STRESS PATTERN ANALYSIS USING THERMAL CAMERA

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Abstract
This report aims to illustrate the use of infrared thermography as a nondestructive and noncontact technique to do stress pattern analysis on metallic specimen when subjected to tensile force under static loading In addition, this thermal imaging technique readily shows the structural failure mechanism and location of damage. For this report, the stress pattern analysis was done on mild steel specimen and the thermal images of the specimen while loading/experimentation were obtained with the help of thermal camera. With the experimentation, stress and temperature values were obtained and with mathematical modeling, the experimental results were validated. These findings have significant implications for industrial application in material inspection technique under dynamic condition. Further research will also help in site inspection of materials in real time structures.

Index Terms: Nondestructive technique, Thermal camera, Stress, mathematical modeling.

I. INTRODUCTION

Measuring instruments play a vital role in every technical field. These measuring instruments are basically divided into two types, one is the contact type of measuring instruments and other is the non contacting type measuring instruments. The non contacting type of measuring instruments have the advantage of having no physical contact with the specimen, thus does not cause even a minute deformation on the specimen. One of the non-contacting measuring field is thermal imaging. Thermal imaging is a very powerful field of noncontact technique that can be used to measure the temperature. It has a wide range of applications in all industrial sectors like chemistry, agriculture, medicine etc. Most of applications deal with high temperature measurements of static objects and measurements on moving, very minute or inaccessible objects. It is very less known that thermal imaging can be used even in measurement of minute changes of temperature and quantities associated [1]. Circa-1930 Evaporagraph was the first thermal imaging device. It was insensitive and nonscanning. This device could not successfully satisfy thermal imaging properties due to its inherent contrast, the sensitivity, and also because of the long response time it took [2].

There are not much non contacting techniques to monitor the stresses on material on real time structures. Stress applied on an object can be defined as force per unit area and the amount of deformation an object experiences compared to its original size and shape is strain. The concept of material changing its temperature when subjected to loading is known. With this background, the above said non contact technique with the help of thermal cameras can be established for monitoring purpose. From statistical consideration of loading, engineers can obtain the basic characteristics of a material. For this, it takes large amount of specimen and time for analysis. This discourages the engineer to get into the detail property of material under dynamic loading. With the help of thermal imaging technology, one can also characterize the properties of material under static and dynamic loading with ease. In this report an attempt to find a relation between stress and temperature for a material is made by studying the stress pattern analysis using thermal imaging.

II. THERMAL IMAGING AND RELATED WORK

A. *THERMAL IMAGING: WORKING*

Thermal imaging help human to see wavelengths beyond the ability of naked human eye. With the help of thermal imaging, humans can view objects even in dark night as the human eye does in the day.

Following are the basic working of thermal imaging [3]:

1. All the infrared emitted by the objects, which are in view, are focused by a special lens.
2. The light which is focused is scanned by a infrared detector element, which then creates a thermogram, which is a detailed temperature pattern.
3. The so created thermogram is converted into impulses in electric form.
4. The electric impulse are then sent to a signal processing unit, having a circuit board that consists of a dedicated chip which helps in translating the received information into data for the display.
5. The data for the display appears as different colors which depend on the IR emission intensity.

B. *Types Of Thermal Imaging Devices*

There are basically two common types of thermal imaging devices:

i. Cryogenically cooled devices
ii. Un-cooled Thermal imaging devices

Cooled thermal imaging: - These devices are more prone to damage due to rough use and are also expensive than un-cooled thermal imaging. These systems basically have elements sealed in a container which will cool them to below 32F or 0^{O}C. These systems have incredible sensitivity & resolution that are results from cooling the elements. A

difference as minute as 0.2 Fahrenheit (0.1^{O}C) can be seen from a cryogenically cooled system from more than 300m away, i.e. an operator is possessing a gun can be view at that distance. The modern thermography camera consists an imaging sensor which is combined with a cryocooler. The cryocooler reduces the temperature of sensor to cryogenic temperatures. The cryogenic temperature is needed to minimize the noise which is induced thermally to a lower level than that of signal from the scene which is getting imaged. They can be used to get thermal imaging in the long-wave infrared (MWIR) band & the mid-wave infrared (LWIR) band of spectrum.

