REDUCING RESIDUAL STRESSES USING CRYOGENIC THERMAL TREATMENT

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ABSTRACT

This work deals with the reduction of residual stresses using cryogenic thermal treatment as an alternative to normal thermal treatment .The work was performed on a solid z-shaped model component. The models were fabricated from two different types of materials (alloy steel & aluminum). If any residual stresses exist in a manufactured component, then these residual stresses will have an effect on the natural frequency of that component. A new type of measurement method was used to measure the level of residual stresses present. The natural frequency of the models at a stress free state was used as a reference. This method was also used to find the extent of the residual stress relief and percentage of reduction. Residual stresses were induced by flame heating with different boundary conditions and at different rates of cooling. They were stress relieved by the use of liquid nitrogen (-198^{0}C) and at different various treatment times. This was done to find the effect of time on the treatment. Reduction in residual stress level reached 92.38%. This reduction was compared with a normal thermal stress relief. Also a comparison was made between the two types of material that were stress relieved. It was found that over treatment tends to re-stress the models.

الخلاصة

يخص هذا العمل الاجهادات الداخلية و ازالتها باستخدام التبريد المفرط. تم العمل على نماذج شكل حرف (z) مصنوعة من الألمنيوم و الفولأذ. تم قياس الاجهادات الداخلية باستخدام مقدار التغير في التردد الطبيعي استخدم التردد الطبيعي للحالة الخالية من اجهادات الداخلية كمعيار لمقدار الاجهادات الداخلية كما استخدمت الطريقة نفسها لمعرفة مقدار نسبة ازالة هذه الاجهادات تم توليد الاجهادات الداخلية في النماذج باستخدام الشعلة مع تغير المحددات وسرع تبريد مختلفة . تم ازالة هذه الاجهادات باستخدام سائل النايتروجين (-198^{0}C) حيث كانت تغمر في سائل النايتروجين في فترات زمنية مختلفة لمعرفة تاثير الزمن على نسبة ازالة الاجهادات فتم ازالة نسبة الاجهادات الداخلية 92.38% تم مقارنة هذه النسبة مع الطرق التقليدية كما تم المقارنة بين النوعين من المواد المستخدمة في النماذج وجد ان افراط في فترة المكوث في سائل النايتروجين يؤدي الى اعادة تولد الاجهدات الدخلية في النماذج.

KEY WORDS

Cryogenic Treatment, Thermal treatment, Residual Stresses, Internal Stresses

INTRODUCTION

In the last years of the past century, a new exploration into a new method for residual stress relieving has been explored.

Cryogenic International [Dr.H.E.Trucks] use cryogenic treatment for the treatment of castings. They are treated in a chamber at a temperature of -300 F (–185 ^{0}C) at a controlled time /temperature cycle. They claim that all internal stresses are relieved due to the re-alignment of the molecular structure. They use this process for treating die casting dies and the cutting tools used to produce these dies.

Controlled thermal processing INC.&APPLIED cryogenics inc. Use cryogenics treatment on the gears of racing cars. Before treatment, after each race, metal shavings were found in the grease. After treatment when the gearbox is opened, the grease does not contain metal shavings. They claim that is because after treatment the wear resistance increased.

[Paul Bos 1998] uses cryogenic stress relieving in manufacturing custom made knives .He claims that taking a mass to extremely low temperatures creates a very dense molecular state. Technically absolute zero -457 F (-272 ^{0}C) is the temperature at which there is zero motion for the molecular state of mass. If the rate of temperature is slow enough. Thermal compression and expansion take place equally from the core to the surface, releasing internal stresses. The result is a homogeneously stabilized material.

Metalurgical Testing & Consulting Engingeers have been conducting research and applying cryogenic treatment for the removal of residual stress in metals and alloys. They treat gearboxes for racing cars and found that there is an increase in output capacity of 200% without pitting or wear of the teeth. After treatment, they are allowed to operate for 5 hours at a temperature of 190 degrees without evidence of metal flow, or cracking.

[Fanju Meng et al 1999] declare that cold treatment is an indispensable part of heat treatment of alloy tool steels, offered significant increases in the wear resistance. It is widely accepted that a major factor contributing towards its success is the removal of retained austenite. Conventional cold treatment has been carried out at higher than 173 K. This temperature is believed to be sufficient to fully transform any retained austenite to martensite in the quenched microstructure. However more recent evidence has shown that wear resistance is further enhanced by cryogenic treatment at ultra-low temperature, such as liquid nitrogen temperature. Despite numerous practical successes of cryogenic treatment and research projects undertaken worldwide, no conclusive metallurgical understanding of this treatment has been established.

In 2002 [Shakir K. Al-Samarrai et al] used sub zero temperature for relieving residual stresses that were induced in mild steel strips and aluminum plate. The strips were then inserted in a closed environmentally controlled enclosure of –30 ^{0}C for 168 hrs. After this period had elapsed they were removed and tested for any remaining residual stresses. It was found that the reduction in residual stresses reached 94.7% Prolonged exposure to this temperature for the aluminum plate caused stress relief and then moving on to restressing the aluminum plate.

In 1975 J.E.M. JUBB et al examined the vibration characteristics of welded plate. They guillotined plates and stress relieved them by heating at 550° c and then the 1st order of natural frequency was recorded. They induced residual stresses by ox-acetylene and Tig. welding at different traversing speeds. Tests were carried out to see whether residual welding stresses do have a significant effect on the vibration characteristics within the clamped boundaries.

