Energy efficient material normalisation with vibratrory stress relief

An efficient way to reduce residual stress for optimal machining

INTRODUCTION

In the following it is investigated how the manufacturing industry can apply an alternative to heat treatment to control residual stress in metals, as this affect the productivity and the energy consumption in the metal industry. It is suggested to use vibrations to release the residual stress as this may be faster and more energy efficient than thermal methods. The technique, Vibratory Stress Relief (VSR), is tested on 13 different types of components to measure the energy consumption for comparison with traditional Thermal Stress Relief (TSR). By replacing TSR with VSR, energy savings in the range from 72 % to 100 % are obtained in the test cases. The material parameters of selected components are analysed to compare the result of both thermal and vibratory stress relief.

PROBLEM: UNCONTROLLED RESIDUAL STRESS REDUCES RELIABILITY AND INCREASES COST

Residual stresses are important as they influence fatigue and fracture strength, corrosion resistance and the dimensional stability of parts (Totten 2002). With uncontrolled residual stresses, the service life may be reduced or parts scrapped during machining due to excessive distortions. All are factors that increase cost and limit the product reliability. The scope of this whitepaper is to present methods for residual stress relief, compare the energy consumption of these methods and to answer the question:

How can residual stresses be controlled effectively in an environmental friendly way?

The answer is sought trough the following, starting with an introduction to residual stresses.

An introduction to residual stresses

Residual stress is the state of compression, tension and shear that exist inside materials when they are without external loadings and have uniform temperature. This is an inevitable result of the processes any metal undergoes through its production. Processes like casting, forging, heat treatment and rolling, all lead to residual stress.

Materials with residual stress are said to be in equilibrium, as all material in tension is balanced by areas in compression. During machining, some material is removed and the balance between the material in tension and compression changes. This distorts the component as the stresses they find a new state of equilibrium. This is problematic when high dimensionally accuracy is required of the finished products.

Traditionally this is overcome by use of annealing heat treatment also known as Thermal Stress Relief (TSR), or by additional roughing processes which are time consuming. TSR involves heating the components to high temperatures over several hours, and cannot be applied on all alloys. Examples of problematic alloys are austenitic stainless steel which loses its corrosion resistance if heat treated, and there are age hardened (precipitation hardened) alloys that lose their strength characteristics if heat treated. For these materials VSR is an effective solution (Mordfin, for Testing, and on Mechanical Testing 1988). The TSR process is energy demanding and time consuming. Further, the process is limited by the furnace size, which means large components typically cannot be heat treated. Small components can be treated relatively effectively by lumping them together in batches. This increases energy efficiency but also increases lead time.

SOLUTION: REDUCE RESIDUAL STRESS

In the following two methods for relieving residual stress are presented, starting with the traditional heat treatment.

Thermal stress relief - Annealing

The traditional method to overcome this challenge is to use an annealing heat treatment specially designed to release the residual stress. TSR is a well-known technology that has been applied in industry for decades. It is proven to work well for common steels and cast-irons (Brooks, n.d.; Davis and Committee 1996). TSR is performed by raising the temperature to approximately $T_a = \frac{T_m}{2}$, where T_m [K] is the absolute melting temperature of the material. At the T_a temperature the macroscopic stresses are completely released, however some microscopic stress may remain as result of dislocations and varying thermal expansion rates of the different phases of the microstructure. The time needed at T_a is influenced by the component size (Totten 2002). Typically, steel and cast-iron components are held at 620 °C for 3 hours followed by a controlled cooling over several hours.

