The cost effective alternative to heat treatment

Report on Vibratory Stress Relief

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CROSS RAILS JOB

INGERSOLL, a manufacturer of special machine tools, is a regular user of the VSR Process. This Report describes the successful use of the VSR System on the Cross-Rail member of a Gantry-style Milling Machine.

Despite being thermally stress relieved twice during the manufacturing process, the Cross-Rails suffered dimensional instability problems. The VSR System eliminated thermal treatment, and provided Cross-Rails that met all dimensional tolerances.

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In 1997, INGERSOLL MILLING MACHINE COMPANY contracted VSR TECHNOLOGY to stress relieve a series of fabrications (Pallet Frames) that had undergone weld repair. Bad welding had been discovered in the Frames during machining, and almost 20 % of the welding had to be reworked. The Pallet Frames were square tubing fabrications, and measured 30' x 18' x 1.5'.

Further, since some machining had already been performed, the prospects of causing additional distortion with yet another thermal treatment and the resultant need for scale removal made thermal treatment an impractical solution. By using the VSR Process on these weld-repaired components rework costs and production delays were minimized. Photos 1 and 2, seen on pages 7 & 8, show a Pallet Frame and a VSR Treatment Chart made while the Frame was being stress relieved.

Based on the success of this job, INGERSOLL's manufacturing engineers started exploring other potential applications for the VSR System. This report describes one of the applications chosen by the engineers: a 23'L Cross Rail. INGERSOLL chose this workpiece because even after multiple thermal treatments during its production, it continually suffered dimensional instability. The success of VSR Process in stabilizing this Cross-Rail not only provided additional proof of the true effectiveness of VSR Technology's vibratory metal stabilization process (*vs* thermal treatment), but also underscored a severe limitation in the use of furnace treatment as a means of reliable stress relief.

A Cross-Rail is the top member of a gantry style milling machine on which rides the milling machine's spindle. INGERSOLL's design of these milling machines includes a precisely machined, detail arc, not more than a 0.002", machined into the Cross-Rail's "weighs" so that the calculated sag of the Cross-Rail (due to the weight of the spindle), would allow a straight path for the spindle's travel.

In this Gantry design, the precision and stability of the Cross-Rail's dimensions define the accuracy that the machine tool can achieve. This workpiece is an irregular, rectangular configuration, measuring 23'L x 4' H x 40" (overall), and, *as shown* in the photos on page 9, is relatively uniform on its underside, but quite irregular and complex on the opposite, upper-side. This highly asymmetrical configuration, *ie*, the large differential between the contours on opposite sides of the workpiece, will be discussed in greater detail later in this report.

A Cross-Rail's normal sequence of manufacturing steps had been:

1. Weld.
2. Thermally Stress Relieve.
3. Rough Machine.
4. Thermally Stress Relieve.
5. Grit Blast.
6. Paint.
7. Final Machine.

Unfortunately, most Cross-Rails required additional, unscheduled, steps because of the severely out-of-tolerance dimensional problems. This was usually uncovered after the “final” machining was performed, the Cross-Rail was trial assembled on its mating columns, a spindle was assembled upon the Cross-Rail, and the whole assembly laser inspected to determine accuracy.

When a Cross-Rail was found to be out-of-tolerance, the test assembly was torn down, the Cross-Rail was, again, setup and machined, the test assembly was rebuilt and then re-inspected for dimensional accuracy, and alignment. INGERSOLL estimated the cost of performing these four additional steps to be > $3500.

VSR SETUP

As shown in Photo 3, page 9, the workpiece was placed on three (3) Isolation Load Cushions which were placed far in from its corners, so as to minimize damping. This placement allows not only the greatest number of resonance peaks to be generated, but also the largest amplitude of those peaks, which enhance the effectiveness of the Vibratory Treatment. Due to the contour variations of the underside of the workpiece, rigid wood planks were needed under two of the Load Cushions to keep the Cross-Rail level. In Photo 3, page 9, these two wood planks can be seen at two points along the length of the workpiece, each 1/3rd in from its end. The third Load Cushion, was located on the opposite side, centered along the workpiece's length as shown in Photo 4, page 9.

