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PRODUCTIVE APPLICATIONS OF MECHANICAL VIBRATIONS

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A PROGRESS REPORT ON THE USE AND UNDERSTANDING OF VIBRATORY STRESS RELIEF

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A survey of users of vibrational stress relief, together with in-depth analysis of several specific case histories of applications to larger weldments, has led to a clearer understanding of the purposes and effects of the technique. At the same time, a refined methodology has been and is being evolved from field experience with ever-improving equipment and instrumentation.

Those manifestations of the effects of vibration which can be observed during or immediately following treatment include:

(1) The amplitude-frequency spectrum is affected. The resonant peaks become sharper, of higher amplitude, and occur at slightly decreased vibration frequency, as a consequence of treatment. These responses are consistent with reduction in residual stresses brought about by local plastic flow in the metal.

(2) The power-frequency spectrum is also changed by treatment, but this is a less sensitive response.

(3) Static readings from strain gauges, strategically placed at locations suspected to harbor high stresses, exhibit "zero shifts", evidencing minute local plastic flows.

(4) Dynamic strain gauge, readings give local strains during treatment; these can be expressed as fractions of (elastic) yield strain magnitude to assess the severity of treatment.

Longer range effects can only be developed by protracted field experience - - that was the purpose of the survey.

There are two major conclusions:

(1) Metallurgical effects of vibrational stress relief treatment are negligible. There are no changes in structure or properties. Contrary to often-expressed concerns, fatigue life is not shortened -- the total number of cycles imposed at less than half yield stress magnitude is vastly smaller than that which might lead to fatigue damage.

2) The main aim and effect of vibrational stress relief is to improve dimensional stability by selectively reducing the intensity of just those residual stresses so located as to cause dimensional problems, either during machining or in service. It is to this purpose the method has had its most successful applications.

Introduction

It has been well documented and often experienced that residual stress can be a major cause of dimensional instability in metallic components. Two of the most common methods of producing large metal components, casting and welding, inevitably leave residual stresses within a part which are capable of causing dimensional change, often of an unacceptable magnitude. The common method of correcting this problem is to perform a thermal stress relieving treatment. Another method that has been used in the U.S. for more than twenty years, with isolated examples of use dating back to 1943[1] is vibratory stress relief.

Much controversy remains within the metal working industry as to the effectiveness of the VSR mechanism. The exact number of companies using VSR is not known, but is probably between 200—700 in the U.S. alone. Nevertheless, the majority of companies that would benefit do not use the method for numerous reasons. Amongst them are:

(1) Lack of a concensus as to any VSR theory or mechanism. This is reflected in the diversity of both the design approach and recommended procedures of the various manufacturers of VSR equipment and also by the scant amount of research available on the process.

(2) Difficulty in verifying the effectiveness of a VSR, as compared with thermal, treatment, short of machining and/or test loading an appropriate candidate for the process. For reasons discussed later, the common nondestructive methods of measuring residual stress, or plastic flow due to stress relief, do not always provide conclusive results.

It is the intention of this paper to address these two points. The paper consists of two parts: a theoretical portion that pertains chiefly to items 1 and 2 above, and a survey portion that outlines the use of VSR equipment by twenty—six companies that represent a cross section of the North American metal working industry.

Dimensional instability

Consider the career of a metal part containing residual stresses. These stresses most often result from hindered thermal contraction of welds or from nonuniform cooling after casting or heat treatment, and threaten the dimensional stability of the part broadly in two ways:

(1) During machining, stressed material may be removed, causing elastic deflection.

(2) During assembly, transport, erection or in-service loading, local plastic flow often develops in regions of high residual stress, provoking unanticipated and potentially harmful dimensional shifts.

The VSR treatment only affects those residual stresses so located as to overlap the regions where flexure tends to induce high stresses, and these are precisely the locations where residual stresses are most likely to induce dimensional change. In other words, the VSR treatment selectively reduces just those residual stresses of maximum concern. The most offensive residual stresses are, fortunately, the most responsive to VSR.

