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In-line laser thermography for crack detection at elevated temperature: A Numerical modeling study

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Abstract

The detection and characterization of cracks prior to damage is a technologically and economically highly significant task and is of very importance when it comes to safety-relevant structures. The evaluation of a components life is closely related to the presence of cracks in it. Laser thermography has already high capability for the detection of surface cracks and for the characterization of the geometry of artificial surface flaws in metallic samples. Crack detection in metallic samples at high temperature is highly significant in present manufacturing scenario. During the casting process of billets, surface cracks form, due to the suboptimal cooling rates. These cracks reduce value of the billet and must be removed using machining process after cooling. This secondary process increases cost of manufacturing. In this work we developed a heat transfer model for laser thermography to study the thermal contrast variation with increase in surface temperature using finite element method (FEM). Here we are mainly concentrating the capability of the scanning laser thermography in crack detection which are in elevated temperature and numerical modeling study of thermal contrast variation of crack with respect increase in metal surface temperature. This study is important to prove the capability of laser thermography for crack detection in elevated temperature. Since we are using High power CW Laser to local heating of the metal surface which can give relatively high thermal contrast even at elevated temperature compare to other heating source. Here we are modeled and simulated 2D laser scanning across a surface breaking crack and developed an algorithm to produce the vicinity of crack. The algorithm we developed applied for various surface temperature data. And validated the credibility of the algorithm with experimental data.

Keywords: Thermal contrast, Laser Thermography, FEM, Elevated temperature, Surface cracks

1. INTRODUCTION

Surface breaking cracks are the most critical issue in most of the metal steel manufacturing industries. The life of the component is closely related to the presence of cracks in it. On-going research during the last years has identified the laser- thermography as a powerful thermographic technique, which has already high capability for the detection of surface cracks and for the characterization of the geometry of artificial surface flaws in metallic samples. Crack detection in metallic samples at high temperature is highly significant in present manufacturing scenario. During the casting process billets are already at high temperature, the cracks presence in the billet reduce value of the component and must be removed using machining process after cooling. This secondary process increases cost and time of production. Now a days there are very limited NDT methods available having the capability of crack detection in hostile and hazardous environment. Since laser thermography method has following pros as high speed data collection, 2D imaging, 3D quantitative measurements, non-contact remote capabilities , can handle hostile environment and can be employed for measurement of defects, process and product parameters. Which has already proven its capability for the detection of surface cracks and for the characterization of the geometry of artificial surface flaws in metallic samples in room temperature.

This concept of flying spot thermography was suggested for the first time in the late 1960s by Kubiak et al,[1] then technique was developed for few decades [4,3, 5] and accompanied by extensive advance in infrared (IR) detector and laser technology became a promising tool now a days [2, 6, 7, 8].Among the thermographic methods, Laser thermography which currently in intense research activities has a promising capability in surface crack detection in metals. Local heating of the sample surface is realized by a laser that is scanned over the surface then lead to changes in the heat conductivity then lead to changes in the thermal footprint, which is used for crack detection by using an infrared thermal camera.

In this work we are mainly concentrating the capability of the scanning laser thermography in crack detection which are in elevated temperature and numerical modeling study of thermal contrast variation of crack with respect increase in metal surface temperature. This study is important to prove the capability of laser thermography for crack detection in elevated temperature. Since we are using High power CW Laser for local heating of the metal surface which can give relatively high thermal contrast even at elevated temperature compare to other heating source. Here we are developed a promising model to 2D laser scanning across a surface breaking crack and developed an algorithm to produce the vicinity of crack. The algorithm we developed applied for various surface temperature data. And validated the credibility of the algorithm with experimental data.