The VSR System’s MV1 Vibrator (visible on top of the workpiece in both photos on page 10), was securely clamped to the workpiece above one of the Load Cushions on the nearside, and oriented so the its axis of rotation was parallel to the length of the Workpiece. This Vibrator orientation was chosen so as to excite the workpiece in the directions it would most likely resonate, specifically, the two directions perpendicular to the length of the workpiece. If the length of the workpiece is considered to be the X-axis, the width, the Y-axis, and the height, the Z-axis, the workpiece would most likely resonate in the YZ plane. The location of the Vibrator was chosen because it was likely to be near one of the *nodes* of the workpiece. Nodes are those locations, typically “lines” in 3 dimensional structures, that undergo minimal movement during resonance. Nodes are good locations to place the Vibrator for two reasons: (1) The clarity of the data generated during a VSR Treatment will be enhanced; (2) As the most dynamically rigid mounting location, we can not only cause better vibration transmission but also extend the longevity of the Vibrator.

NB: The nodes generated on a VSR workpiece can often be seen by sprinkling a dry powder, *eg,* Oil Dry, on the workpiece during resonating. The powder gathers on the nodes because it is driven from those areas undergoing high amplitude. Photos 5 and 6, page 10, show some of the nodes generated on the Cross-Rail. As can be seen, the Vibrator was relatively close to one of the nodes.

An Accelerometer (a unidirectional acceleration sensor), was placed on a corner of the Cross-Rail, and oriented so as to be most sensitive to vertical deflections (the Z-axis direction).

After two Quick-Scan calibrations through the Vibrator's RPM speed range, the MV1's unbalance was set at 3 in-lbs (50% of the available 6.0 in-lbs). The correct unbalance setting combined with strategically locating the Vibrator on the workpiece are critical to producing the greatest number of resonance peaks of the largest amplitude, while avoiding significant peaks in the Vibrator's input power.

VSR TREATMENT

The equipment used to perform the treatment was a VSR-790A System, which, in addition to the MV1 Vibrator already mentioned, includes:

- A Control Console. This Console contains a highly accurate, servo-motor speed drive; an accelerometer amplifier; digital readouts of the workpiece acceleration (expressed in g-units), Vibrator RPM, and input power (in watts); plus outputs that supply signal to . . .

- An XYY Plotter. This Plotter uses the X-axis (horizontal) to depict Vibrator RPM, its upper, Y-axis (vertical) to depict workpiece acceleration, and its lower Y-axis to show Vibrator input power.

The Console has an Auto-Scan feature which slowly sweeps the Vibrator through its factory-set RPM range and causes the Plotter to generate a Pre-Treatment Scan. The VSR Treatment Chart shown on page 11, shows the results of this Pre-Treatment Scan: the Green curve (upper) shows acceleration, and the Red curve (lower) shows Vibrator input power. The pre-set RPM range on the Auto-Scan for this job was 1000 - 5980 RPM; the scan took 7 minutes.

Peaks displayed in the Green Acceleration Curve are resonant peaks of the workpiece. Tuning the Vibrator directly upon each of these peaks causes the workpiece to undergo the maximum amount of flexure. This flexure, if sufficiently intense, causes stress relieving activity (SRA). SRA releases the potential energy trapped within the workpiece – the energy that threatens its dimensional stability and, therefore, its dimensional integrity. *To achieve target dimensional specifications, trapped potential energy must be released,* and this is best achieved when resonate vibration is used.

During the release of potential energy, the workpiece becomes less rigid due to the lowering of the *spring ratio*, which after stress relief (*ie,* stabilizing) will become the *spring constant*. This lowering of rigidity not only affects the workpiece's static behavior (as can be seen during a cold-straightening operation), but also its dynamic behavior. This change in dynamic behavior can be seen during an effective VSR Treatment by monitoring two specific changes in the workpiece's response to resonant vibration:

- *Growth* of the resonant peaks to higher amplitudes (upward movement on the VSR Treatment Chart). *Growth* is generally the stronger response.

- *Shift* of the resonant peaks to lower frequencies (movement to the left on the VSR Treatment Chart). *Shift* is generally the weaker response.

VSR Treatment is accomplished by tuning the Vibrator RPM directly upon a resonant peak and allowing it to dwell on that peak. This was done, first, on the shorter resonant peak which was located at 3222 RPM and at slightly more than 3g. This peak showed rapid *growth* and slight *shift*, and its progress was tracked by a series of progress dots. These progress dots are made by lowering the Plotter's pens to make a mark (a dot), which depicts both the peak's location and its height at that moment. If the operator systematically uses progress dot charting (*eg,* every 45-60 sec), the resulting pattern will show a history of peak *growth* and *shift*, *ie,* its treatment progress, hence "progress dots" as shown in VSR Treatment Chart on page 11.