The VSR Mechanism

In a fashion reflective of the loading experience the part sees in its lifetime, VSR treatment subjects a metal component to dynamic forces in an attempt to cause any dimensional change that can occur to occur before final machining. This loading causes plastic flow to occur at points in the part where two conditions coexist:

1) A concentration of high level residual stresses is present, and

2) Flexure due to the dynamic loading is of sufficient magnitude to combine with the residual stresses so as to exceed, if only momentarily, the yield point.

The success of any VSR treatment therefore depends upon producing sufficiently severe dynamic loading that approximates or surpasses future loading.

This explains the limited success of detecting stress relief using strain gauges or other non-destructive methods. The chances of pinpointing the stress relieved area can be very small. It might even be impossible to examine the part at this location. That is why successful VSR procedures normally rely upon the acoustic character of the part to detect both the correct driving frequency and treatment time. Low frequency acoustic data will give an overview of the entire part rather than a small sample such as that monitored with a strain gauge.

The Type of Vibration Required to Perform VSR

In order to produce the degree of loading sufficient for VSR, normal practice attempts to take advantage of the phenomenon of resonance. Vibrating a structure at a frequency equal to one of its fundamental frequencies loads the structure far more than mere random vibration. At resonance the driving force is multiplied by a number minimally of 1/2, which occurs with severely damped structures, but more typically by a number substantially larger than 1. How great the force multiplication factor is depends on the ratio between the actual and the critical damping.

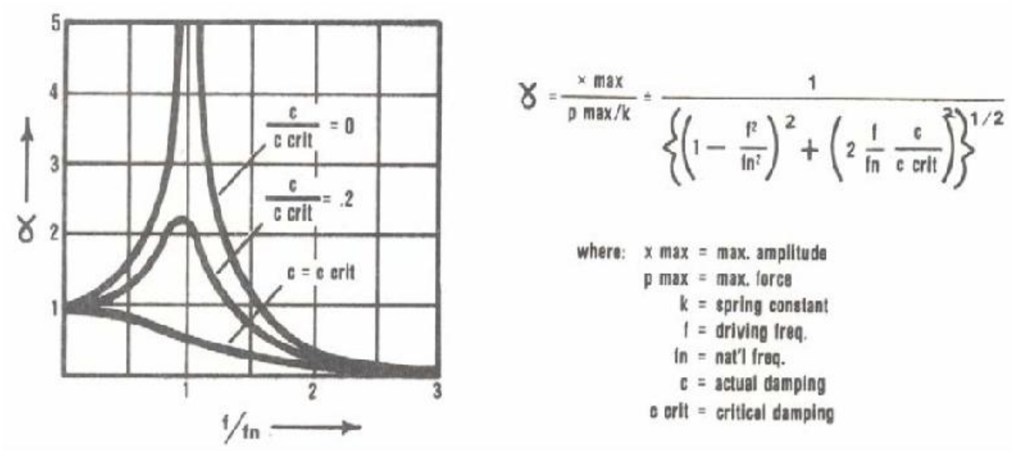

Figure 1: The damping determines the amount of force multiplication at resonance.

An example of a part typically susceptible to VSR treatment would be a steel weldment weighing more than 1,000 lbs. and of a configuration exhibiting high aspect ratio (i.e. gross envelope dimensions relatively larger compared to average cross sectional area). This is the type of part encountered in practice, wherein:

(1) Without any stress relief, there may well be severe dimensional instability.

(2) The VSR treatment is particularly effective.

(3) The effect of VSR treatment is readily manifested by changes in the vibrational behavior of the weldment.

In such an example, if treatment has been effective, the acceleration/frequency spectrum changes in several ways:

(1) The resonant peaks become narrower and more sharply defined,

(2) The peaks become more intense, higher in magnitude; and,

(3) The peak(s) shift to lower frequencie(s).