The heat treatment is performed in furnaces of different types, mainly gas fired (80 %) or electrically heated (10 %) (Lawrence Berkeley National Laboratory 2007). Electrical furnaces are expected to have a high efficiency as the only energy loss occur as heat conduction through the side of the furnace. This can be limited with proper use of insulation materials. Gas fired furnaces rely on combustion which results in exhaust gases that must leave the furnace, or heater. The hot exhaust gasses result in an substantial energy loss from the furnace. The thermal efficiency, η, that is the fraction of the supplied energy that goes into the workpiece, of this type of furnace is reported to be 30 % (Schifo and Radia 2004). The energy efficiency can be improved to 39 % if the exhaust gas is used to preheat the air intake (Schifo and Radia 2004). These numbers for efficiency does only concern heating of the workpieces, and does not consider the heat loss during the holding time, hence the efficiency for a complete heat treatment is expected to be lower. Through this report energy consumption per part for TSR, Q_{TSR} [MJ], is estimated from the parts mass, m [kg], and heat capacity, C [J / (kg K)]. Assuming a temperature increase, ΔT [K], of 600 °C. The calculations are done for gas fired furnaces, as these are most common. To provide conservative results the better reported efficiency η of 39 % is used. Thus, the energy requirement for each component is calculated as:

$$Q_{TSR} = \frac{\Delta T \; m \; C}{\eta}$$

An alternative method for stress release is presented in the following, which holds the potential to omit some of the challenges of TSR and reduce the energy consumption considerably.

Vibratory Stress Relief (VSR)

The use of vibrations for reliving stresses has been applied with varying success. The technology and its underlaying process are not completely understood. However, the technology has been demonstrated to work well in different cases, for example for securing the dimensional stability of Maglev rails (Walker 2011), and for several larger structures of welded steel, (Mordfin, for Testing, and on Mechanical Testing 1988). Research indicates that dimensional stability of such components can be achieved, even without complete stress release (Mordfin, for Testing, and on Mechanical Testing 1988). This means that the need for partial or complete stress release is influenced by tolerances and how much material is removed with machining.

Throughout this project the VSR treatments are performed according to instructions provided by the equipment supplier VSR Systems and Service, USA. In general, these correspond to the practice provided by (Mordfin, for Testing, and on Mechanical Testing 1988). We use a BL8 vibrator, consisting of a vibrator with a 2 kW electric servo motor, a control unit, and an accelerometer. For medium (40 – 500 kg) and small (0 – 40 kg) parts, a fixture is required. The set-up is shown in Figure 1. Vibratory stress relief is performed by exciting a resonance frequency of the work piece for a short period, usually about 20-40 minutes. Large (over 500 kg) parts are placed on blocks made from soft polyurethane that isolate the vibrating part from the surroundings. Smaller parts are placed in a fixture which then is placed on polyurethane (PUR) blocks, see Figure 1 and 2. The vibration is powered by an electric motor which drives an eccentric shaft.

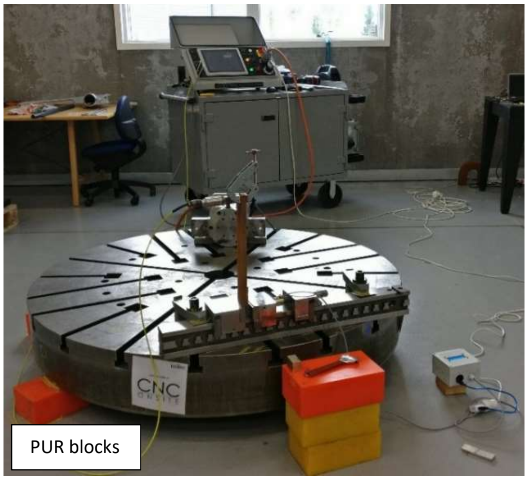


Figure 1 Set-up used for VSR treatment of medium and small parts which require a fixture on a plane supported by 3 polyurethane (PUR) blocks.

The rotation of the unbalanced shaft exerts a cyclic force that makes the work piece vibrate. The motor speed is adjusted until the acceleration of the workpiece peaks, this motor speed corresponds to the resonance frequency of the part. During the VSR treatment the power consumption is measured using a *Smart-me Plug*, which measures the power with a 1 % accuracy (Class 1).

