REPRINT:

PRODUCTIVE APPLICATIONS OF MECHANICAL VIBRATIONS

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Vibratory Stress Relief: Methods used to Monitor and Document Effective Treatment, A Survey of Users and Directions for Further Research

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Effective vibratory stress relief treatment can be performed on a production basis, providing that changes in the workpiece's resonance pattern are carefully monitored. Stability of the new resonance pattern is indicative of completion of the vibration treatment. These changes are consistent with the workpiece's increased mechanical response to dynamic loading.

An increasing number of manufacturers of precision components use vibratory stress relief on a variety of components. A survey of dozens of users of vibratory stress relief, from diverse industries, reveals regular application of the technology upon a wide range of workpiece materials and configurations. At times vibratory treatment replaces thermal stress relief; at other times vibratory stress relief has been found to stress relieve components that respond marginally to thermal treatment, stainless steel weldments being one of the most common examples.

Two promising directions for further research are outlined:

1. A careful examination of resonance patterns of an iron casting reveals a change in both resonance amplitude (expected), but also resonance frequency (unexpected), with varying vibrator unbalance.
2. A new, simple method of measuring residual stresses, using micro-hardness data, could greatly expand the understanding of the vibratory method.

Introduction

The Vibratory stress relief process uses controlled and monitored vibration to cause dynamic loading; this dynamic loading combined with the internal load from residual stresses, enables plastic flow to occur. Flexure is a key requirement of the process.

Residual stresses can be viewed as a form of potential energy, and stress relieving, whether the result vibratory, thermal, long term storage, or unintentional "bumpy" transport, as a release of this potential. It has been observed for decades that a workpiece that has been final machined can change shape during transport, often outside tolerances.

The use of vibratory stress relief has increased steadily over the last two decades. The reasons for this steady increase include:

- The finding that thermal stress relief is, in practice, less effective on certain types of workpiece configurations. Large variations in wall thickness of a workpiece or its topography characterize two such types.
- Weldments made out of 300 series, austenitic stainless steel, which require good dimensional stability, are more effectively stabilized with vibration treatment, than with PWHT (Post Weld Heat Treatment). The high temperature strength of these stainless steels precludes their ability to respond to temperatures used during PWHT.
- Stress relieving both before and after rough machining improves dimensional stability. This is practical with vibration treatment, but often impractical, if not impossible with PWHT.
- The increased use of low-carbon, high strength steel. PWHT of these steels poses risks of either reduction in strength or toughness. Certain grades also suffer increased risk of cracking as a result of PWHT. Of the 141 ASTM grades of steel listed in the International Steel Group Plate Steel Specification Guide, 43 carry the warning that PWHT "may degrade heat-affected zone strength and toughness", while 11 others also "may be susceptible to cracking in the heat-affected zone of welds during post-weld heat treatment (stress relief) or elevated temperature service."
- The increased use of bi-metallic components, for which PWHT is not a viable option.
- The time required to perform vibration treatment is a fraction of that needed to perform PWHT.
- The ability to vibration treat virtually any size or weight of workpiece.
- The increased cost of fossil fuels, and their environmental consequences.

Previous work

The early (1943) notable work of McGoldrick and Saunders[1] on both steel castings and weldments concluded that for the vibration treatment to work, it must cause plastic flow within the workpiece. They further recommended using resonant vibration to achieve effective amplitudes.

Dawson and Moffat[2] were successful in relieving 90% of the residual stress present in samples of three different alloys. This work was complimented and extended by Walker, Waddell and Johnston[3]. In 1995 they concluded that the degree of dynamic loading required to achieve stress relieving was significantly less than previously reported.

Adams and Klauba[4] concluded that, carefully controlled, vibration treatment could be monitored, and had become a frequently used process, based upon a survey of users. This also was the first published work that included a vibratory stress relief treatment chart, which clearly showed a change in resonance pattern resulting form vibration treatment. At the time of this work, a PhD study at Georgia Tech, by A. R. Soto-Raga (supervised by Professors P. Yoder and J.T. Berry) was undertaken to determine whether finite element analysis could be applied to the vibration process.[5]

More recently, the individual works of both Hahn[6] and Yang et al[7] have used a more refined computational approach with finite element analysis to further determine the most effective vibration frequency choice (resonant vs. non-resonant), as well as the effectiveness of vibration treatment.

A recent work by Rao et al[8] has applied vibration treatment to rails intended for a Maglev transportation system. They noted (joining other previous researchers) that after vibration treatment, the resonance peak increased while the resonance frequency decreased. This phenomenon will be touched on later in this paper.