It took 15 min for this peak to change from its highly stressed original condition to its significantly lower stressed, (*ie*, stable) condition. During this time, the resonant peak grew to a height of more than 4.5 g, > 1.5 times its original amplitude, and shifted ≈ 60 RPM to the left (< 2% change).

The next resonant peak to be treated was located at 5980 RPM, it can be seen on the far right side of the VSR Treatment Chart on page 11. Because the apex of the peak could not be tuned upon (it was just outside the Vibrator's RPM range), the Vibrator was tuned upon the peak's leading edge, which, providing sufficient *g* levels (acceleration) are achieved, can be an equally effective means of stress relieving, although the Treatment does take longer. On this workpiece the leading edge of this resonant peak was treated for 25 minutes, during which time it grew from 7g to more than 10g (off the vertical scale of the XYY Plotter – a job-set calibration).

One additional resonant peak was treated (located at approximately 5170 RPM), but there was neither *growth* nor *shift*. When the workpiece was examined to see what areas of excitation this particular peak was associated with, it was determined that a pair of short, light-weight structurals at the end of the workpiece were undergoing deflection. Because these end rails were small and were not intended to stiffen the workpiece, their contribution to the workpiece's resonance pattern was minor. Hence, this peak experienced neither *growth* nor *shift*, despite being treated for 5 minutes.

After all peaks had been treated and stabilized, the pens were reversed (Red on top for acceleration; Green on bottom for input power), and a Post-Treatment Scan was run (superimposed over the Pre-Treatment Scan). The resulting VSR Treatment Chart is reproduced on page 11.

MACHINING AND INSPECTION RESULTS

After VSR Treatment, the Cross-Rail went to final machining and then inspection – *where it met all dimensional tolerances.*

The ultimate test of the effectiveness of the VSR Treatment came when the Cross-Rail test assembly was positioned on its columns, and underwent laser examination. Unlike previous manufactured gantry assemblies, which had always required re-machining due to their failure to meet dimensional requirements – *this Cross-Rail test assembly passed inspection.*

CONCLUSIONS

Based on the results of this job, three conclusions can be drawn about the effectiveness of the resonant vibration approach to metal stabilization:

1. The VSR Process was successful in rendering the Cross-Rail more dimensionally stable. To avoid the re-work costs and lost production time caused by re-machining and re-testing of such parts, use the VSR Process to eliminate dimensional instability problems. Further testing of the VSR Process is absolutely warranted.

2. Despite being thermally stress relieved two or more times during the manufacturing process, a workpiece of this general configuration typically remains dimensionally unstable. The use of the VSR Process to eliminate the 2nd thermal treatment should be immediately considered; in fact, further testing should be done to see if thermal treatment can be eliminated altogether.