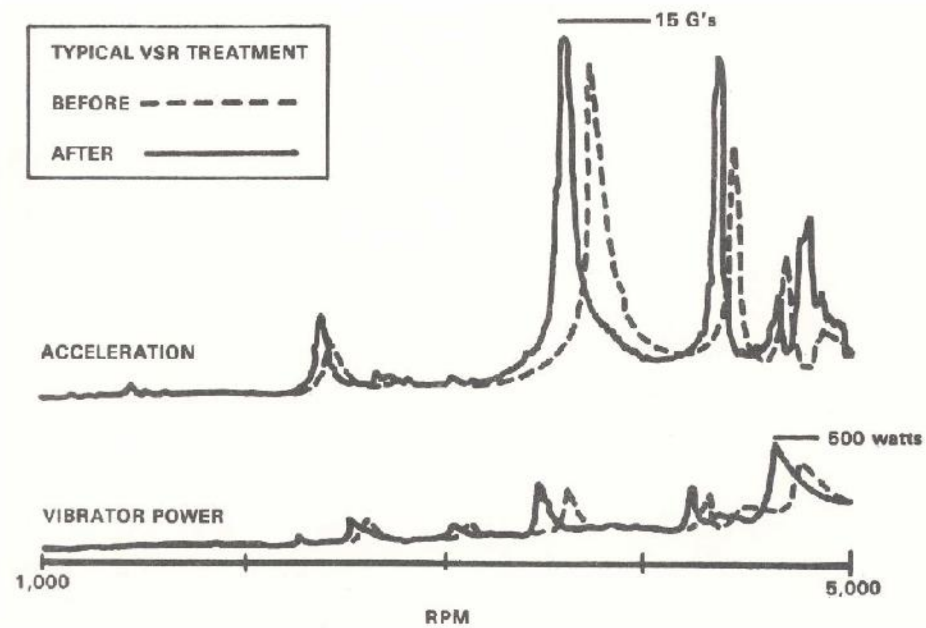

Figure 2

Typical chart produced during VSR treatment of a mild steel square tubing fabrication. Actual part was 23' x 5' x 6" and resembled a ladder. Treatment lasted for one hour and was equally divided between the five resonance peaks displayed. Imbalance of vibrator was .6 in-lbs. Top driving frequency was 5,000 RPM. All scales are linear.

The resonant peak(s) growth and/or shift relates to the effect of residual stresses (esp. shear stresses) on elastic behavior. These stresses cause local changes in the modulus of elasticity. Seismographers have long recognized the effect of residual stress on the velocity of sound through rock, as have those engaged in the use of ultrasonics to diagnose stresses in metal. In effect, the presence of shear stresses in a metal part increases the aggregate stiffness of the part; hence, their reduction tends to lower resonance frequencies, and/or allow resonant peak growth.

Those structures that exhibit comparatively high force multiplication are those with high aspect ratios. As the aspect ratio decreases, the VSR technique becomes increasingly difficult to perform. Lowering of an aspect ratio changes the dynamic character of a part in three ways:

(1) It increases the fundamental frequencies.

(2) It narrows the bandwidth of the fundamental frequencies.

(3) It lowers force multiplication.

Therefore, in order for VSR equipment to be more effective on those parts known to be responsive, and effective on a wider range of parts, the following parameters should be examined:

(a) A wider range of driving frequencies will allow smaller and more rigid (i.e. low aspect ratio) parts to be successfully VSR treated.

(b) Improving the speed accuracy of the vibrator(s) will allow complete detection and driving of resonance frequencies, many of which are only 1/4 hz in bandwidth.

(c) Increasing the available force from the vibrator(s) will permit stronger, more rigid, parts to be treated.

(d) Instrumentation which displays in a simple fashion the resonance frequencies, permits continuous monitoring of the acceleration, and documents the change produced in vibrational response, both of growth and shifting of resonant peaks, would greatly aid the operator.