2. PRINCIPLE AND MODELING

2.1 Principle

To disclose surface cracks a focused laser beam is used to heat the metal surface locally, which results in a heat diffusion of spherical manner rather than a planar fashion as it is in the case for flash thermography. Where the heating is applied homogenously over a large surface area. In case of local heating however, the heat flow is not only axial to the surface, but also in radial direction and thus surface cracks oriented perpendicular to the surface also revamp the heat diffusion. The heat blocked at the crack edges leads to a characteristic temperature contrast on the surface. Capturing and analysing the surface temperature with an IR-camera helps the identification of surface breaking cracks. Not only the crack acting as a resistance for the heat flow, also it is a local increase of the absorption, since the laser radiation is reflected multiple times inside the crack, act similar to an black body whereas every time energy is absorbed and thus heating is more efficient within the crack. Furthermore the crack acts as a good emitter for IR-radiation due to its increased surface area compared to flat surface. Both effects lead to a higher temperature recorded by the IR-camera at the place of a crack.

2.2 .Modeling and Simulation Parameters

The simulations using COMSOL Multiphysics v 5.2 focused on a 3-dimensional model of the steel material of size 50mm×50mm×40mm and a 20W continuous laser beam is used to scan over the surface at a speed of 20mm per second like local heat source, an artificial crack having 200 micron opening and 10mm length and 2.2 depth is introduced the middle of the block. And 2mm is laser having diameter is used to carry out a 2D laser scanning across the crack whereas the initial temperature of the steel block was set to RT. The simulation done for different surface temperature (300K, 400K, 500K, 600K). [9]

Illuminating the metal sample surface generates a temperature gradient exists, due to which an energy transfer will occur from the high-temperature to the low-temperature region. The heat transfer rate due to conduction per unit area is proportional to the normal temperature gradient:

$$\frac{q}{A} = -k\frac{\partial T}{\partial n}$$

Where q is the heat transfer rate, $\frac{\partial T}{\partial n}$ is the temperature gradient in the direction of the heat flow, and the constant k is the thermal conductivity of the material (W/m. K). The negative sign is indicate that heat flows from a higher to a lower temperature value. Considering the energy balance in three dimensions the heat conduction equation in a concise form can be written as:

$$\rho C_p \mathrm{u}.\nabla T + \nabla.(k\nabla T) + \rho C_p \frac{\partial T}{\partial t} = \dot{Q} + Q_{ted}$$

Where $\dot{Q}$ is the heat generation, ρ is the density of the material, and C_p is the specific heat of the material. The ambient temperature is taken room temperature (T_0=298 K) for all domains. *Table .1* gives the thermal properties of the SS304 steel.

Table. 1. *Material parameters for SS304 as used for the simulation.*

Material property	300K	400K	500K	600K
Thermal conductivity k ($Wm^{-1}K^{-1}$)	15.5	16.4	17.7	19.2
Specific heat capacity c ($J\ kg^{-1}K^{-1}$)	435	453	481	508
Density ρ (kgm^{-3})	7930	7880	7834	7790

A surface laser heat source assumes that the beam energy is absorbed over a very small distance into the material (absorption length) compared to the size of the object heated. The finite element mesh only needs to be fine to resolve the temperature fields and the laser spot size. The laser source itself is not explicitly modeled, and it is assumed that the fraction of laser radiation reflected from the surface is not reflected back. The deposited beam power option in heat transfer module is used to model the CW laser beam and a Gaussian laser beam profile is defined as the heat source, written as

10.21611/qirt.2016.092

$$f(O,e) = \frac{1}{2\pi\sigma^2}\exp\left(-\frac{d^2}{2\sigma^2}\right)$$

Where $d = \frac{||e\times(x-O)||}{||e||}$, σ =Standard deviation

Typical mesh type and size for FEM simulations are optimized based on mainly two parameters, width of the crack and the laser spot diameter. The free triangular mesh size near the crack is optimized to 5 times smaller than the width of the crack. Fig.2 shows the geometry of the sample and the corresponding meshed geometry.

