Vibratory Residual Stress Relief and Modifications in Metals to Conserve Resources and Prevent Pollution

Final Report

by

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Project Review

Many manufacturing processes use large amounts of energy in order to make useful products. One such process is the thermal stress relief (TSR) process that is widely used to reduce/modify the internal or residual stresses in parts that are introduced by other manufacturing procedures such as fabrication, machining, or assembly. The TSR process is typically done in large furnaces and is heated by the combustion of fossil fuels. The large consumption of energy, the thermal influence, and air pollution affects on the environment are the biggest concerns of this process. As an alternative to the TSR, Vibratory Stress Relief (VSR) has the advantages of low energy consumption and dramatic reduction of pollution to the environment.

The residual stresses in parts will cause them to distort either during the manufacturing process and/or later during the useful life of the part. The widely used traditional process of thermal stress relief involves raising the temperature of the part under carefully controlled conditions several hundred degrees, holding at the high temperature until the bulk of the stresses have been removed, and then slowly cooling the part in order to prevent introducing new residual stresses. For some parts, this may have to be done several times during the manufacturing process. Thermal heat treatment of stress relief always results in some loss of strength in the part, some distortion during the process, and oxidation of the surface of the part. Vibratory stress modification is an alternative method for altering and/or reducing residual stresses in parts so that they do not distort during subsequent manufacturing processes and during the life of the part. Vibratory stress relief is accomplished by vibrating the part at a particular frequency and amplitude for a short period of time thereby using a minute amount of energy and generating minute amount of pollution compared to the traditional heat treatment process.

To implement an alternative process, a thorough understanding of how it works and why it works must be developed. Without this understanding, it is difficult for engineers and manufacturing managers to determine when, where, and how the vibratory stress relief process can be effectively applied. The objective of this research is to develop an analytical model using Finite Element techniques to show how vibration alters the residual stress in a part in a beneficial way. The results of the analytical modeling demonstrated the reduction in residual stress in a particular part due to vibration.

Mr. Paul Chilcott, Dr. Donald L. Roth, members of Ms. Lin Kuang's thesis advisory committee, Ms. Lin Kuang and Ms. Lingyu Dong, who continues to do experimental work in this area, have contributed to this research effort. Without their hard work, this project could not have been completed.

Analytical Modeling of VSR

A cantilever beam model was developed in ANSYS, commercial finite element analysis software, for VSR analysis. Figure 1 shows the geometry of the designed model.

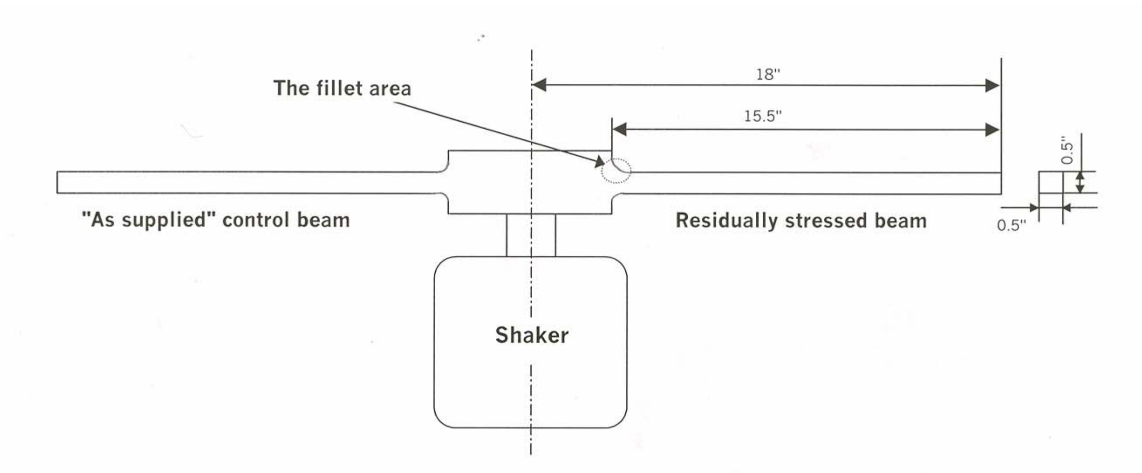

Figure 1. Designed real model

Due to the symmetry design of the cantilever beam specimen, only the half of the beam requires modeling with ANSYS. A two-dimensional model was considered because the stress introduced across the thickness of the beam was assumed uniform. To model plastic deformation, elastic-plastic material was employed in the ANSYS model database.

Aluminum 6061-T6 was selected as the material for the model. The material properties are shown in Table 1 and the stress- strain curve of the material is shown in Figure 2.