Techniques used to Treat Low Aspect Ratio Parts

Besides the equipment design features, a – d, listed above, three other techniques have been used to improve the effectiveness of VSR on low aspect ratio parts.

(1) Adding weights. The addition of weights to the peripheral members of a part will increase the force multiplication and/or lower the resonance frequency.

(2) Routing. Doing VSR treatment after rough, or before and after, rough machining in cases where large amounts of stock removal take place has advantages. The rough machined part has a higher aspect than the as welded or cast part.

(3) Minimize damping. Normally parts to be VSR'd are placed on rubber blocks which permit deflection during vibration. Placement of these rubber blocks should be such as to avoid increasing the damping of the part.

(a) Avoid corner placement.
(b) Use a minimum number of rubber blocks.

Limitations and Side effects of the VSR Process

Metallurgical effects of VSR treatment are negligible. There are no changes in structure or properties. Therefore, those applications where softening of the material is required to enhance machinability cannot be properly handled with VSR. However, many of the difficulties in machining welded components are only partially caused by hardness. Much of the resistance to machining has little to do with hardness and relates to the presence of residual stress. This is evidenced by two points:

(1) The hardness of common mild steel weld fill (like E7018) is negligibly affected by heat treating to typical stress relieving temperatures.

(2) Users of VSR (eight of the 26 in the survey) indicate improvements in machinability due to VSR.

The theory best able to explain this seeming anamoly is that while material is being removed, due to residual stress being present, elastic strain occurs; the true feed rates are not what the machine tool is commanded. The part warps in fixture. If the residual stresses that would interfere with dimension were relieved, little or no warpage would take place. This observation on the part of VSR users was most common with two types of parts:

(1) Cylindrical (warpage severely effects machinability).

(2) High amount of stock removed. (High probability of elastic strain during machining).

Material Size

Small parts often are difficult to VSR becuase of their relatively low aspect ratio and/or relatively high resonances. Most VSR users are limiting their parts to above 2'–3' in 3D diameter, and more than 500 lbs. with the notable exception of square tubing fabrications which possess very high aspect ratios.

Fatigue

Concern is occasionally expressed that VU treatment "uses up" part of the fatigue life of the component being treated.

Theoretically, this is possible, but only when the VSR method is driven to unreasonable extremes of vibration amplitudes and times. Experience has taught that vibration within the frequency range of about 40 to 80 hertz for about 10 minutes (at each resonant peak) on parts of reasonable and typical aspect ratios, while imposing strains substantially less than half yield strain magnitude, effects substantial stress relief, as reflected in changes in the vibration spectrum and enhanced dimensional stability.

In other words, less than 50,000 cycles at less than half yield strain typifies successful VSR treatment, and has negligible effect on fatigue *life*.

VSR User Survey

The following is a tabulation of a survey of VSR users taken in the first half of 1982. Approximately sixty questionaires were sent out; all 26 that responded are represented here. Although not great in number, the users form a cross section of the North American metal working industry. The single largest category is machine tool builders. Manufacturers of specialized machinery, railcars, aircraft assembly tooling, pumps, mining equipment, rolls and conveyor components are also present. The common element these companies share in their various pursuits is the production of large metallic components that must exhibit dimensional stability. Most of these companies have eliminated thermal stress relieving on large parts either for economic and/or performance reasons.