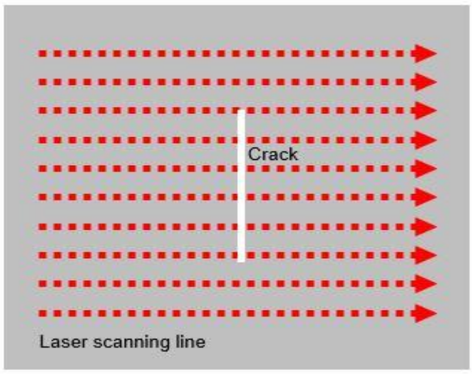

Fig.1 *2D Scanning schematic*

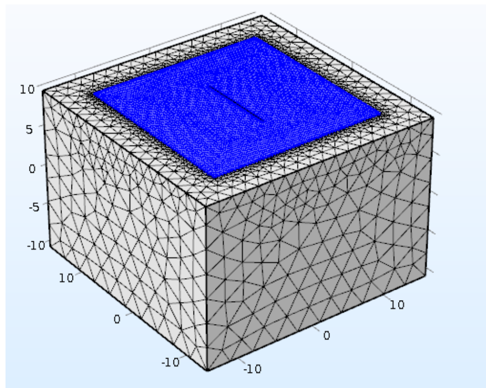

Fig. 2 *Meshed geometry for simulation*

3. RESULTS AND DISCUSSION

Our main objective of this work is to ensconce the crack detection capability with respect to increasing surface temperature of the sample. We are adopted two analyzing methods to investigate our data one is direct measurement of temperature variation happening at the crack edge due thermal heat blockage and second we developed a dedicated image processing algorithm to identify the vicinity of the crack. First we are analyzing the simulation results with first method and proceeded by other

3.1 Point probe and Line probe analysis

3.1.1 Line probe analysis

In line probe analysis we are measuring the maximum temperature of the line probe at a particular time, which is placed in scanning surface vertical to scanning direction. Since every line scanning crossing this line probe maximum temperature profile of this line probe have many hikes, and the number of hike is equal to the number of the scanning line. In our study we are placing two line probes at both edge of the crack (either sides) and the temperature profile is noted is shown in **Fig.3**. Red line shows the maximum temperature profile of the line probe which placed at left edge of the crack and blue line shows another line probe placed at right edge of the crack. From the temperature profile graph it is clear that if the laser scanning is not crossing the crack both probe shows nearly same maximum temperature. We can identify the presence of the crack there is some variation between the maximum temperature of the probes we placed either side of the crack. In order to highlight the effect of crack in fig we took the difference between this two probes. **Fig.4** shows the variation of the thermal contrast in different surface temperature. By Line probe analysis we can getting a clear indication of the crack due to the thermal blockage. But thermal contrast is decreasing with respect to increase in surface temperature. When the thermal contrast decreases it's become difficult to the crack detection. In the case of laser beam since its highly focused and coherent the variation of thermal contrast very less even at 600K approximately 15% decrease only with room temperature. Which shows the capability of the laser thermography in surface breaking crack detection even at elevated temperature.