Un-cooled thermal imaging: - Un-cooled TI cameras are those which do not need any cryogenic cooling. The device has a detector which is based on micro bolometer, which are small resistor of vanadium oxide and has high temperature coefficient on a silicon element with thermal insulation, excellent thermal isolation and less heat. When the temperature of scene changes, bolometer temperature changes which are converted to electrical signals and the images are processed. Un-cooled sensors work in LWIR band, where the most of IR energy is emitted by targets in terrestrial temperature. Cheaper than the cooled cameras, they have less moving components in number and have long product life than cooled cameras under same operating conditions

C. *Current Thermal Imaging Technology*

Currently the thermal imaging technology allows detectors for infrared systems to operate at higher temperatures using small and compact systems at a very low cost. The technology is easily available. The cost of the cheapest thermal camera is starting from 10000 Indian rupees [2].Thermal camera are also available as an accessory for modern mobile phones which has a sensitivity of 0^{0}C and can be used to sense scene temperatures from 0^{0}C to 100^{0}C.

D. *Applications*

Thermal imaging in the future will make significant applications into consumer and commercial sector. The significant improvements are bringing down the cost of this technology, while promising that thermal imaging devices become lighter & smaller and which also consumes less power. Initially built for military purpose, thermo graphic cameras have moved into other fields as varied as archaeology and medical. Firefighters use thermal cams to see through smoke, localize hot spots of fires and find people who are trapped when it's smoky around. Law and enforcement uses the technology for surveillance activities, locate and catch suspects, crime scenes investigation and to conduct search operations and rescue operations. Power line maintenance technicians locate overheating joints and parts to eliminate potential failures. Where the thermal insulation becomes faulty, construction technicians can see heat leaks and improve the efficiency of heating or cooling. Fever in human beings and other warm-blooded animals can be viewed with thermal imaging. Thermo graphic cameras are common tools used by home inspectors. Some of the applications are listed below:

1. Security
2. Law and enforcement
3. Surveillance of building/house to determine water leaks or heat losses.
4. To find out hot spots in electrical devices.
5. A vision tool for driving in dark places.
6. Inspection of overheated mechanical parts in a system.
7. To determine material defects like crack on parts.
8 .Thermal imaging in medical health.
9. Veterinary thermal imaging.
10. Non destructive technique.
11. Chemical imaging.
12. Process control.
13. Volcanology, etc

E. *Industrial Use Of Thermal Imaging*

Some of the industrial uses of thermal imaging are as follows:

i. Construction Inspection

Building constructions can benefit a lot using thermal imaging. Heat loss due to wall, poor window and root performance can be viewed before hand and hence can be repaired. The air quantity inside the building can also be viewed using thermal imaging. Possible moisture content & water leaks can be easily predicted and repaired using thermal imaging. It can view exhaust gases from vehicles or factories nearby which are leaking into the building.

ii. Mechanical

Inspections of mechanical system require similar pieces of equipment's to be compared and their actual temperature of operations are also needed to be compared. For an example, two motors having same specifications and which is working under the same load must look alike through a thermal camera. If they don't, the reason for the failure can be analyzed and precautive measures can be taken. Using the thermal camera, a technician can make out if the mechanical device or parts are working in prescribed temperature design tolerance.

iii. Process Monitoring

All the process applications can be viewed and the problem can detected to ensure proper conditions for operations. Potential problems of operations consisting of robots in assembly line can be continuously monitored.

F. *Temperature- Stress Relation*

Metals in microscopic level are having a crystalline structure. These crystals form the grains and each grain is a distinct crystal with its very own orientation. The area which divides two grain areas is known as grain boundary. These grain boundaries are defects in the crystal structure. When a metal is under increasing tensile load, it's structural defects like grain boundary, point vacancies, line and screw dislocation gets displaced and gets thermally activated. This causes an increase in the temperature at the area of defect. In this report, an attempt to bring up a template for a metal showing a mathematical relation between its stress and temperature under static loading is made.

III. METHODOLOGY

A. *Methodology Flow Chart*

The following chart represents the methodology for this report:

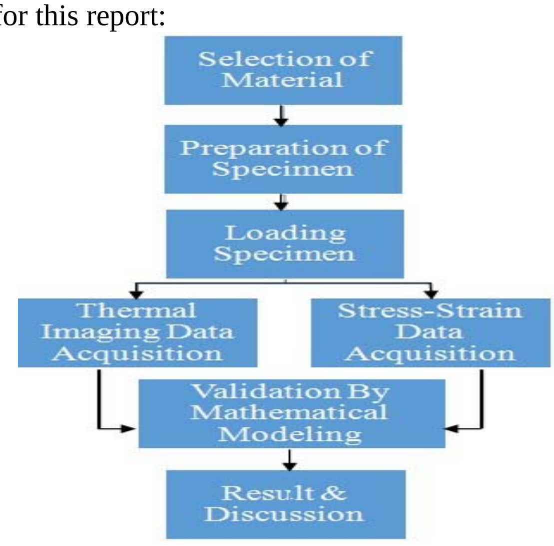

Fig 1. Methodology Flow Chart

B. *Methodology Explanation*

The first step to perform the experiment is to select the suitable material; the material selected is Mild Steel, as mild steel has enormous application in various industrial sectors. The next step is to prepare the specimen so that the specimen would be clamped into the experimental setup, which is to take the thermal images of the specimen when applied when forces are applied. The specimen is then tensile loaded under static condition into the universal testing machine, where the tensile force is applied by the machine onto the specimen. The force applied ranges from zero KN to the force where the specimen ultimately breaks. The feed rate is selected before loading the specimen. After performing many experiments and observing the thermal pattern, the feed rate of 0.25mm/s was selected. The feed rate is selected considering the adiabatic conditions that are given to the specimen while performing the experiment. The thermal camera is then mounted onto the experimental setup (the lens of the thermal camera is focused in such a way that notch area is covered). The data of temperature and the stress strain are obtained. The experimental results so obtained are substituted in the mathematical model generated and validated. In this way the result from one specimen is obtained. After obtaining the result, a new mild steel specimen is loaded and the same method is repeated. The results are compared for its consistency and the overall result is plotted.

IV. EXPERIMENTATION

A. Experimental Setup

1. Specimen

Due to wide range of application of mild steel in industrial & commercial purpose, the specimen material used was mild steel. Mild steel are also known as plain carbon steel having carbon percentage of 0.02-0.2%. The less percentage of carbon content makes it ductile and malleable. It has tensile strength ranging between 42 -54 kgf/mm2 and yield stress around 26 kgf/mm2.

2. Preparation Of Specimen

Mild steel at bar was used. Flat bars compared to round bars can show better thermal pattern on the surface. Length, width and thickness of the specimen used are 400mm, 25mm and 5mm respectively. V-type notch was made at the center of the specimen, as shown in the figure. The purpose of the notch was to concentrate the stress produced in the material, while loading in universal testing machine, to a region.

Fig. 2 Specimen Mild Steel with V-Notch

3. Testing Machine

For loading the specimen with constant feed rate for tension stress, a 40TR manually operating universal testing machine is used. The setup is as shown in the figure.

Fig. 3 Thermal Camera Setup on UTM

4. Flat Jaws

To hold the mild steel bar specimen, appropriate jaws were made as shown in the figure. The jaw dimensions are as follows:

_ Length: 100 mm
_ Base Width: 79 mm
_ Top Width: 67 mm
_ Thickness: 20 mm
_ Groove Depth: 2 mm
_ Groove Width: 25 mm

Knurling was done on the upper surface of the jaw for extra gripping.

Fig. 4 Flat Gripping Jaws

5. Thermal Camera

FLIR ONE First generation for Iphone 5/5s is used as thermal camera. Its specifications are as follows [4]:

1. Scene temperature range: 0^{O}C to 100^{O}C.
2. Operating temperature: 0^{O}C to 35^{O}C.

3. Weight: 110 grams.
4. Sensitivity: ability to detect temperature difference as small as 0.1^{O}C.

Fig. 5 Thermal Imaging Camera [4]

6. Camera Clamp

To clamp the thermal camera to the universal testing machine, a 3d printed camera mount was made in Ultimaker 2 Extended 3d printer. This 3d printed mount was fixed to a grooved wooden support as shown in the figure and the upper at surface of wooden support was fixed to the machine with the help of a at circular neodymium magnet.

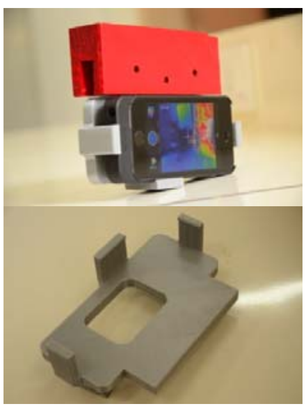

Fig. 6 Camera Clamp

V. MATHEMATICAL MODELING

From M.P.Luong's paper on "Fatigue limit evaluation of metals using an infrared thermographic technique" [5] and his other paper on "Infrared thermography of fatigue in metals" [6], the following thermo-mechanical equation was obtained

$$\rho C_V \dot{T} + r_O + k\nabla^2 T - (\beta : D : E^e)T + S : E^I$$

Where;
ρ = Density
C_V= Specific Heat
$\dot{T}$= Absolute Temperature per Unit Time
r_O= Heat Generated
k= Thermal Conductivity
β= Coefficient of Thermal Expansion
D= Elastic Tensor
E^e= Strain Tensor
S= Stress Tensor
E^I= Inelastic Strain Tensor