Name & Location	Type of Wkpcs.	Yrs. of Use	Configuration	Type of Equip. Used	Problems Solved: Dim. Instab.	Problems Solved: Resists Machining	Problems Solved: Other or Specifically	Materials C - Casting, F - Fabrication: Mild Stl. & Tool	Materials: Stainless	Materials: Iron	Materials: Alum.	Comments, Complaints Suggestions
Allied Chemical Corp. Solvay, N.Y.	Conveyor components motor & pump base feed screws	[illegible]	(Approx.) flat or box, and screw shaped	VSR-190	X			1020-F				
American Hercules Corp. (reorganized as Deem Corp.) Shelbyville, IN	Machine tool assemblies, bases, frames, rams, for hydraulic shears	5	Consist of assemblies made out of burn out plates	Martin	X	X	Stress relief of welds	1010 or A36 F				
Beech Aircraft Corp. Wichita, KS	Jig frames, boiler plate cutouts, Heavy aluminum shapers, machine tool bases, master gauges	14	Various	Martin C-575	X			1018 as rcvd. 4130			6061-T6 2024-T6	The VSR process has greatly improved the efficiency of fixing large structural assemblies at Beech. Recommended over thermal.
Benedict & Miller, Inc. Lyndhurst, N.J.	Machine tool bases, mostly fabs, some castings.	13	Rectangular & Cylindrical	Martin C-575	X							
Brown & Sharpe Mfg.	Machine tool, bases thin steel. Machine tool tables in cast iron	10	Large hollow & rectangular castings	Strs. Rlf. Eng. E-62 CSP	X			1018-F				No rejects. Avoids cracking in some castings.
County Heat Treat Millbury, MA	Cast housings, cast alum. fabs. Large die sections after straightening		All shapes	Martin	X		Weld relief at areas adjacent to weld				C	VSR of large welded tanks appears to be quite effective. Effective when hardness is not problem
John Crowley, Inc. Jackson, MI	Machine bases, transfer beams	8	All shapes	Martin CCC Vibro-	X			1010F 1020F				Combined with good welding distortion is minimum.
Fab R Cat ion Warren, MI	Machine tool bases	1	Rectangular	Martin VSR-79C	X			1020F				
H & K, Inc. New Berlin, WI	Bottle filling machinery comps.	5	Cylindrical	Martin CCC-100	X	X	Less dis-coloration		X			
Iron Ore Co. of Canada Labrador City, Newfoundland	Grinding mills, crushers, ball mills, shovel boom, shovel sticks, crawler frames, industrial fans	2	Many different shapes	Martin CCC-100 & Martin VSR 79C	X	X	Low stress levels in large welding jobs	Fabs.& castings				Equipment lasts longer if VSR'd. Vibrators could last longer, but receive rugged use.

Name & Location	Type of Wkpcs.	Yrs. of Use	Configuration	Type of Equip Used	Problems Solved: Dim. Instab.	Problems Solved: Resists Machining	Problems Solved: Other or Specifically	Materials (C - Casting, F - Fabrication): Mild Stl. & Tool	Materials: Stainless	Materials: Iron	Materials: Alum.	Comments. Complaints Suggestions
Kearney & Trecker Corp Milwaukee, W.	Machine tool beds & up-rights, mostly stl fabs., some castings	1	Rectangular	Martin VRK-790	X		Good for certain pts. with certain physical conditions which do not lend themselves well to thermal	1018F Boiler Plt F		35-C 45-C	2024-C	Charts are clearer if vibrator is warm. (Note: recent mod. to pick up amp design seems to have reduced this problem.)
Landis Tool Co. Waynesboro, PA	Machine tool fab'd beds & other fab'd configurations. Cast iron beds & bases.	2	Square-rectangular & irregular	Martin VRK-790	X	X	Alleviated requirement for a large annealing furnace	1025 F		Cast		Procedure new to us, some difficulty with fixture design. Recent updates allowing more use
WD Corp. Plainville, CT	Large fabs. for sheet metal equip. Hyd. shears & press brakes	5	All types	Martin MX-780	X	X		1020 F				
Magnat Corp. Easthampton, MA	Industrial rolls, quarry equipment, misc. fabs.	13	Mostly cylindrical, some rectangular	Martin CE-575-2	X		Joining low & medium carbon steels	4140-4142	300 series			Eliminates most distortion while machining & helps maintain closer tolerances.
Makson Corp. St. Paul, MN	Heavy duty railroad frt. cars	14	Rectangular	Strs. Rlf. Eng F 62			Removal of stress due to welding	A 36 F, A 572, GR 50-F, A 633, GRC R				
McKenico, Inc. Buffalo, NY	Machine tool bases, transmission cases	3	Rectangular	Martin ---	X		Convenience. We don't have facilities for thermal stress relieving	1018 F				
New Britain Machine New Britain, CT	Machine bases, columns & oil pans, 99% fabs.	4	Rectangular or box	Martin MX 780 (Modified)			Weldments too large for our furnace can be stress relieved avoiding cost of new, larger furnace	1015 F 1020 F				We have exp'd some maintenance problems w/equipment, but process works very well