Vibratory Stress Relief Case Studies

Two examples of large, precision components that underwent vibration treatment are described below: The first is a 23-foot long Cross-Rail for a milling machine. This component in operation rests on columns, with a gap of about seventeen feet between the columns. A precision way, responsible for the path of the spindle assembly, is machined into the Cross-Rail. To compensate for sagging caused by the weight of the spindle, a crown is machined into the way. The crown is 0.0012-inches (≈0.030 mm).

Standard manufacturing procedure for this machine tool builder is to PWHT both before and after rough machining. Inspections during a trial assembly showed these critical components failed to meet dimensional tolerances, despite the two thermal treatments. Almost all required an additional final machining (costing \$3,000 to \$4,000 USD).

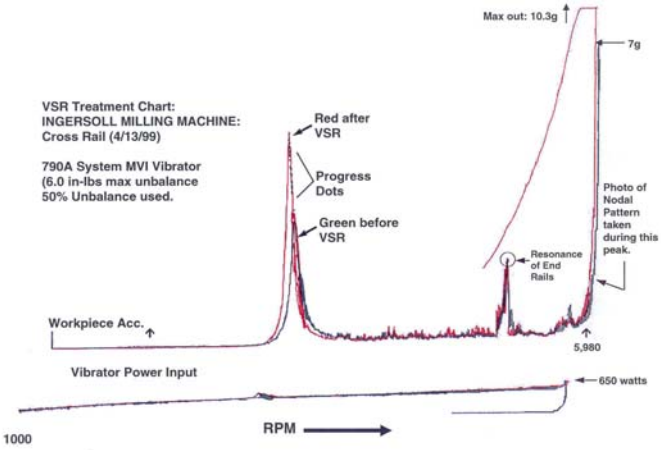

Figure 1

Shown in Fig.1 is a photo of the Cross-Rail setup for vibration treatment. The workpiece was set on three (3) isolation load cushions, which were placed on wood to level, and provide floor clearance. One cushion is visible in the photo. The other two cushions were on the other side, centered, and spaced only four feet apart. This three point – far from corner – cushion placement, minimizes damping, enabling maximum workpiece flexture during vibration treatment.

Figure 2

Figure 2 is the vibration treatment chart made during stress relieving of the Cross-Rail. The X axis is vibrator speed in RPM. There are two vertical axis: The upper is the workpiece acceleration; the lower is vibrator power. Both the Pre-Treatment and Post-Treatment Scans are superimposed, allowing changes in resonance pattern to be easily seen. Both the resonance peaks at ≈3200 and ≈6000 RPM grew 30% to 40% during treatment, which lasted for about forty minutes. Peak growth, which is indicative of stress relieving activity, eventually subsides, resulting in: permanently larger resonance peaks; a stable resonance pattern; and a stable workpiece to machine.

This Cross-Rail met tolerances after final machining, unlike all similar ones.

The second case study is of a 59.5-foot (18 meter) long gantry for an even larger milling machine. Again, straightness of the ways was a key tolerance in the design.

Figure 3 shows a photo of the gantry setup for vibration treatment. Isolation load cushions were placed on both sides of the workpiece, at the 1/3rd and 2/3rds locales. Vibration treatment was done both before and after rough machining. No PWHT was performed.

Figure 3

Figure 4 shows a dimensional inspection chart for the gantry. The Horizontal axis is the length of the gantry, running from 0 to 700-inches. The shape of the gantry is depicted in the two hill-shaped curves, both of which are scaled on the left. These show that the gantry was straight ±0.002-inches, changing little over the course of two weeks, when the dashed curve's data was gathered. The difference, scaled on the right, and depicted in the valley-shaped curve, is 0.0008-inches, indicating very stable dimensional behavior.

Figure 4

A New Approach to Estimating the Degree of Effectiveness of Vibratory Stress Relief

One factor which may have limited the acceptance of Vibratory Stress Relief, has been the lack of precise information regarding the extent to which residual stresses have diminished during treatment. Recently one of the authors (Berry) and a colleague (John Wyatt at Mississippi State University) have developed a highly practical technique by which residual stresses on a surface can be effectively measured. This technique, for which a patent has been applied, involves the change in geometry and spacing of micro-hardness indentations. Appendix II contains a description of the method concerned.

Survey of Users of Vibratory Stress Relief Equipment

Appendix I is a tabulation of the survey responses of twenty users of vibratory stress relief equipment. The tabulated information includes the type of business, department in which the respondent works, size range of workpieces, types of materials, criteria for choosing the form of stress relief to be employed, the types of problems solved by using vibratory stress relief, and the builder of the vibration equipment.

Effects of Vibratory Stress Relief on Fatigue

An important and largely unanswered question is the matter of how vibratory treatment affects fatigue life. Dawson and Moffat[2] concluded that some amount of fatigue damage, though small, might accompany vibration treatment. Walker, Waddell and Johnston[3], however, showed that effective stress relieving took place at lower induced stress levels in mild steel (250 Mpa) than previously observed, a level unlikely to cause fatigue damage.