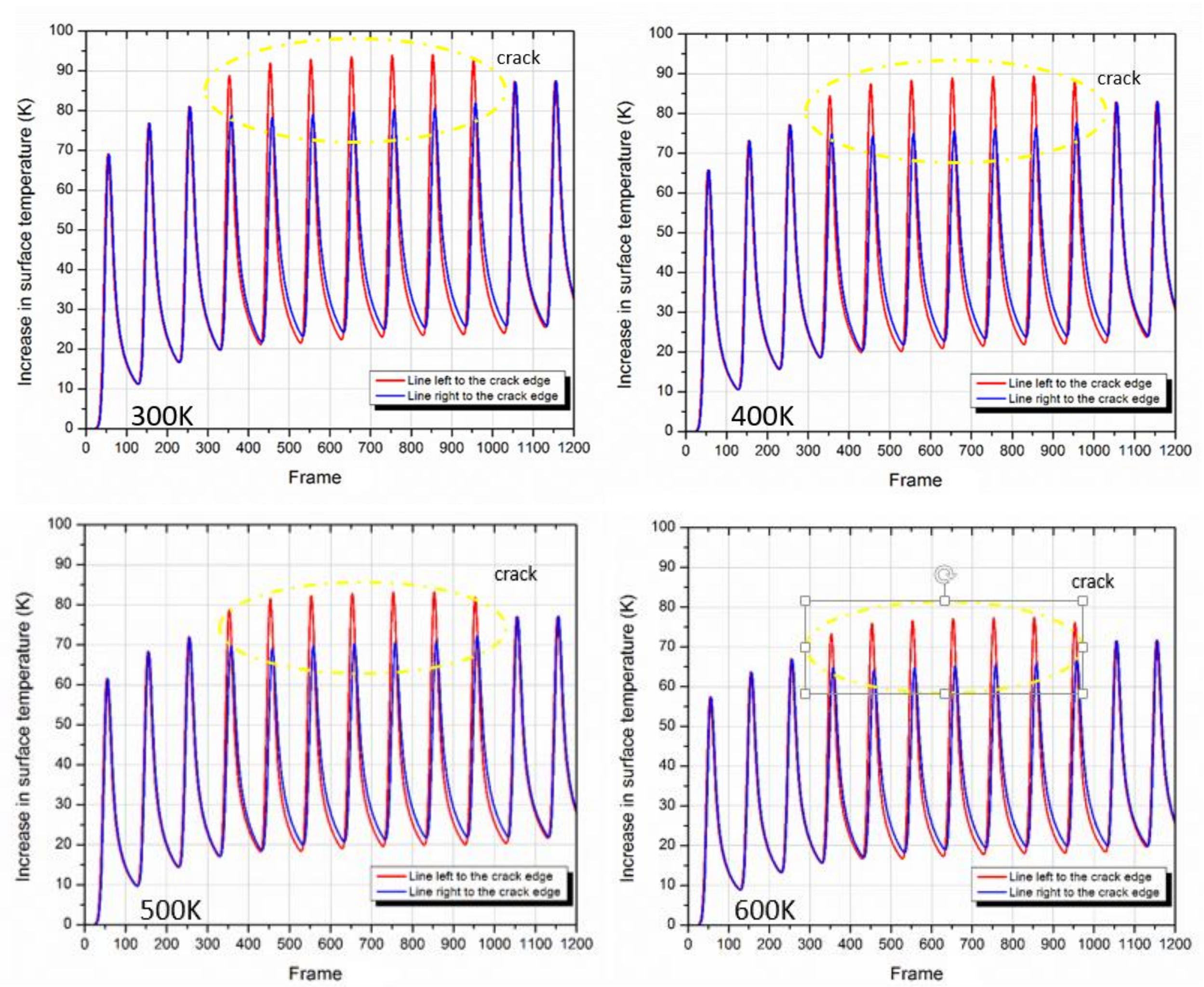

Fig.3. *Line profile analysis with respect to base metal surface temperature*

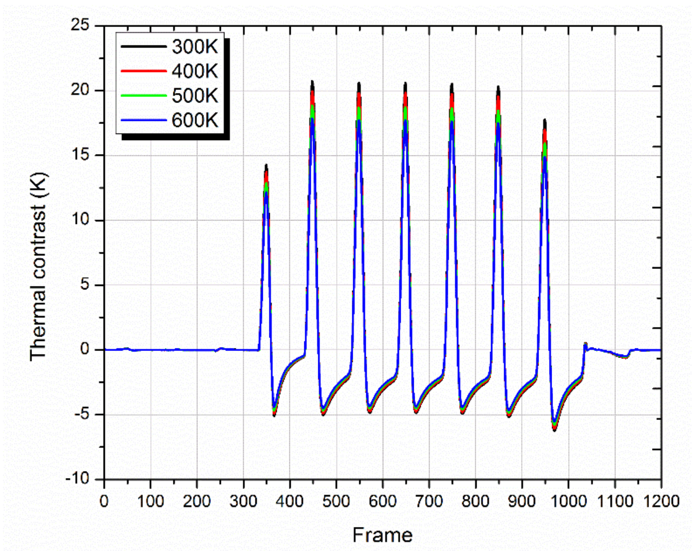

Fig.4 *Thermal contrast variation with respect to base metal surface temperature*