Name & Location	Type of Wkpcs.	Yrs. of Use	Configuration	Type of Equip. Used	Problems Solved: Dim. Instab.	Problems Solved: Resists Machining	Problems Solved: Other or Specifically	Materials (C - Casting, F - Fabrication): Mild Stl. & Tool	Stainless	Iron	Alum.	Comments
Northwest Marine Iron Works, Portland, OR	Fabrications both new & repairs pipe	-	All types	Martin CB-375-2 & Strs. Rlf. Eng. F-62	X	X	Relieve stress F points, used before & after straightening	F	F			
Producto Machine Bridgeport, CT	Machine tool bases, col- Umns, slides. Rotary table bases, & table tops over 500 lbs.	1	Many	Martin VSR-790			No facilities in house to treat large pts., no guarantee that outside vendor's stress relive pts. Also, increased insert life due to elimination of sandblast clean up.	1020 F		GR 35 Cast		Update instruction manual to cover: a) Greasing & bi eccentric adj. (Note: Done 3/82)
Rice Barton Corp. Worcester, MA	Paper mill machy., fabs., & rolls	14	Long rectangles & cylinders	Lodding (Martin) C 375	X	X	Stress relieving stainless steel fabs without applying elevated temperatures	1018 F	304-F 316L-F			We have learned to use effectively but could improve in future.
Rodney Hunt Co. Orange, MA	Industrial rolls for paper & plastic inds. slice & slide gates	2	Both cylindrical & rectangular	Martin VSR 790A	X	X		1018 F 1020 F 1040 F	304 F 316 F	Grey C	6061T6F 5083-0-F	
Roussell Corp. Chicago, IL	Welded punch press components. crowns, slides, beds & frames	3	Rectangular	Martin MX 780	X	X		1018 F				Pick up cables are too weak. (Design since changed)
		2	All shapes	Martin VSR 790A	X		Stress in fab'd pts.	A36F 1020F				Does not normalize hard spots as does thermal

Name & Location	Type of Wkpcs.	Yrs. of Use	Configuration	Type of Equip. Used	Problems Solved: Dim. Instab.	Problems Solved: Resists Machining	Problems Solved: Other or Specifically	Materials (C - Casting, F - Fabrication): Mild Stl. & Tool	Stainless	Iron	Alum.	Comments
Steward Machine Co. Birmingham, AL	Lock & dam operating machinery & pipe	4	Rectangles & flat plates	Martin	X		Straightening	A36F	Stainless clad			Needs imaginative Operator
United Centrifugal Pumps San Jose, CA	Pump shaft material	3	Round	Martin MX 780	X	X		4140	316			
Vanguard Supreme Mach.	Knitting mach. components	9 (Est.)	Cylindrical	Martin JCC-100R	X		Flatness			Cast		Not total solution to instability. But helps.

Bibliography

1) McGoldrick, R.T. and Saunders, H.E., "Some Experiments in Stress Relieving Castings and Welded Structures by Vibration, "Journal of the American Society of Naval Engineers, Vol. 55, 1943, No. 4 pp 589 - 609.

2) We also wish to cite and recommend for additional reading:

Dawson, R. and Moffat, D.G., "Vibrating Stress Relief: A Fundamental Study if Its Effectiveness, "Journal of Engineering Materials and Technology, Vol. 102, April 1980, pp 169 - 176.