None of the users responding to the survey reported any damage caused by vibration treatment to any workpiece. One respondent, a manufacturer of vibratory screening equipment, reported that their sole reason for using vibratory stress relief was for the purpose of extending fatigue life in the frames of their equipment, which are mild steel weldments.

The Lowering of Resonance Frequency with Increasing Driving Force

The progress of vibration treatment can be monitored accurately by tightly regulating the vibrator speed, and watching for changes in resonance pattern. The greatest of these changes is the growth of the resonance peaks. This change is accompanied by a shift to lower frequency of the resonance, a change that requires re-tuning of the vibrator speed, so as to stay on top of the peak.

A similar lowering of resonance frequency as a result of increased driving force on structures not containing residual stresses has been observed. The phenomena appear to be related.

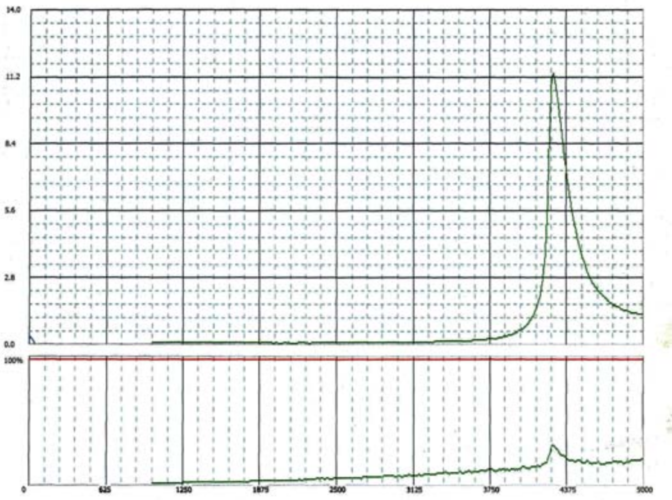

Figure 5

To explore this, a cast iron vibration test block, which had been acquired from a scrap yard (no stresses), was setup in a manner similar to preparation for vibration treatment. Figure 5 shows the resonance pattern of the block. The vibrator was then adjusted to a series of four lower unbalance settings, and the resonance patterns of these were recorded. A composite of these five charts, show in Fig. 6, clearly shows that the lower driving force results in higher resonance frequency. Conversely, higher driving force results in lower resonance frequency.

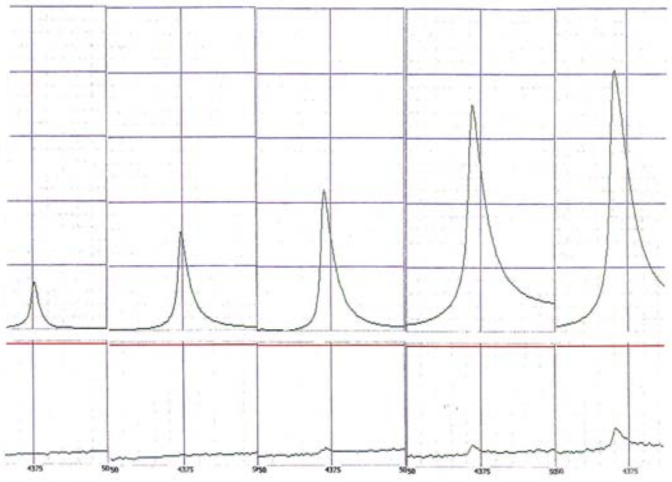

Figure 6

This is further depicted in Fig. 7, which is a plot of the shift in resonance frequency vs. acceleration.

This would indicate that peak shifting, in the direction of lower frequency, is caused by an increase in flexure of the structure. This increase might be due to an increase in driving force, as in this test, or due to peak growth, as a result of effective vibratory stress relief.

The variation in resonance frequency is subtle. In the example, which is consistent with similar tests of this phenomenon, five-fold range of driving force caused a change of resonance frequency of only 2.7%. This degree of change is resonance frequency is very much in agreement with what is seen during vibratory stress relief.