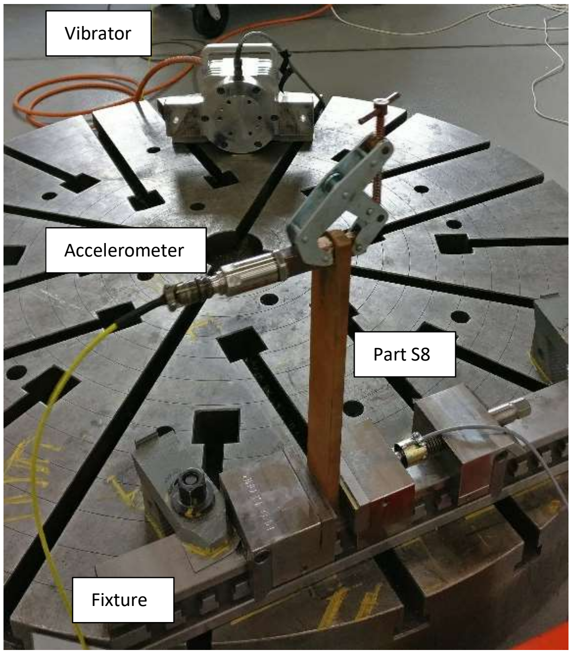
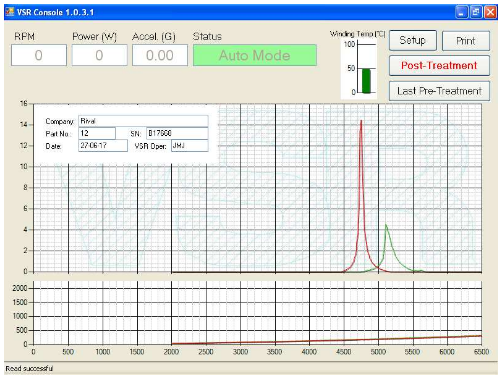


Figure 2 Part 8 mounted in vice with accelerometer on top. The vice is equipped with a load cell for ensuring constant clamping force.

The power consumption is in general low, even for large parts. As an example, a wind turbine tower section of 126 ton, was vibrated using less than 500 W, see Figure 3. This is possible as the treatment is done at the resonance frequency where the vibrator input is amplified by the structure.

Figure 3 Test of vibrations on part 2, a 126 ton tower section for a wind turbine.

Before the actual treatment, the acceleration response of the part is recorded. This is done by steady acceleration of the vibrator, scanning the frequencies from 33 to 133 Hz, while plotting the obtained acceleration as a green line, see Figure 4. The scanning procedure is repeated after the treatment, plotting a red line as shown in Figure 4. The change in frequency response indicates a change to the treated material.



RPM: 0
Power (W): 0
Accel. (G): 0.00
Status: Auto Mode
Company: Rival
Part No.: 12
SN: B17668
Date: 27-06-17
VSR Oper: JMJ
Read successful

Figure 4 Screenshot from VSR equipment. The upper graph shows the frequency response of the M5 part in g [9.8 m/s²]. The treatment changes the response of the part. The green curve represents before treatment situation and red one after VSR treatment. The lower grahp shows the power consumption [W].

COMPARING TSR AND VSR

For small work pieces, the TSR is cost effective as multiple parts can be treated together. The process does however, require large investments in furnaces and typically transportation to the furnaces, costs that increase with the size of the components.

VSR is different, as it can be done on-site and represents a modest investment in equipment. Time and cost for transportation is omitted, as the parts can be larger than 100 ton and treated directly in the production line. The main cost of VSR is the required labour. The current VSR technology treats one work piece at a time, which makes it relatively ineffective and expensive for small parts. However, as parts increase in size the cost changes in favour for the VSR process, as indicated in Figure 5, the point of breakeven is about 110 kg.

In this project, 13 different types of workpieces were treated with the VSR technology. Repetitions were performed and in total 77 parts were treated. These workpieces were chosen as they represent a broad range of the products made in the Danish manufacturing industry. The workpieces vary greatly in size, material and shape and include both parts that are TSR treated and parts that are used untreated – sometimes with great problems during milling processes.

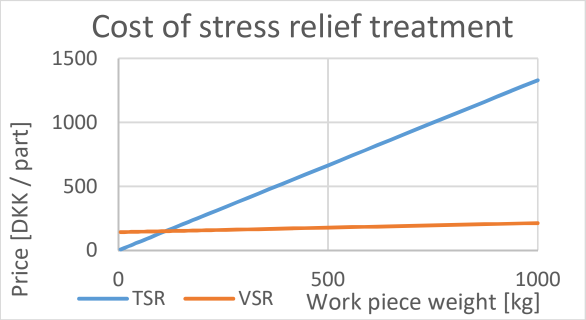


Figure 5 Cost of stress relieving treatments changes as function of weight. VSR becomes increasingly competitive as weight goes up.