They showed that natural frequencies could be increased or decreased by the introduction of appropriate patterns of residual stresses caused by local heating. And that the boundary conditions of the plate element are a critical factor in determining the effect of the introduction of residual stresses.

In this work, the change in the natural frequency will be the indication of residual stress measurement. In addition to this the natural frequency that is obtained from its annealed state will act as a reference for the amount of residual stress relieving.

The Models

The models that we used in the set of experiments of the Cryogenic treatment had the same dimensions as shown in **Fig. (1)** Two types were manufactured the first from alloy steel which was manufactured by milling. Whilst the second was made from aluminum and was manufactured by sand casting.

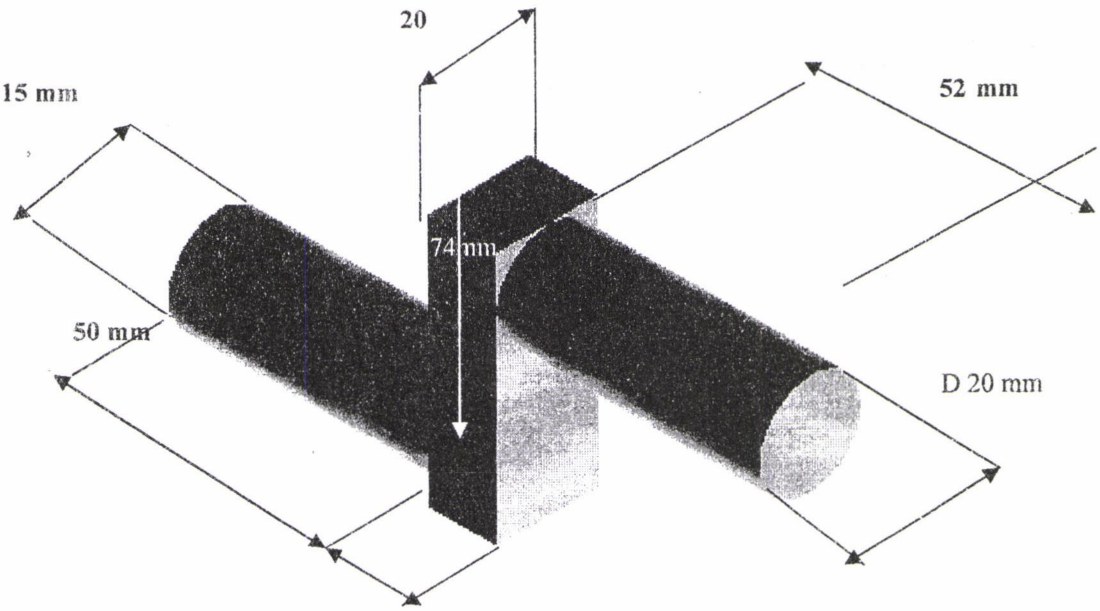

Fig. (1) The Model Together With Its Dimensions

Measurement Of Natural Frequency

Measurements of natural frequency for all models were performed before performing each process; this was done in order to find the effect of the process on the natural frequency.

Generally if the material contains any residual stresses due to the operations that were performed on it, it will display a shift in its natural frequency when it is compared with its free of residual stress state condition. When Cryogenic treatment is performed on it the initial harmonic curve will shift to a more stable position. The measurement of the natural frequency was performed with the aid of the following devices:

1- Electromagnetic shaker type B & K 4810
2- Sine Generator type B&K 1023
3- Accelerometer type B&K 4344
4- Pre-Amplifier type B&k 2626
5- Oscilloscope.

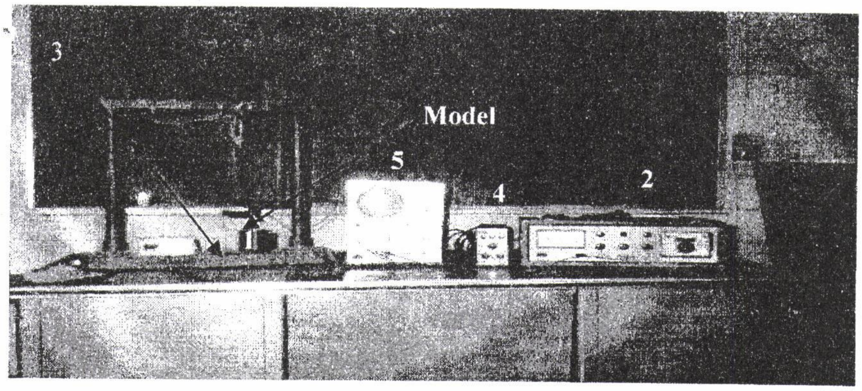

Fig. (2) Setup for Natural Frequency Measurement of Rocker Arm Models .The Model Is Held By The Aid Of Strings for a Free-Free Boundary Condition

A natural frequency was distinguished by observing a sharp increase in amplitude of the pickup output, which was amplified and displayed on the oscilloscope, and by the intensity of the tone emitted. The accelerometer and shaker were placed at different points in order to get more experimental data and avoid the possibility of having the accelerometer and/or the shaker at a nodal line.

This same type of measurement was performed after any operation that was done concerning cryogenic treatment, in order to evaluate the effectiveness of the process, and calculate the reduction of the residual stresses which is related to the natural frequency due to cryogenic treatment.

Heat treatment

In all the experiments that were performed heat treatment (residual stress relieving) was performed on the models and their natural frequencies were measured. This was done in order to find their natural frequency in their stress -free state.