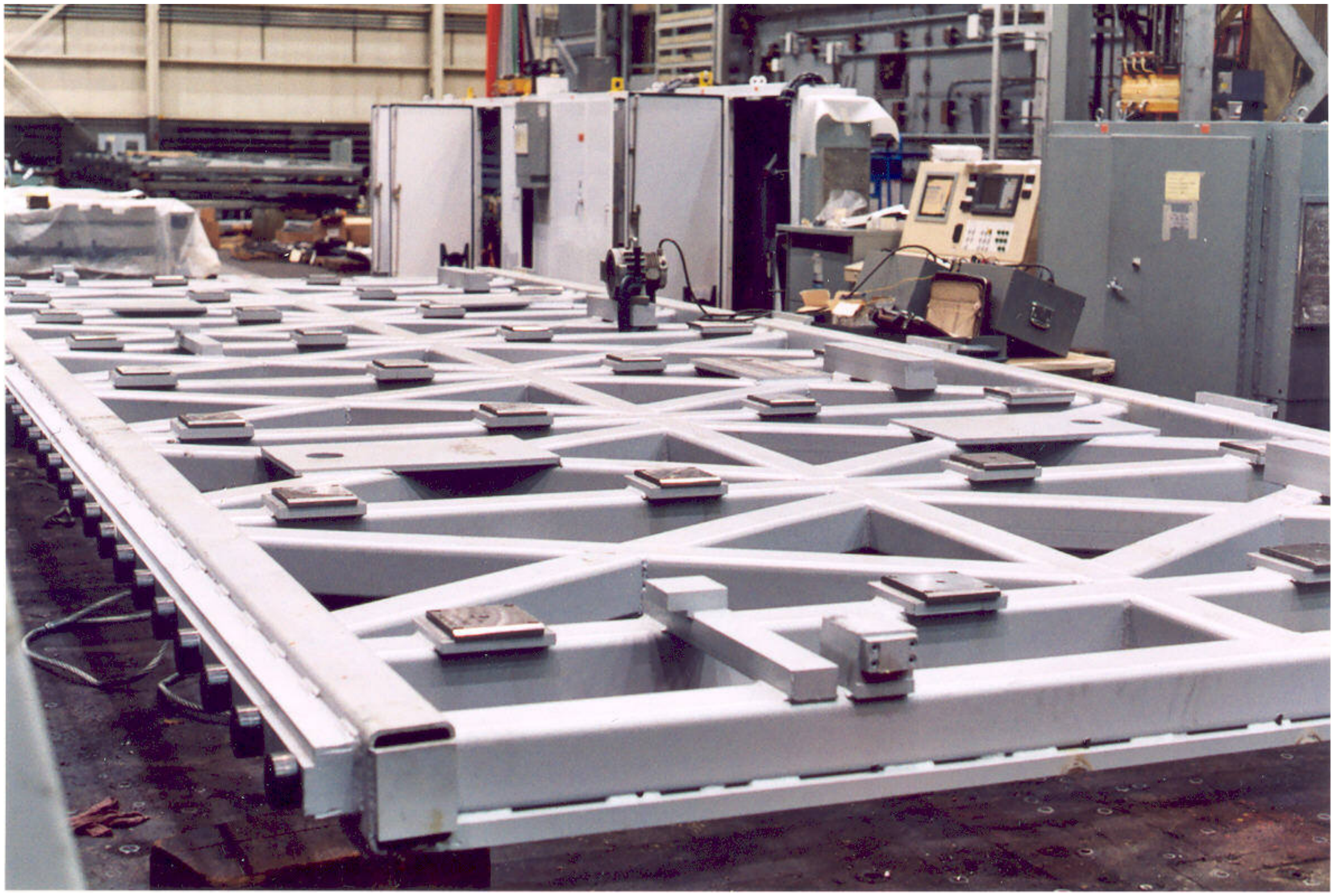
3. If thermal treatment is to be kept as part of the Cross-Rail manufacturing process, the effectiveness of thermal treatment must be improved. In all likelihood, the thermal treatment could be improved by slowing down the cooling rate. This could be done by using thermocouples and a process controller, so as to not re-introduce residual stresses during what is supposed to be a stress relieving procedure.

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

1. "Use and Understanding of Vibratory Stress Relief", *Productive Applications of Mechanical Vibration*, 1983, American Society of Mechanical Engineers.
2. "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.