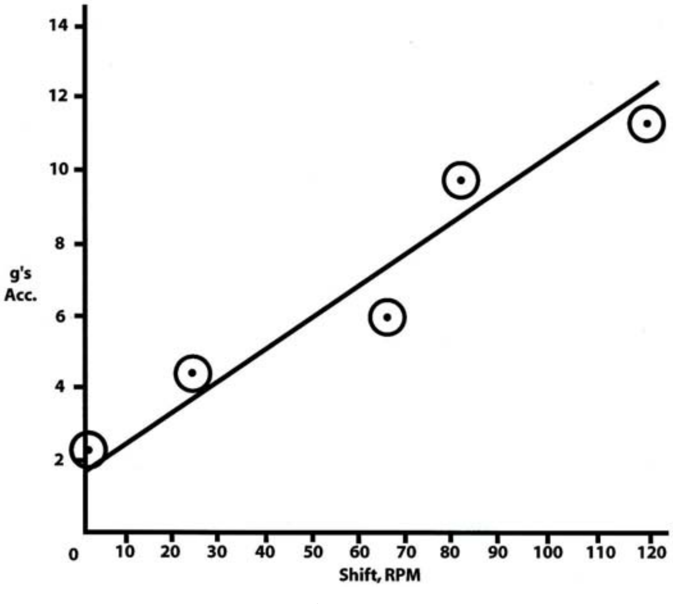

Figure 7

Conclusions

Vibratory stress relief has evolved over the last few decades into a repeatable industrial process:

- Used primarily for purposes of dimensional stability, it will render large precision metal components more stable and predictable than PWHT, and do so at significant savings in cost and time.
- Progress of an effective vibration treatment can be monitored by controlling the vibration, and watching the resonance pattern of the workpiece. Resonance peak growth is the key parameter to monitor.
- Vibration treatment allows a wider range of materials, including low-carbon, high-strength steels, stainless steels, bi-metallics, and weldments with aluminum alloy members to be made dimensionally stable, with absolutely no effect upon their physical properties.
- Additional applications of vibratory stress relief are likely to emerge once a more complete picture of the actual mechanism through which it operates becomes available.
- Measures of the effectiveness of vibratory stress relief will become more readily available using a new, practical method of measuring residual stress.
- Manufacturers using vibration treatment can enhance the quality of the precision metal components they make, and the assembled equipment containing them.

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Appendix 1: Survey of Users of Vibratory Stress Relief

Types of business:	
Machine tool builders:	4
Job shops:	4
Fab shops:	2
Industrial saw builders:	2
Cement making machinery:	1
Steel and aluminum mill equipment:	1
Plunger pumps, 3 and 5 cylinder:	1
Aerospace tooling:	1
Hydraulic cylinders:	1
Mining, quarry and pit equipment:	1
Bolster plates, mold bases:	1

Departments:	
Design:	8
Plant management:	6
Welding:	3
Assembly:	1
Machining:	1
Quality Assurance:	1

Workpiece weight varied from as low as 20 – 100 lbs., to as much as 100,000 lbs., the most common workpieces was in the 4,000 lbs to 40,000 lbs range.

Workpiece size varied from 2 to 3-feet long for the smallest, to as much as 60-feet long, with 8 to 24-foot long parts being common.

Material:	
Mild steel:	16, including 1010, 1018, 1020, and A36
Cast:	2, including Cl 35 grey iron
Stainless steel:	5, including 304, 304L, 316, 316L, 410
Low-Carbon, High-Strength Steel:	4, including HY80, ASTM 514
Alloy Steels:	4, 1045, 4140, 4340

Criteria for type of stress relief:	
Size of workpiece:	8
Avoiding distortion from PWHT:	4
Avoiding scaling from PWHT:	2
Customer requirements:	4

Problems solved by using vibratory stress relief:	
Dimensional instability:	19
Machinability:	14
Reduced cracking in finished product:	6
Surface finish:	4

Manufacturer of vibratory stress relief equipment:	
Airmatic Inc., VSR Technology Group:	11
Bonal Technologies:	5
Stress Relief Engineering:	3
Aaronson:	1

Appendix 2: A New Method for the Determination of Superficial Residual Stress

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The measurement of residual stresses in metallic components is often a long, laborious and expensive task. Recently a technique has been evolved which is both simple and inexpensive and capable of determining the magnitude and orientation of residual stresses present at the surface of metals and alloys (A1). It has thus far been applied to wrought components which have been subject to high speed machining (A2) and also to as-cast alloys of aluminum (A3).

The technique concerned is based on the change in shape and spacing of hardness (preferably microhardness) indents which came about when a component containing residual stresses is stress relieved. The paper cited earlier (Wyatt and Berry, 2005) describes how stresses present at the surface of a 2024-T6 aluminum alloy machined at a variety of cutting speeds were measured using this technique.

The principle involved follows work by Simes, Mellor, and Hills,(A4) which describes the change in indent shape measured before and after the application of a biaxial stress state to a special cruciform shape. This work has been extended to include the change in spacing of pairs of indents which will also follow up removal of the residual stresses concerned.

Knowing the change in spacings (i.e., the displacements concerned) and applying simple elasticity theory, the magnitude and sense (i.e., sign) of the stresses concerned can be estimated with reasonable accuracy. The technique evolved holds considerable promise for application to structures that have been subjected to vibratory stress relief. Because of its simplicity and inexpensive nature it would seem readily applicable to on-site application.

REFERENCES TO APPENDIX 2

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