Table 1. Material properties of Aluminum 6061-T6

Yield Stress (psi)	Modulus of Elasticity E (Mpsi)	Poisson's Ratio	Density (lb/in^3)	Damping Ratio
38800	9.7	0.33	0.1	0.003

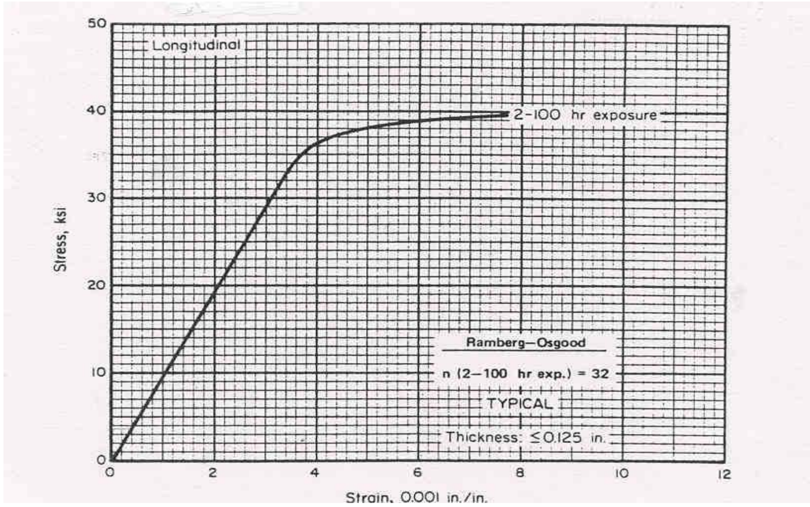

Figure 2. Tensile stress-strain curve of Aluminum alloy 6061-T6

For finite element analysis, the model was meshed with linear, four-node, quadrilateral elements. The mesh in the fillet areas is shown in Figure 3.

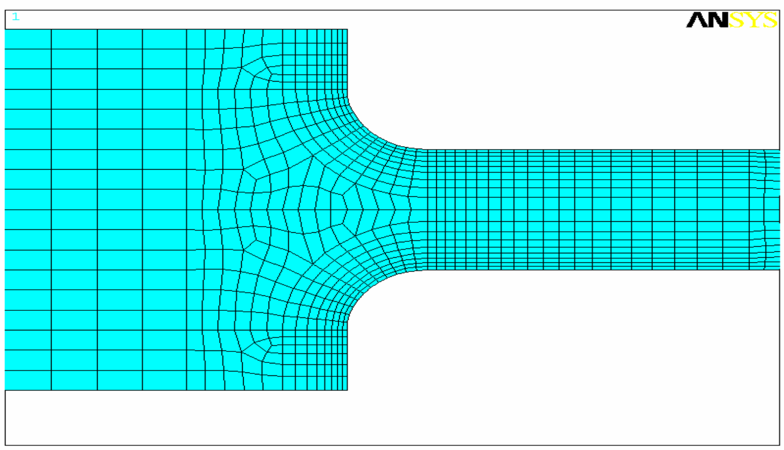

Figure 3. ANSYS finite element mesh in the fillet areas.

To simulate the vibratory stress relief, residual stress was first introduced into the model by applying and releasing an external force on the tip of the beam. Static non-linear analysis was conducted to introduce the residual stress and calculate the resulting internal stress distribution. The relationship between the external load and tip deflection shown in Table 2 was also obtained as information for later determining the vibration amplitude.

Table 2. Relationship between tip deflection and maximum stress before and after load P

	When P is applied		After P is removed		
	Max stresses in X-dir at the top fillet (psi)	Tip deflection in Y-direction (in)	Max residual stresses in X-dir at the top fillet (psi)	Tip deflection in Y-direction (in)	$\frac{\text{residual stresses}}{\text{yield stress}}$ x 100%
P = 52 lb	37878	-1.291	-7085	-0.003327	18.26%
P = 66 lb	39717	-1.695	-17400	-0.69068	44.85%

The controlling parameters for the vibratory stress relief considered were existing residual stress level, driven frequency, and excitation amplitude. These parameters were obtained from static nonlinear, modal, and harmonic analyses.

Table 3 shows the selected excitation displacement magnitudes that would lead to relief of residual stress based on the mechanical theory that the peak residual stress will decrease when the summation of external cyclic and residual stresses exceed the elastic limit of the material.

Table 3. Selected excitation displacement magnitudes and corresponding tip deflections at the first natural frequency

Excitation displacement amplitude (in)	Tip deflection at the first natural frequency (in)	Tip deflection to cause beam yielding (in)
0.004	1.044	1.291
0.006	1.566	1.291

Results and Discussions

To investigate the frequency range that vibration works to relieve residual stress in parts and the driven frequencies that maximize the relief of residual stress in parts, the following 4 cases shown in Table 4 were run to compare the effect of resonance frequency and sub-resonance frequency on VSR. The frequencies investigated are illustrated in Table 5. Table 6 shows the results of residual stress reduction.