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

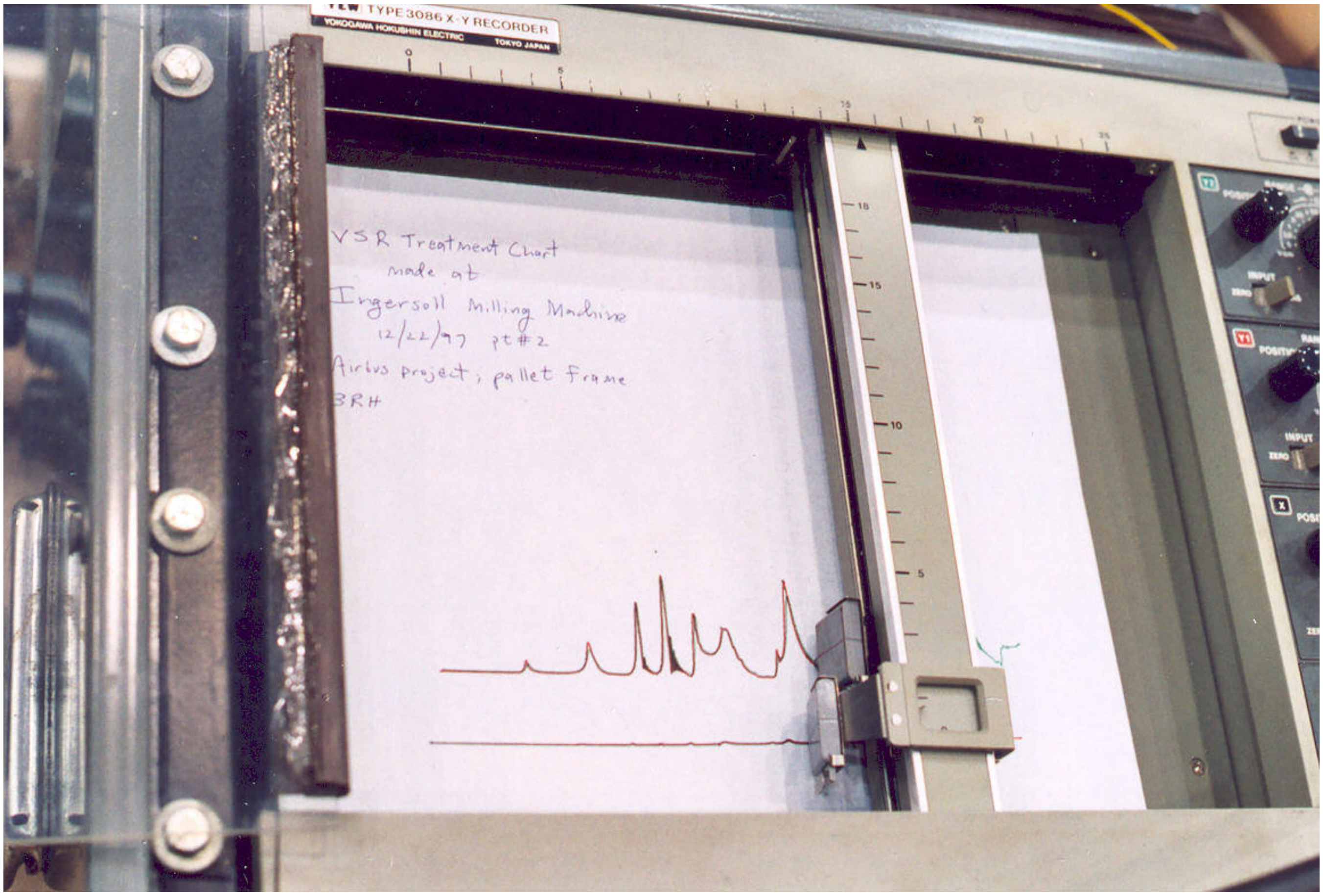
Photo 1



Shown here is one of several Pallet Frames being VSR processed. During the machining process it was discovered that the Frames had a number of severe welding defects. Rather than bear the risks and costly delays associated with a second thermal treatment after re-work, INGERSOLL chose to use the VSR process to stabilize these parts.

Based on the results, INGERSOLL continued exploring the capabilities of VSR Treatment and because of success they achieved, eventually chose it for the super critical components of their machine tools, such as the Cross-Rail component (the subject of this Report), and even larger components, such as a 59'L gantry (see INGERSOLL MILLING REPORT: Stressed Relieved 59'L Milling Machine Gantry).

Photo 2



This photo of a VSR Treatment Chart shows the mild, but discernable, VSR Response that occurred during the stress relieving of a Pallet Frame. Because only a minimal number of welds had to be replaced, this is a typical workpiece response to treatment.

Compare this Treatment Chart to the chart on the Cross-Rail (Page 11), which, despite being thermally treated *twice*, showed a large response, similar, in fact, to an "as-welded" workpiece. This is strong evidence that a combination of the geometry of the Cross-Rail, and the too rapid cool-down rate used during thermal treatment, actually *reintroduced residual stress* into the Cross-Rail. INGERSOLL's history of Cross-Rail dimensional instability is consistent with this conclusion, as is the success in achieving dimensional stability when using the VSR Process.