In order to relieve any internal stresses for the alloy steel, the model was inserted into the oven and the thermostat was set for 650^{0}C. Treatment time was ½ hr for each 25 mm thickness, as for the aluminum model, the temperature was set for 350^{0}C. After the mentioned time has elapsed the power to the oven was switched off and the model left overnight to cool inside the oven.

The Experiments

In this set of experiments, the rocker arm scale models were 1st thermally treated to relieve any residual stresses that may be embedded in the models. They were then measured for their natural frequencies in their stress free state.

After this the models were encased in paraffin wax as shown in **Fig. (3)** this was done in order to prevent any thermal shock that may occur (mass effect) and prevent any cracking as a result of this, also sudden cooling may result in building residual stresses due to sudden contractions and expansions happening at the same time in the models.

Six wax-coated models with the scale models inside them were made four for aluminum and two for the alloy steel. The type of scale models that were used were of the dimensions of model shown in **Fig. (1)**.The wax was cast in a block shape mold with the model inside the mold: i.e. the model had a thickness of 10mm wax surrounding it.

The wax block had the dimension (136x94x40) mm as shown in **Fig. (3)**.A hole was then drilled in the mould towards the center of the block of wax and a thermocouple of the K-type was inserted inside the block, molten wax was then poured to close the hole. The thermocouple was embedded inside the block in order to monitor the rate of temperature decrease and the final temperature the block will reach in the center. **Fig. (4)** shows three of the waxed blocks with the digital thermometer and thermocouple attached to it.

Liquid nitrogen was supplied inside special containers for containing the liquid this is because materials tend to behave brittle at ultra low temperatures; The container is formed from austenetic stainless steel, which maintains its toughness at cryogenic temperature.

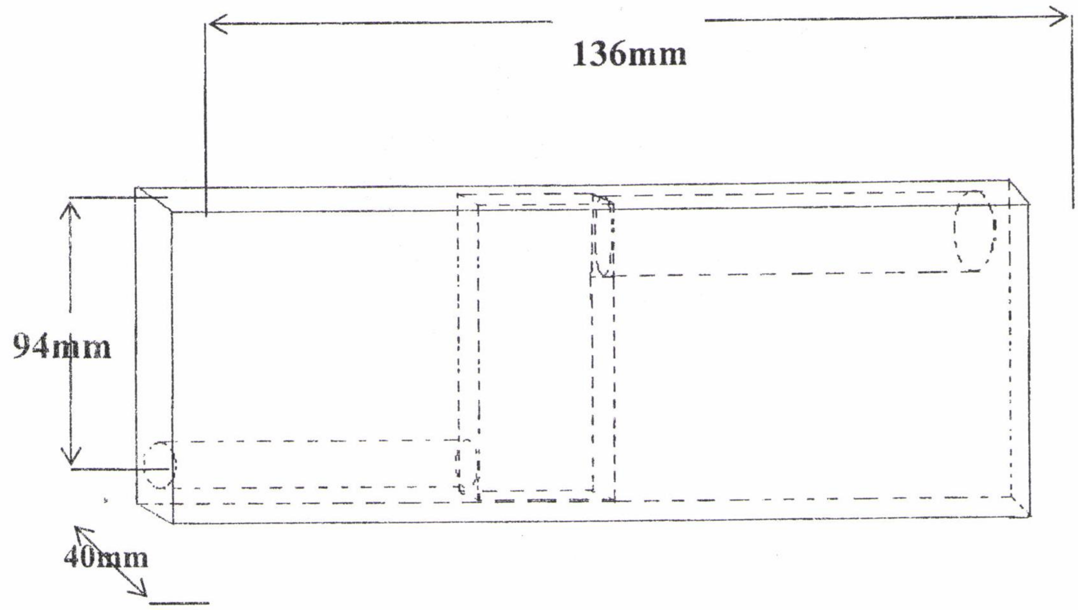

Fig. (3) the model encased in wax with a thickness layer of 10mm surrounding it in side the wax block.

Its ability to absorb impact. The container also had a safety valve; this is to ventilate any ascending pressure as a result from the constant evaporation