The included parts can all benefit from a reduction of residual stress, as this may improve their dimensional stability. Due to the limitations on heat treatable materials and furnaces sizes, not all the chosen parts are TSR treated, they are however, included to identify the potential of VSR treatments.

Results of performed VSR treatments

The performed treatments vary from short vibration tests, to actual serial production. Table 1 lists the treated workpieces and the potential for saving energy if a TSR process is replaced by a VSR treatment. For large parts, the energy savings approaches 100 %, as energy requirements for TSR go up with parts sizes, while the energy consumption of the VSR process is only weakly related to the weight of the treated workpiece. For smaller work pieces, the energy savings are reduced, but all cases show more than 72 % savings. VSR treatment of the medium sized part, M5, requires 0,39 kW/h corresponding to 2 % of the energy required for a similar TSR treatment. 47 parts of the M5 were treated, see Table1. The parts weigh 45 kg and are cast from GJS-600-3 spherical cast iron. For reference, untreated parts were machined, which distorted to an unacceptable parallelism of 0,3 - 0,4 mm. With the use of VSR same parallelism changed to 0,03 - 0,07mm, while the machining time could be reduced from 12 hours per part to 5 hours, as finishing cuts were avoided.

The part L3, an 18 ton generator platform, was treated with VSR in Latvia. For this part, the customer required stress relief, either VSR or TSR. Nearest adequate TSR facility is placed in Finland, thus treatment and transport would represent a substantial expense. To remedy this, the part was VSR treated on-site. It is estimated that the choice of VSR over TSR represents an energy saving of 32 GJ. This corresponds to avoiding burning natural gas that would have emitted 1.8 ton of CO_2 (emission factor 56 kg/GJ, (Vreuls 2005)).

GENERAL UNCERTAINTIES IN RELATION TO VSR TREATMENT

The commercial VSR equipment available provides for successful and repeatable VSR treatments, as has been demonstrated on the M5 part in this project. The technology does however, have shortcomings as not all treatments were successful. The main challenge is to identify how to apply VSR, which is difficult as the effect is only evident after the treatment. Further, general recommendations for applied strain level or vibration level for various materials exist. The commercial equipment does only consider the possible change in the used set-ups frequency response. This is, an indirect measure of the stress relaxation and may be disturbed by any change of boundary conditions.

Through this project, emphasis has been put on ensuring constant boundary conditions and improved process monitoring. To ensure this, the clamping force of the used fixture has been logged during the treatments. Further experiments with strain gauge monitoring of the workpiece during vibration has been conducted. During treatment of M3-1, the strains were monitored along with clamping force.

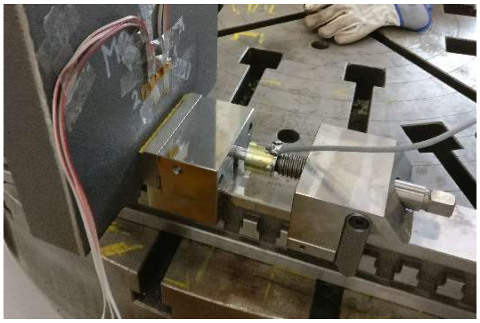


Figure 6 M3-1 clamped in vice, which is monitored with load cell. Workpiece is equipped with strain gauges.

The treatment of the M3 parts showed no reduction in residual stress, during and after treatment. Similar results were found for part S1. Both parts have compressive stress near the yield stress of the material.

Material properties and VSR

The effect of VSR on the microstructure, has been analysed in this project for the small part, S8 in Table 1. The microstructure of the cast iron was examined with a scanning electron microscope as cast, and compared to TSR and VSR treated samples.

