bad welds, mistakes in weld-layout or machining, are part of the reality associated with large-scale machining operations. Corrective measures, often in the form of weld-repair, produce stresses that can interfere with the dimensional requirements of subsequent machining operations. The VSR Process is frequently the most efficient and practical means of addressing these weld-repair stresses, since it minimizes interference in the production flow of precision components.

CONCLUSION

The VSR Process has demonstrated that it can render production runs of precision components highly dimensionally stable. Based on this and other case histories, VSR Technology Group's VSR Process should be considered as a best-practice method within the precision metal working industry.

3ruce Klauba has a degree in Physics and a Level II Vibration Analysis Certification from the American Society of Non-Destructive ˈesting (ASNDT). As a pioneer in the cause and effect of Vibratory Stress Relief, Mr. Klauba was named chief inventor (*Klauba et ıl.*) in U.S. Patent 4,381,673, which is both an equipment and process patent describing advances in the technology. He has authored ıumerous articles and original research papers on the subject, which have been published in leading magazines and periodicals. ʼublished papers include:

. "Use and Understanding of Vibratory Stress Relief", *Productive Applications of Mechanical Vibration*, 1983, American Society of Mechanical Engineers.

:. "Vibratory Stress Relief: Methods used to Monitor and Document Effective Treatment, A Survey of Users, and Directions for Further Research", 2005, *Trends in Welding Research*, ASM International.

ⱡ co-author in both papers, Dr. C. Mel Adams, is a leading authority in metallurgy and co-founder of MIT's Welding Research)epartment. In addition, Mr. Klauba has extensive experience in designing, building, and troubleshooting Industrial and Commercial :lectrical Controls with a focus on extending the performance and reliability of Electric Motors and the systems they power.