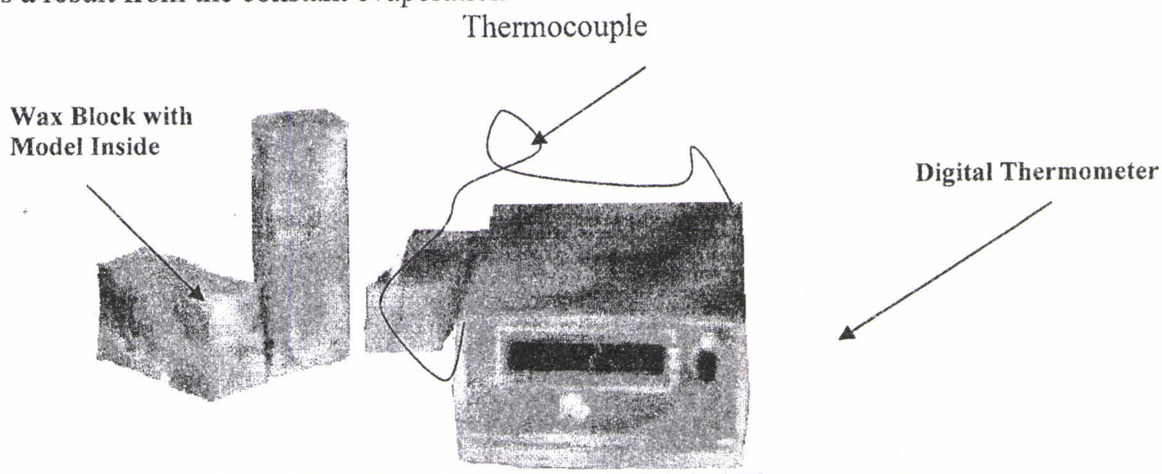

Fig. (4) The Wax Blocks with the Digital Thermometer

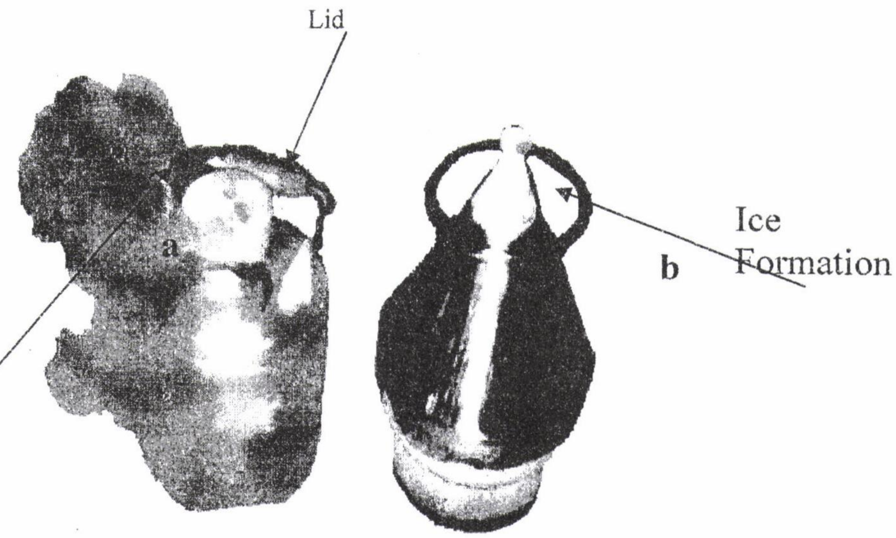

Fig (5) the containers that were used for the cryogenic experiment: a- the container in which the models were immersed
b- The container which acted as a spare reservoir.

And of the liquid nitrogen, which is continually happening during the whole process this vapor if it is not let out will cause the bursting of the container and resulting in fatal injuries **Fig. (4.6)** shows the containers that were used for the storage of the liquid nitrogen.
The temperature of the liquid nitrogen was first measured and found to be (-198^0C) at atmospheric pressure. The wax, that contained the 1st alloy steel model, was then inserted inside the liquid nitrogen slowly with the aid of a long thin wire and tongs. The decrease of the temperature inside the center of the wax block was monitored. The change was rapid in the first 15 minutes and the center reached a temperature of (-175^0C) in the first 1800-Sec and then at a slow rate of (1^0C) every 3 min, after 5400 sec it reached equilibrium.
Time of immersion for the alloy steel block was 3 hrs. After the time had elapsed, the block was extracted from the liquid. The block was wrapped in insulation and left to absorb heat and reach room temperature at a slow rate. In addition to the insulation the block was left overnight to reach room temperature. This was done in order to obtain uniform contraction followed by uniform expansion, so as to prevent further stressing.
This same procedure was repeated for the six blocks that were prepared in advance. The blocks were two for the alloy steel model and four for the aluminum blocks. Each one of the blocks was taken out from the liquid at a different time. Time of immersion for the alloy steel blocks was 3 hrs & 0.5 hrs. Time of immersion for the aluminum blocks was 3, 2,1& 0.5 hrs. the reason for this was to find the effect of the time of immersion on the residual stress level.

Discussion

The natural frequency (N.F) of any component shifts to lower or higher levels when stress inducement is performed. This shift depends on

1- THE magnitude of the residual stresses.
2- Type of residual stresses (whether compressive or tensile or both).
3- The boundary condition of the component when the stress inducement was performed. This is verified in published papers [Shakir K. Al-Samarrai et al 2002], [Jubb J.E.M 1975], [Porter Goff R.F.D 1976].

In the work that was done in this research study, the N.F was taken as a reference for the stress free state and the level of stresses when stress inducement was made.
This shift in the N.F occurs because of the changeable variables, residual stresses tend to inflate or may deflate these variables, [Claxton R.A 2002], which are:

1- Stiffness
2- Modulus of elasticity

Fig. (6) shows the drop in temperature inside the wax block. We find that the drop is very rapid at the beginning and slows after reaching –175 ^{0}C.
The **Tables (2, 4)** shows that the shift in N.F is towards higher levels which is a result of tensile residual stress inducement [Porter Goff R.F.D 1976]. The residual tensile stresses tend to increase both the rigidity parameters of the model [Claxton R.A 1991], these stresses are a result of the B.C (free -free), which was applied to the model when the stresses were induced from line heating [J.E.M.Jubb1975], [Porter Goff R.F.D 1976] this shift can be seen in **Figs. (8) & (9).**
Tables (4 & 5) show that the N.F shifted towards lower levels. This shows that the residual stresses that were induced were of the compressive type [J.E.M.Jubb 1975]. Clamping the model while line heating it created these compressive stresses [V.G.POLNOV1988]. These shifts are graphically represented in **Figs. (7 & 12).**
Stress inducement by line heating followed by immediate quenching induces both tensile and compressive residual stresses. This is seen in **Table (3)**.
The highest shifts that occurred in the N.F were the stress inducement tables in which the stresses were obtained as a result of quenching. This is explained from the known fact that quenching forms the highest residual stresses.
The level of change to which the N.F shifts as a result of stress inducement also depends on the heat input which has a relationship with the level of residual stresses, and the rate of cooling [Vino Kurov 1968], [Dwight J.B,Yong.b.w].
From **Tables (1 & 2)** it was observed that the residual stress reduction reached 28.49% & 92.38% respectively. As the time of treatment decreased, the stress reduction increased.
This is also shown in the results that were obtained from **Tables (3 to 6)** for the aluminum models. Treatment time of 3 hrs for the aluminum models reduced the residual stress level to 18%. While the reduction in residual stresses for a treatment time of 0.5 hrs was 85.31%.
Comparing the treatment time of 3 hrs and 0.5 hrs for both materials, we find that the greatest reduction of residual stresses was in the alloy steel model. This can be explained when calculated the shift in the N.F as a result of the stress inducement in **Table (1)** (alloy steel) find that it is (- 0.0287 x10^3 Hz) and that for table 3 (aluminum) it is (1.2888 x 10^3 Hz). This shows that the residual stress level was higher in the aluminum model of the mentioned table. Because of this, the reduction of the residual stress level was 28.49% for **Table (1)** and 18% for **Table (3).** If we had left the aluminum model for further treatment the reduction would have been greater.
Yet, treatment time does not necessary need to be long. Over treatment may cause re-stressesing of the component. **Fig. (7)** shows that is drawn from the results of **Table (1).** When the model underwent stress inducement the N.F shifted to a lower mode. But when it was subjected to cryogenic treatment it re-shifted to the stress free state and continued its journey to a higher mode causing the model to be re-stressed in addition to changing the type of residual stresses from compressive to tensile stresses.

CONCLUSIONS

1- Residual stress relieving can be achieved by cryogenic temperature treatment.
2- Effectiveness of cryogenic treatment depends on the mass of the component and exposure time to cryogenic temperature
3- Over exposure to cryogenic temperature leads to re-stressing of the component.

The Results

Table (1) Cryogenic Treatment Performed on Alloy Steel Model

Measured Freq. stress free KHz	Stressed Freq. Quenched KHz	Cryogenic Treatment 3 Hrs	% Reduction of Residual Stress Level
2.5600	2.5951	2.5851	28.49 % Reduction 1st Mode As Reference
2.5903	2.5980	2.5860	
4.6640	4.6730	4.6690	

Table (2) Cryogenic Treatment Performed on Alloy Steel Model

Measured Freq. stress free KHz	Stressed Freq. Heated while clamped KHz	Cryogenic Treatment 0.5 Hrs	% Reduction of Residual Stress Level
2.5590	2.5303	2.5568	92.38 % Reduction 1st Mode As Reference
2.5910	2.6203	2.5890	
4.6660	4.6680	4.6580	

Table (3) Cryogenic Treatment Performed On Aluminum Model

Measured Freq. stress free KHz	Stressed Freq. Quenched KHz	Cryogenic Treatment 3 Hrs	% Reduction of Residual Stress Level
2.4824	2.2068	2.2564	18 % Reduction 1st Mode As Reference
2.5210	2.5020	2.6947	
4.7100	4.8897	4.6376	

Table (4) Cryogenic Treatment Performed On Aluminum Model

Measured Freq. stress free KHz	Stressed Freq. Heated while clamped KHz	Cryogenic Treatment 2 Hrs	% Reduction of Residual Stress Level
2.4822	1.2068	1.7031	35.8 % Reduction 1st Mode As Reference
2.5212	2.3858	2.4252	
4.7070	4.5991	4.7553	

Table (5) Cryogenic Treatment Performed on Aluminum Model

Measured Freq. stress free KHz	Stressed Freq. Heated while clamped KHz	Cryogenic Treatment 1.5 Hrs	% Reduction of Residual Stress Level
2.48215	2.1851	----------	58.2% Reduction 2nd Mode As Reference
2.52110	2.50170	2.5129	
4.71030	4.69290	4.78090	

Table (6) Cryogenic Treatment Performed on Aluminum Model

Measured Freq. stress free KHz	Stressed Freq. Heated while clamped KHz	Cryogenic Treatment 0.5 Hrs	% Reduction of Residual Stress Level
2.4824	3.7712	2.6721	85.31% Reduction 1st Mode As Reference
2.5219	2.5528	5.5222	
4.7107	4.6765	4.7119	