3.1.2 Point probe analysis

In point probe analysis we are measuring the temperature of two points with respect to time, here we selected points such that one is at the left edge of the crack and other is selected in right edge of the crack. Due to the thermal blockage there is some variation in the temperature of this points. **Fig.5** shows the temperature profile of this two points which are positioned either side of the crack where metal surface is at 300K. Red line shows the temperature profile of the point just before the crack and the blue line shows the temperature profile of the point which is just after the crack. There is an increase in maximum temperature of the point in the case of red plot is explainable because of the heat blockage due to the presence of crack. And there is the decrease in maximum temperature of the point just after the crack is due to the thermal blockage by the crack will reduce the preheating of area after the crack. The difference between this maximum temperatures of these point (either side) is termed as thermal contrast, this difference is significant in the crack detection capability

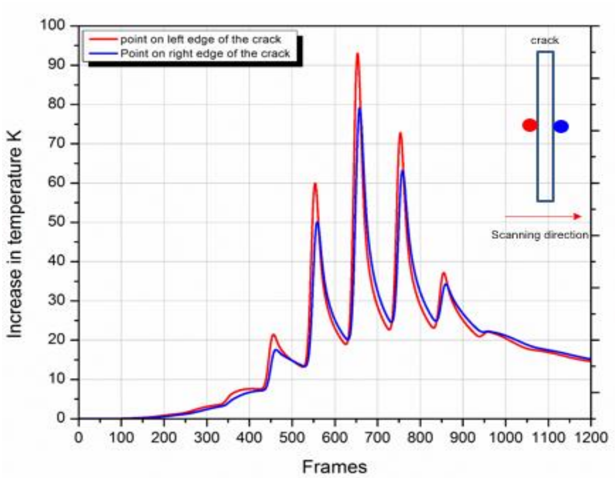

Fig.5 *Temperature profile of the points just before and after the crack*

Fig.6 Indicating the temperature profile of the point just before the crack (on left crack edge) at different sample surface temperature and **Fig.7** shows the temperature profile of the point just after the crack (on right edge of the crack) at different elevated temperature. From the graph it is very clear that the maximum temperature of the both points are decreasing with increase in the metal surf ace temperature.