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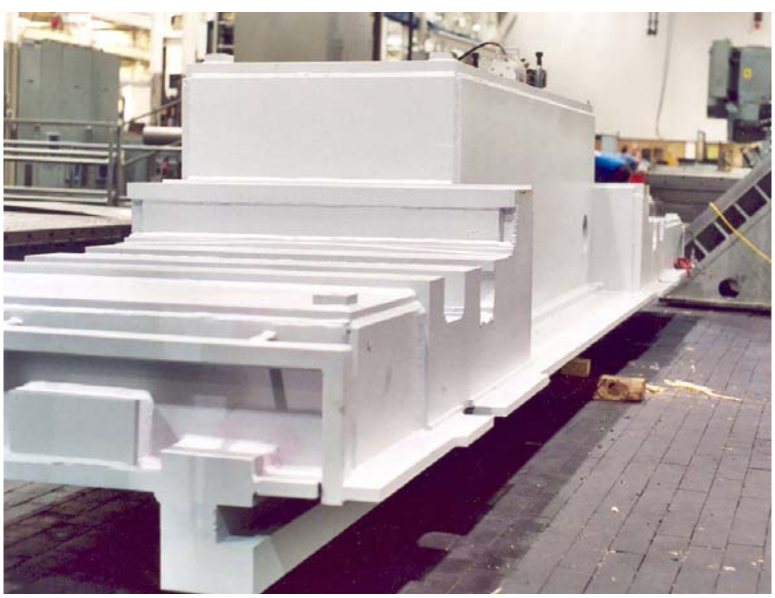
Photo 3

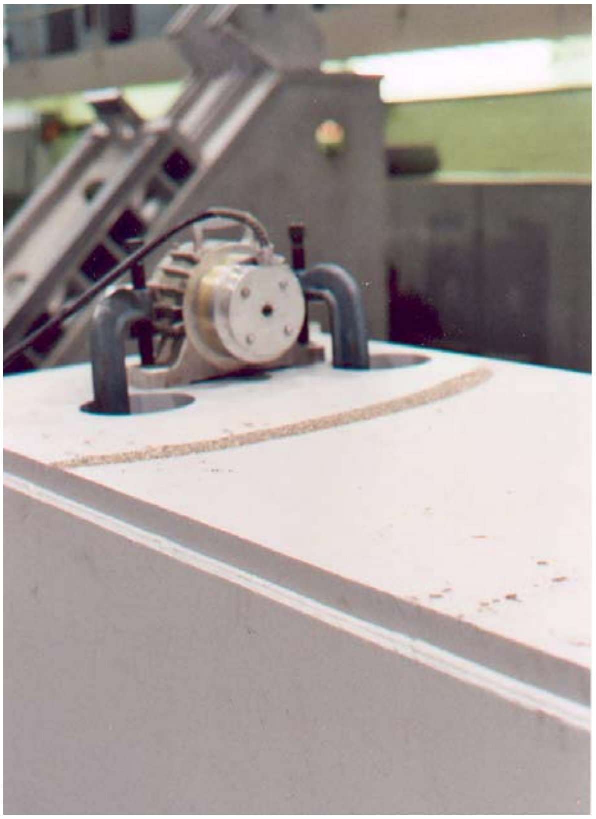
Cross-Rail setup for VSR Treatment. Two (of the three) Isolation Load Cushions were placed on top of wood planks used to support and level the workpiece. The third Load Cushion (not shown) is centered on the opposite side. The Vibrator, mounted securely to the workpiece over one of the Load Cushions, has its axis of rotation oriented parallel to the length (X-axis) of the workpiece, so as to drive the workpiece in the directions it can resonate.

Photo 4

Side view of VSR Setup. Note the complex contour of the upper portion of the Cross-Rail, as compared to its underside. It is this extreme asymmetry that causes difficulties in the effective thermal stress relief treatment of such configurations. The thermal cycle's cool-down rate must be slowed so as to not re-introduce stresses during what is supposed to be a stress relieving process. Such complexities in workpiece geometry actually enhance the effectiveness of the VSR Process, since they increase the responsiveness to vibration.