Restricting this equation to only single dimension, we get:

$$\rho C_v \frac{dT}{dt} = r_0 + k\frac{d^2T}{dx^2} - (\beta D\epsilon)T + \sigma\frac{d\epsilon}{dt} \ldots(1)$$

where t is time, x is the distance along the length of specimen, $\in$ is the strain and σ is the stress. The term
order close to one. From equation 1, the heat generated and the coefficient of thermal expansion terms can be neglected due to its negligible value. The heat dissipation in the form of conduction along the length of the specimen is less due to its feed rate. Therefore the conductions term can also be neglected.

$$\rho C_V \frac{dT}{dt} = \sigma \frac{d\varepsilon}{dt}$$

Integrating both sides,

$$\rho C_V \int_{Ti}^{T} dT = \int_0^{\varepsilon\sigma} \sigma d\varepsilon$$

$$\boxed{T = \frac{1}{\rho C v}\int_0^{\varepsilon\sigma} \sigma d\varepsilon + Ti}$$

Where Ti is the initial temperature of the specimen & $\varepsilon\sigma$ is the value of strain corresponding to the stress.

VI. RESULTS AND DISCUSSION

The following images show the change in temperature and thermal pattern around the notch area when the tensile force applied on the specimen increases. These images shows the increase in temperature where the specimen subsequently failed and was clearly evident virtually few seconds after beginning of the test.

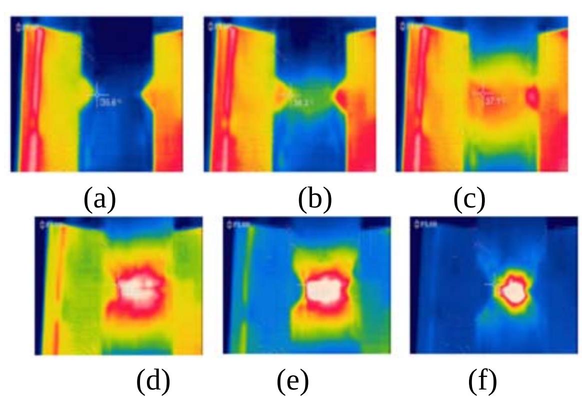

Fig. 7 Thermal images showing increase in

temperature as the load increases.

From the mathematical modeling the following relation was obtained,

$$T - Ti = \frac{1}{\rho C v} \int_0^{\varepsilon\sigma} \sigma d\varepsilon$$

If a graph with [T-Ti] values from the experimental data is plotted on the x-axis and on the y-axis $\int_0^{\varepsilon\sigma} \sigma d\varepsilon$ values are plotted, a linear curve is obtained with slope equal to the constant value 1/ρCv. Computing the logic on matlab software we get the following graph.

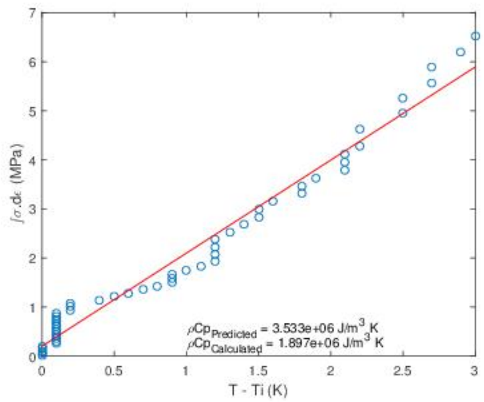

Fig. 8 Stress- Strain energy Vs Temperature Difference

From the graph it can be clearly seen that there is an error between the predicted value and the calculated value. Ideally there should not have been any mode of heat transfer like conduction, convection and radiation while loading the specimen. But practically from the thermal pattern, conduction of heat along the length of the specimen and convection of heat to the surrounding can be seen. Also while mathematical modeling the conduction part was ignored, though it had a significant value when scaled. If all the above parameters are taken into consideration, the error can be minimized significantly and a more accurate mathematical relation can be obtained.

VII. CONCLUSION AND FUTUREWORK

The relation of stress and temperature for mild steel under static loading was obtained through mathematical modeling. More accurate results can be obtained by minimizing the heat transfer from the notches where the stresses are generated. Apart from the static loading, the mathematical relation of stress and temperature under dynamic loading can also be determined, which can help engineers in material selection. Like the test carried on mild steel, the relation can be obtained for other metals and alloys and a standard template for materials can be formed.

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