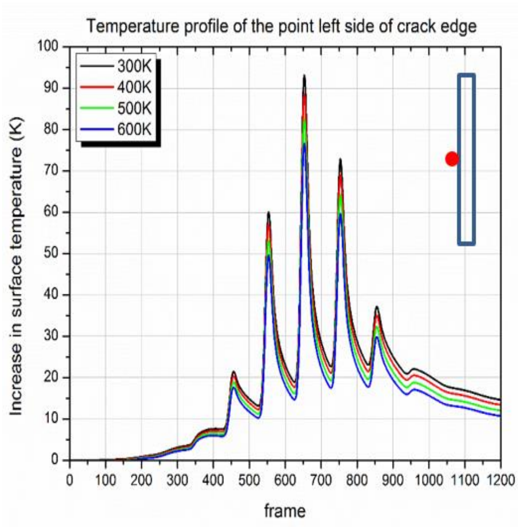

Fig.*4 Temperature profile of point just before the crack*

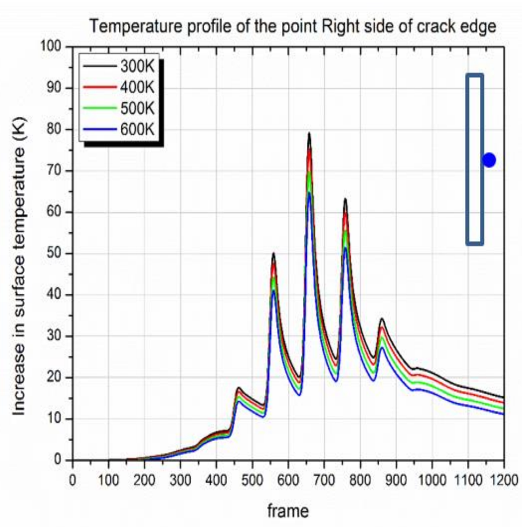

Fig.5 *Temperature profile of point just before the crack*

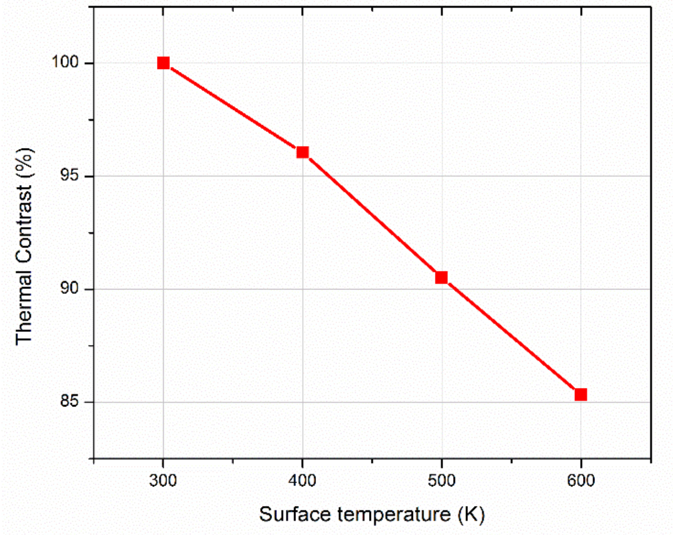

Fig.8 *Thermal contrast variation with respect to base metal surface temperature*

Fig.8 shows the thermal contrast variation with respect to increase in the base metal surface temperature. The thermal contrast is decreasing with increasing base metal temperature. When the thermal contrast decreases it's become difficult to the crack detection. There is only 15% decrease in thermal contrast in the case of 600K compared to room temperature. Which shows the capability of the laser thermography in surface breaking crack detection even at elevated temperature

3.2 Image processing

The primary objective of this work is to study the detectability of a surface breaking cracks at different base metal surface temperature by using a high power continuous laser used to scan across this crack. The thermal heat distribution due to the 2D laser scanning can be captured using the IR camera. So the rear the region near to crack is expected to contain the anomalies in the temperature behavior and also the fluctuations in the shape of thermal foot print. Accordingly the temperature history of a pixel near to the crack side contains the effect of thermal blockage due to the presence of crack. This idea is employed in the image processing algorithm developed using Mat lab@. The maximum temperature attained by each pixel is at different instances of time which is related to the speed of the laser scanning. These maximum temperatures of every pixels are aligned in a single frame and the subsequent temperatures in the cooling cycle are shown in consecutive frames. Thus another set of images was created which represents the cooling of each pixel. The cooling rates are different for each pixel depending upon its locations. The difference between the maximum temperature and the temperature attained after cooling of 0.1s and 0.5s is plotted [10]. **Fig8,Fig9** and **Fig10** shows the processed images after the 0.1,0.25 and 0.5s here the indication of the crack is easily identified, but still there is a small drop in thermal contrast of the crack when the metal surface is elevated temperature. In the case of crack at 300K and 400K after 0.1s crack is visible but the crack at 500K and 600K are not identified after 0.1s. Cracks at all surface temperature are identified after 0.25s.