Figure 7 shows the microstructure after VSR treatment, which consists of ferrite, perlite and nodes of graphite. In the figure, two bands of different ferrite pearlite distribution are visible. This was observed in two VSR samples and not in the as cast and TSR samples, which showed a more random distribution.

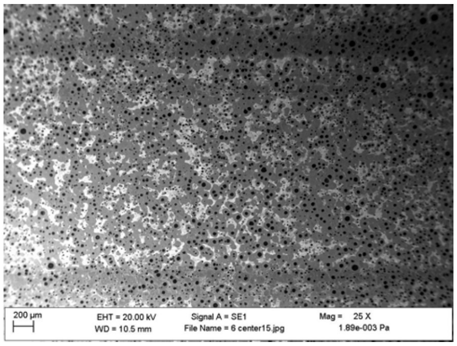


Figure 7 VSR treated S8-6, with bands of pearlite (grey) / ferrite (white). The two bands are about 2,5 mm apart. Black nodes are graphite.

Category	Part ID	Number of parts	Company	Part	kWh/part	Weight [kg]	Materials	Heat capacity [MJ]	Potential energy saving	Saved CO2 emission [kg]
Large	L1	1	GLOBAL CASTINGS	V112 MK2 hub	0.7	16141	EN-GJS-400-18U-LT	12362	100%	1775
	L2	1	WELCON	Wind turbine tower section	0.7	126000	S355	87321	100%	12538
	L3	1	EAST METAL	Generator platform	0.7	18000	Structural steel	12474	100%	1791.2
Medium	M1	6	RUNI	Bearing house	0.4	126	S355	87	100%	13
	M2	1	RUNI	Screw conveyor	0.52	100	S355, Hardox 400, 34CrNiMo6	69	99%	10
	M3	2	FERRODAN	Plane	0.35	84	GJL 250 EN-1561	67	100%	10
	M5	47	RIVAL	Gearbox cover	0.39	45	EN-GJS-600-3	36	98%	5.1
Small	S1	2	FERRODAN	Sheave	0.35	27	GJL 200 EN-1561	21	100%	3
	S2	8	GPV	Alu plates	0.28	6.8	7075 T7351 AMS-QQ-A-250/12		-	
	S3	3	RUNI	Testpart steel 52	0.36	9	S355, 34CrNiMo6	6	92%	1
	S4	3	RUNI	Testpart hardox	0.36	9	Hardox 400, 34CrNiMo6		-	
	S5	1	JAI	Thin-walled alu casting	0.25	4.4	EN AC 43000, F		-	
	S8	2	FERRODAN	flat cast bar	0.25	1.6	EN-GJS 500-7	1	72%	0.2

Material	**Heat capacity**	
GJL-200, 20 - 600 °C	535	J/ kg K
Steel, S355	466	J/ kg K
GJS-400, GJS-500	515	J/ kg K

Table 1 Overview of VSR treated workpieces from various industries. The list starts with large and ends with small parts. * indicates estimated values

The hardness of the treated parts was tested and found to be slightly reduced by TSR and unchanged by VSR. Table 2 shows the average results for microhardness in centre and near the surface.

	Centre [HB]	Surface [HB]
As cast	141	142
TSR	138	137
VSR	141	142

Table 2 Result of microhardness test on part S8.

The residual stresses in the S8 parts are highly compressive near the surface, as shown in Figure 8. These stresses are induced as result of the casting and the subsequent shot peening used to clean the surface. The average principal stresses were measured using the hole drilling method (ASTM E387-13 uniform stress) on the different samples.

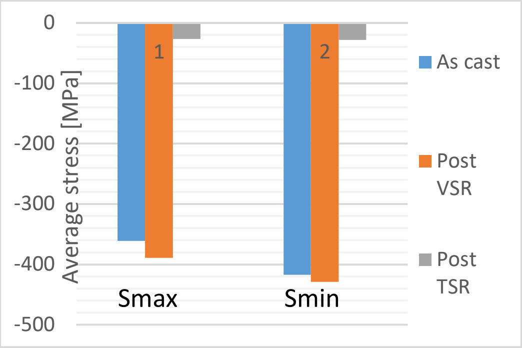


Figure 8 Average of stress measurements using the hole drilling method on part S8. Stress according to ASTM E837-13 uniform stress.