Photos 5 & 6

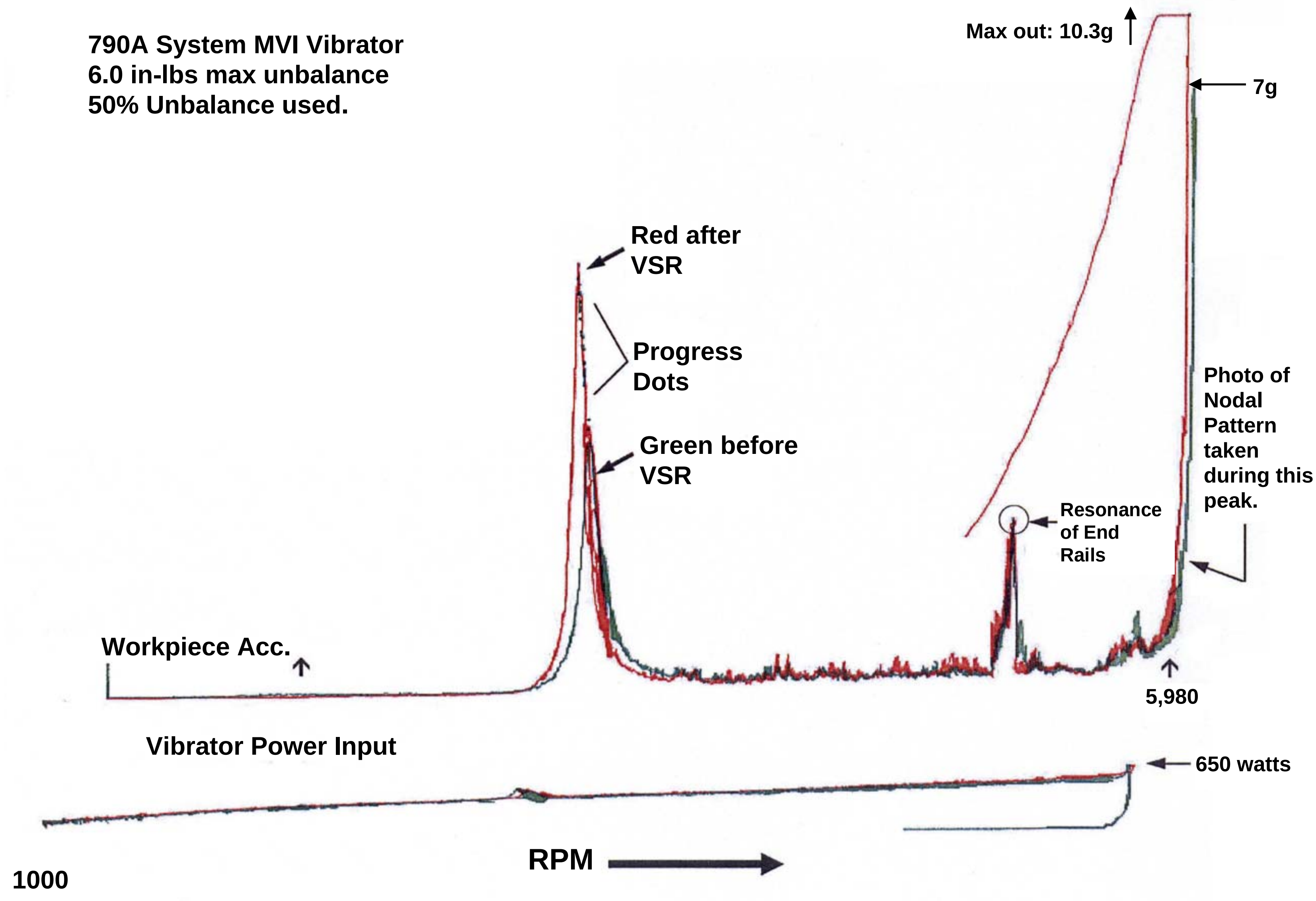
 

Resonance is distinguished not only by producing peaks in the acceleration (and force) that a workpiece experiences, but also by producing a clearly defined Nodal pattern of high and low (virtually zero) amplitude on the workpiece. This is sometimes referred to as a *standing wave*, since the nodal wave pattern on the workpiece is stationary.

Shown here is the nodel pattern produced on the Cross-Rail. Photo 5 shows the end of the workpiece where the Vibrator is mounted, while Photo 6 shows the opposite end. Oil Dry, which had been sprinkled on the top of the workpiece, was driven off the high amplitude locations, and settled on the low amplitude locations. These are the *nodes*. These node areas are good locations for mounting the Vibrator and installing the Load Cushions, they are not, however, suitable areas for attaching the Accelerometer.

VSR Treatment Chart:
INGERSOLL MILLING MACHINE:
Cross Rail (4/13/99)

790A System MVI Vibrator
6.0 in-lbs max unbalance
50% Unbalance used.



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