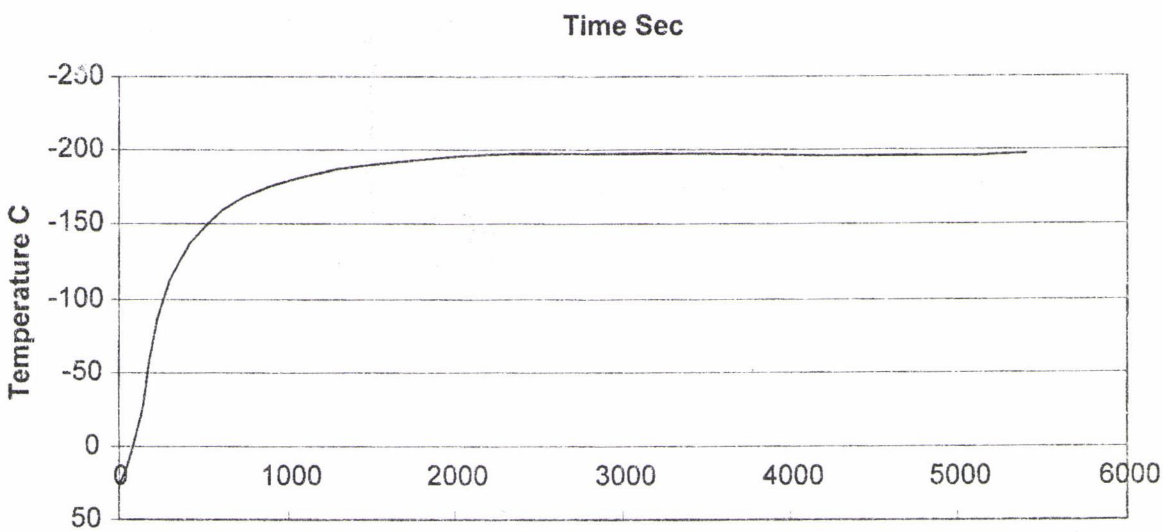

Fig (6) Decrease in Temperature inside the Wax Block With Respect To Time

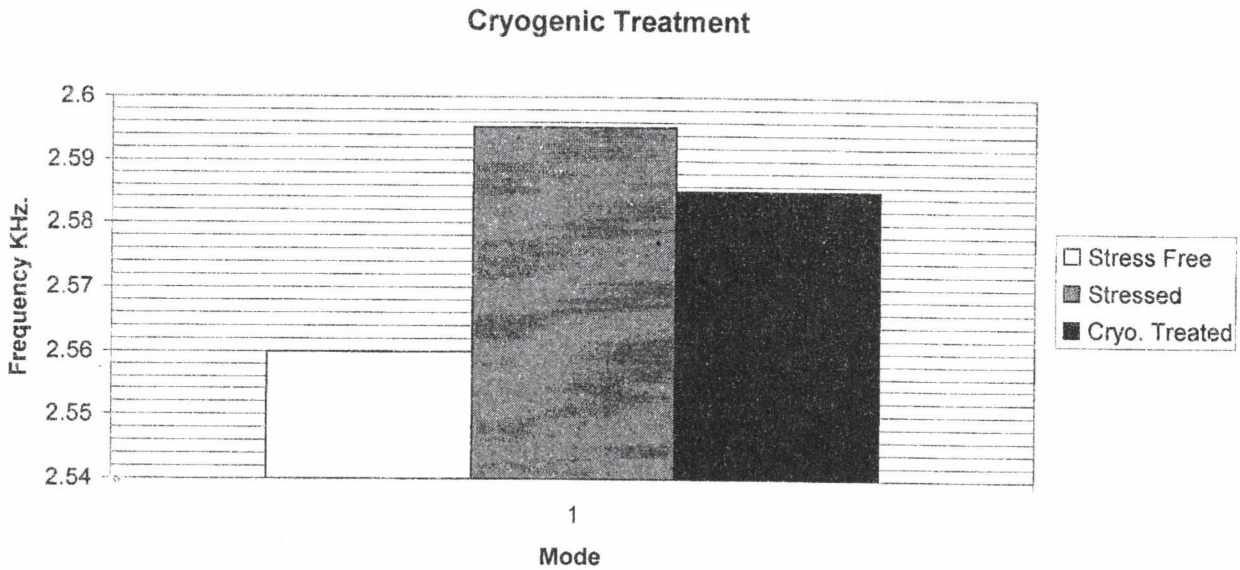

Fig. (7) 1st Mode Change Due To Cryogenic Treatment 3 Hr S for Alloy Steel Model.
28.35 % Stress Relief

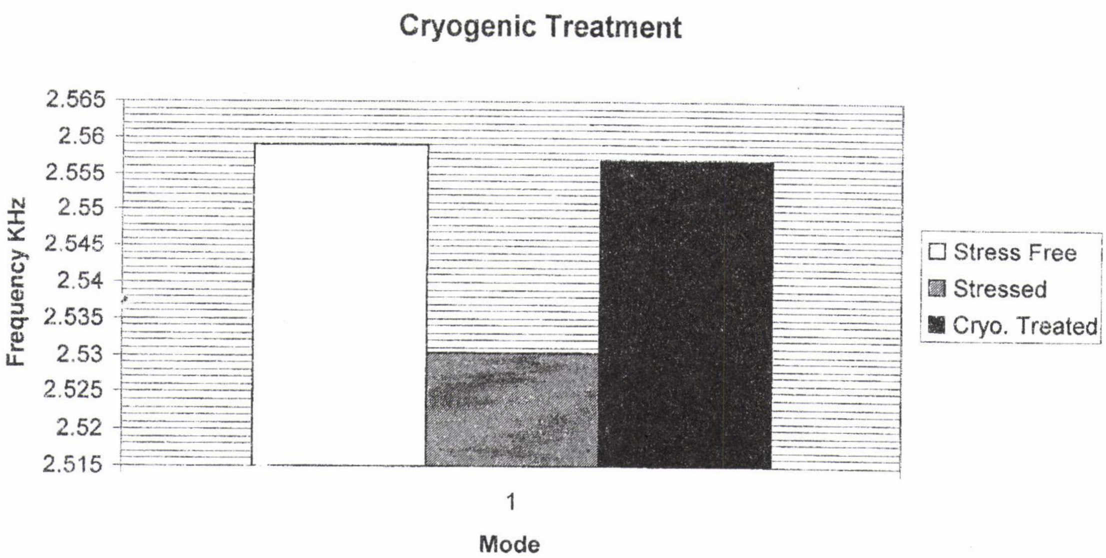

Fig. (8) 1st Mode Change Due To Cryogenic Treatment 2 Hr S For Alloy Steel Model.
92.38 % Stress Relief