Table 4. Analysis conditions with various driven frequencies

	Applied load P (lb)	Residual stresses before VSR in the beam (psi)*	Driven frequency f_n (Hz)	Excitation displacement Amplitude (in)
Case 1	-52	-6877	64.486	0.004
Case 2	-52	-6877	64.195	0.004
Case 3	-52	-6877	63.922	0.004
Case 4	-52	-6877	61.2617	0.004

Table 5. Driven frequencies selected for investigation

	Frequency (Hz)	Description
f_1	64.486	First natual frequency of cantilever beam
f_2	64.195	Frequncy prodcuing 55% of tip deflection of resonant peak
f_3	63.922	Frequncy prodcuing 1/3 of tip deflection of resonant peak
f_4	61.2617	Frequency that equals to 95% of first natual frequency

Table 6. Reduction of residual stress by VSR treatment with various driven frequencies

	Driven frequency f_n (Hz)	$\frac{\text{Tip amplitude by driven freq.}}{\text{resonant peak}} \times 100\%$	Residual stresses before VSR in the beam (psi)	Residual stresses after VSR in the beam (psi)	Reduction of residual stresses
Case 1	64.486	100%	-6877	-176	97.4%
Case 2	64.195	55%	-6877	-5054	26.5%
Case 3	63.922	33.3%	-6877	-6877	0%
Case 4	61.2617	5.9%	-6877	-6877	0%

The results show that the frequency producing the greatest stress relief occurs at the resonant peak (natural frequency). The reduction of residual stress after resonant vibratory treatment can attain 97%. Sub-resonant VSR treatments get less or no residual stress relief, depending on the frequency level applied.

Another variable investigated for VSR was the excitation amplitude. Case 5 was conducted and compared with case 2 to see the effect of excitation displacement amplitude on VSR. Table 7 shows the testing condition of case 2 and case 5. Table 8 shows the results comparison. The results show that larger excitation amplitude will produce greater stress relief.

Table 7. Analysis condition with various excitation amplitudes

	Applied load P (lb)	Residual stresses before VSR in the beam (psi)	Driven frequency (Hz)	Excitation displacement Amplitude (in)
Case 2	-52	-6877	64.195	0.004
Case 5	-52	-6877	64.195	0.006

Table 8. Reduction of residual stress by VSR treatment with various excitation amplitudes

	Excitation displacement Amplitude (in)	Residual stresses before VSR in the beam (psi)	Residual stresses after VSR in the beam (psi)	Reduction of residual stresses
Case 2	0.004	-6877	-5054	26.5%
Case 5	0.006	-6877	-214.18	96.9%

Initial residual stress level in parts was also investigated to see its effect on VSR. Two cases were compared with different initial residual stress in the sample. The analysis condition of these two cases is shown in Table 9. Table 10 shows the comparison results.

Table 9. Analysis condition with various initial residual stresses in parts

	Applied load P (lb)	Residual stresses before VSR in the beam (psi)	Driven frequency (Hz)	Excitation displacement Amplitude (in)
Case 1	-52	-6877	64.486	0.004
Case 6	-66	-17141	64.486	0.004

Table 10. Reduction of residual stress by VSR treatment with various initial residual stresses in parts

	Applied load P (lb)	Residual stresses before VSR in the beam (psi)	Residual stresses after VSR in the beam (psi)	Reduction of residual stresses
Case 1	-52	-6877	-176	97.4%
Case 6	-66	-17141	-1876	89.1%

The comparison results show that the part that has less initial residual stress level will get greater stress relief under the same excitation frequency and displacement amplitude.

From the above analyses, the following conclusion can be drawn:

1. Finite element modeling approach can be used to predict the vibratory treatment on residual stress relief.
2. Both resonant and sub-resonant vibrations can relieve residual stresses in parts. Resonant VSR produces the greatest residual stress relief. Sub-resonant VSR can get stress relief, whose effect depends on the driven frequency employed. The larger tip deflection the driven frequency produces, the greater reduction of residual stresses.
3. Larger excitation amplitude produces greater residual stress relief.
4. Stress reduction is greater for parts with lower level of initial residual stresses

Evaluation of VSR

The VSR analysis was done with commercial finite element analysis software, ANSYS; it is a reliable tool to use for analytical modeling. The data that were input in the analysis were all standard engineering data, which included the published ANSI standard material properties. Scripts of various ANSYS analyses were enclosed at the end of the thesis document for reference.

The research work enhanced our understanding of the conditions under which VSR can produce significant reduction of residual stresses in parts. With this understanding, engineers can get expected stress reduction with appropriate environmental friendly VSR treatment, hence reducing the use of environmentally hazardous heat treatment methods.

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