Based on the hardness and stress measurements it is concluded that the VSR treatment was ineffective. This may be caused by the small component size (1.6 kg). Further experiments are needed to identify a suitable treatment for the S8 part.

APPLYING VSR TO REDUCE PRODUCTION COST AND ENERGY CONSUMPTION

VSR can be applied to reduce production time and cost, this can be achieved in some cases by eliminating heat treatment and/or reducing the necessary number of roughing operations during machining. The typical cycle time for VSR treating workpieces is around 50 minutes, but this may be reduced for larger series. The equipment used during the VSR process is transportable and can be applied in the existing production facilities. This eliminates the time used on transportation to heat treating facilities. This allows smaller manufactures to insource their material normalisation. It also increases the flexibility in the production and may create additional jobs. During the project, a series of cast components (M5) were treated, which resulted in improved dimensional accuracy. As result the company Rival has decided to invest in VSR technology and use it in their production.

CONCLUSION

13 various types of parts are treated with VSR, while monitoring the energy consumption. VSR provide energy efficient improvement for some parts, whereas others show no sign of stress release. The treated parts vary in weight from 1.6 kg to 126 ton. Depending on the specific treatment, 0.25 to 0.7 kWh is consumed per part. Compared to the energy requirements for TSR, this represents a reduction from 72 % for small parts, increasing with workpiece weight to approach 100 % of relative energy saving. The L3 part weighing 18 ton is VSR treated, which substituted a TSR treatment and thereby avoided 1.8 ton of CO_2 emission. Furthermore, 47 parts of type M5 are treated, which reduce the deflection of the parts after machining. This reduce machining time from 12 to 5 hours per part.

At the current state, successful application of VSR can be obtained in some cases. Overall, the result shows a great potential for cost and energy savings with the VSR method.

FUTURE WORK

It would be beneficial improving the predictability of the VSR process and understating of the effect VSR has on the microstructure. This would, in turn, improve how VSR is applied and help achieving effective treatments. Further research in high frequency, ultra-sonic VSR, might improve the effectiveness on smaller parts that has high eigenfrequencies.

ABOUT DAMRC

DAMRC, short for Danish Advanced Manufacturing Research Center, is a non-profit member driven organisation that aims at accelerating the adoption of new technology in the manufacturing industry.

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REFERENCES

Brooks, C R. n.d. *Principles of the Heat Treatment of Plain Carbon and Low Alloy Steels*. ASM International. https://books.google.dk/books?id=fVIlbCFTodgC.

Davis, J R, and A.S.M.I.H. Committee. 1996. *ASM Specialty Handbook: Cast Irons*. ASM Specialty Handbook. ASM International. https://books.google.dk/books?id=NbgtnLo7jhwC.

Lawrence Berkeley National Laboratory. 2007. "Improving Process Heating System Performance : A Sourcebook for Industry." doi:10.1049/tpe.1976.0157.

Mordfin, L, American Society for Testing, and Materials. Committee E-28 on Mechanical Testing. 1988. *Mechanical Relaxation of Residual Stresses*. ASTM STP 993. ASTM. https://books.google.dk/books?id=huJ8sum4VsUC.

Schifo, Jf, and Jt Radia. 2004. "Theoretical/Best Practice Energy Use In Metalcasting Operations." *US Department of Energy, Energy Efficiency and Renewable Energy*, 116. http://www.eere.energy.gov/manufacturing/industries_technologies/metalcasting/pdfs/doebestpractice_052804.pdf.

Totten, G E. 2002. *Handbook of Residual Stress and Deformation of Steel*. ASM International. https://books.google.dk/books?id=_a9UEHk4cOwC.

Vreuls, H.H.J. 2005. "The Netherlands: List of Fuels and Standard CO2 Emission Factors," no. December 2004.

Walker, C. 2011. "A Theoretical Review of the Operation of Vibratory Stress Relief with Particular Reference to the Stabilization of Large-Scale Fabrications." *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials Design and Applications* 225 (3): 195–204. doi:10.1177/0954420711402877.