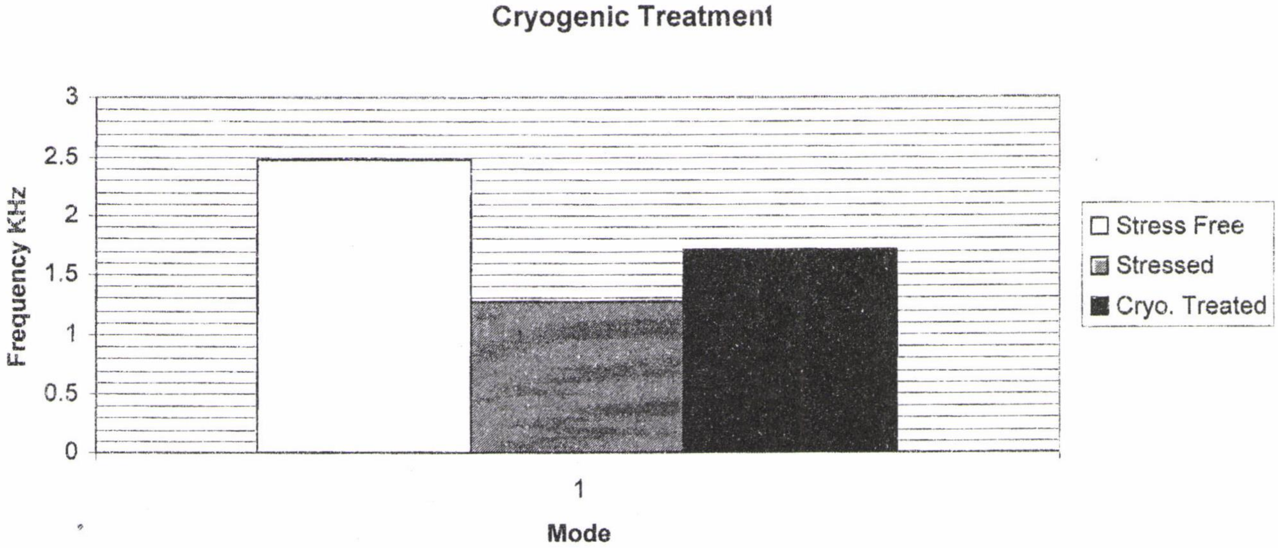

Fig. (9) Cryogenic Treatment for Aluminum Model 3 Hr s. Change in 1st Frequency.
18 % Stress Relief

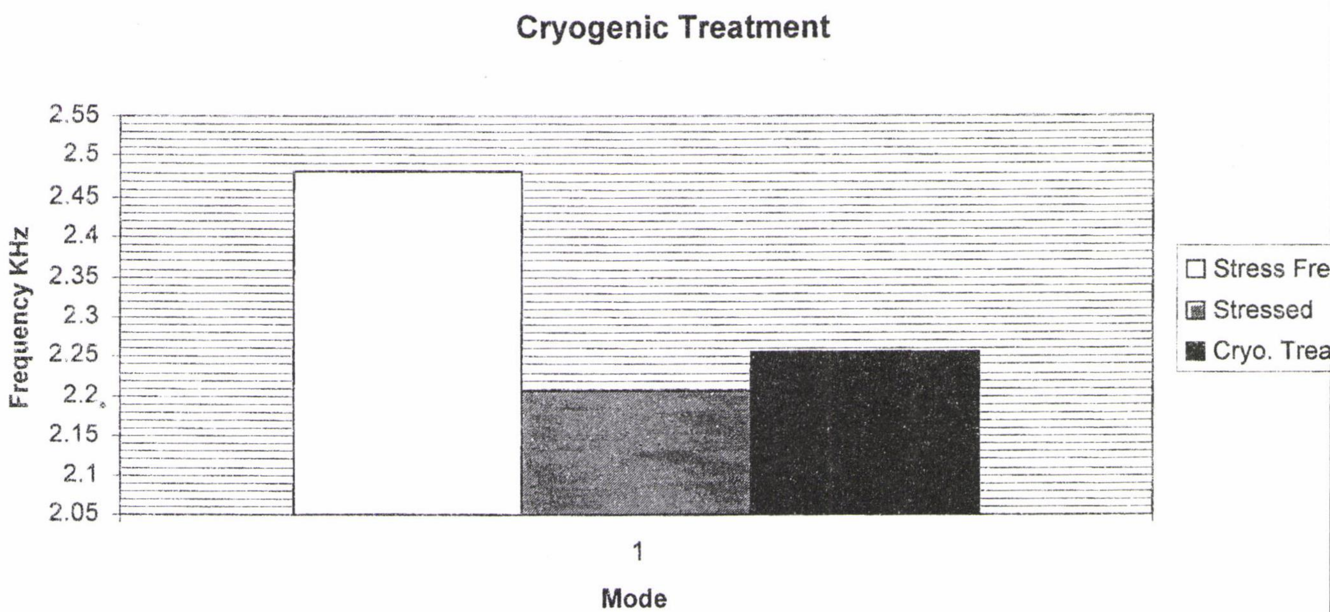

Fig. (10) Cryogenic Treatment for Aluminum Model 2 Hr s. Change in 1st Frequency.
35.8 % Stress Relief.

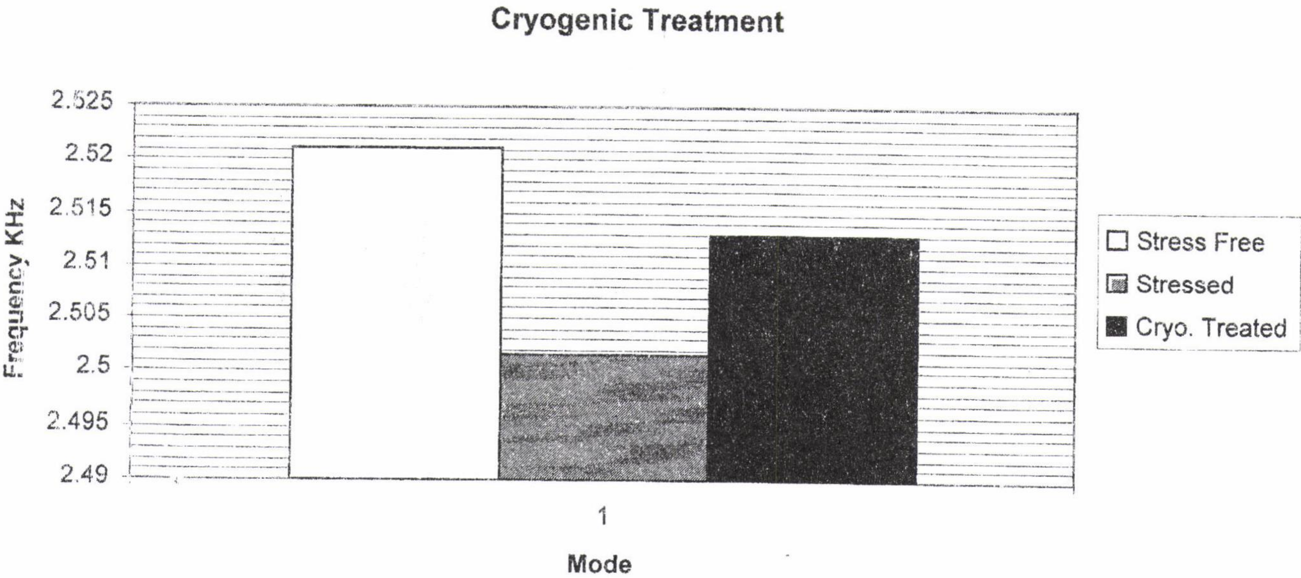

Fig (11) Cryogenic Treatment 1.5 Hr S For Aluminum Model 2nd Mode Change.
58.2 % Stress Relief.

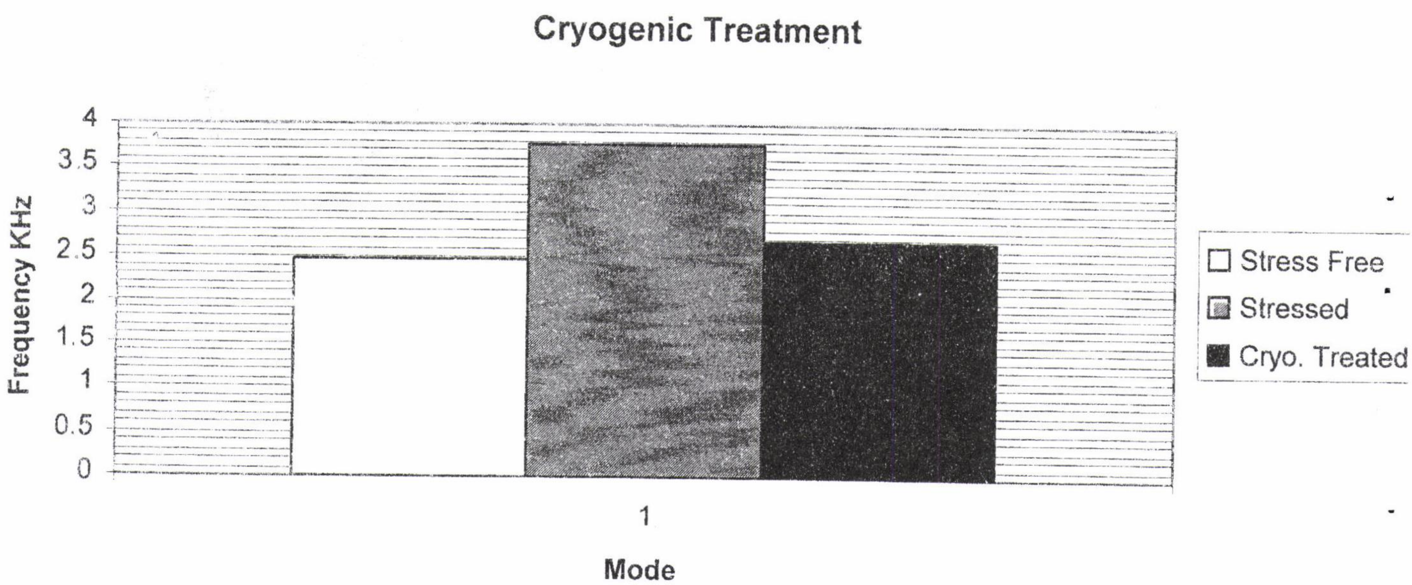

Fig. (12) Cryogenic Treatment 0.5 Hr s For Aluminum Model 1st Mode Change.
85.31 % Stress Relief.

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