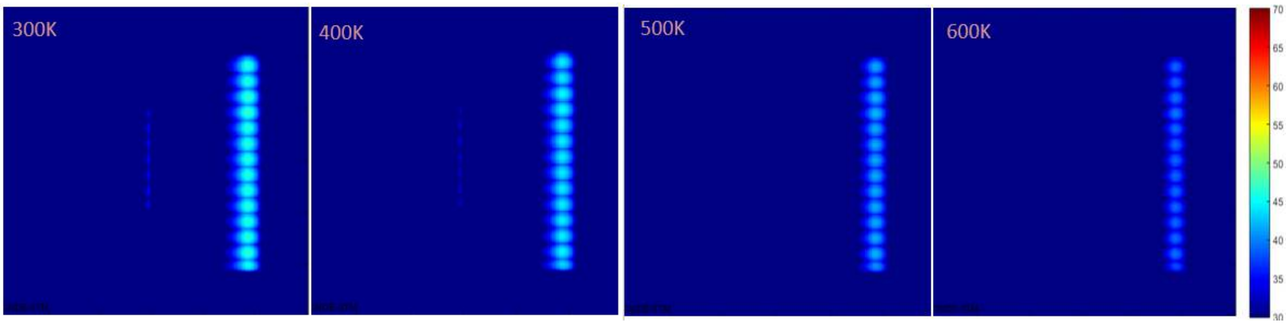

Fig.9 *Processed image on modeling data after 0.1s*

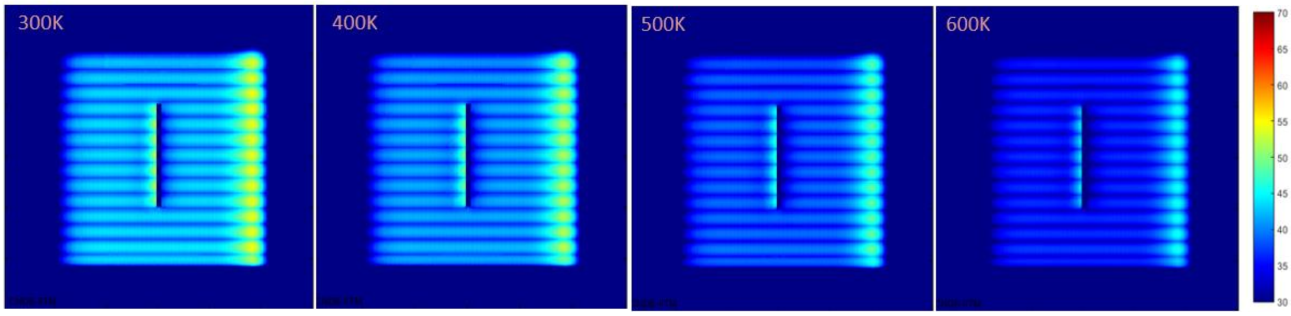

Fig.10 Processed image on modeling data after 0.25s

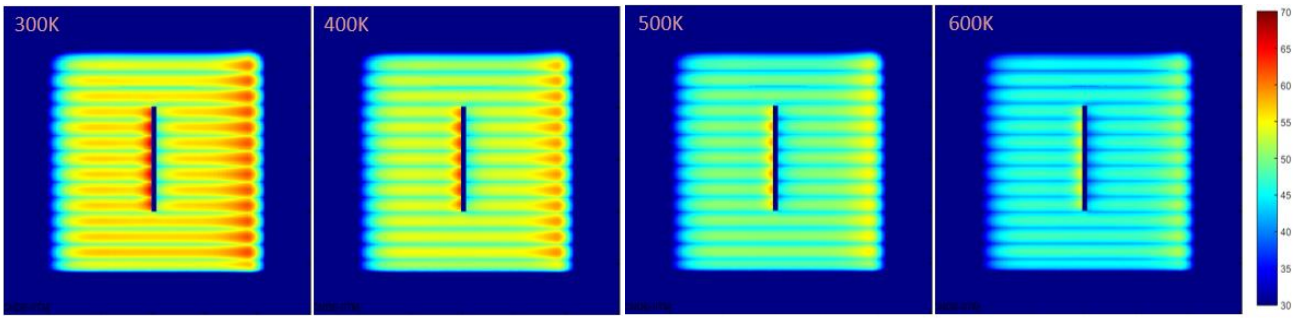

Fig.11 Processed image on modeling data after 0.5s

3.3 Credibility of algorithm with experimental data

In order to the credibility of our algorithm we applied the same algorithm in experimental data. The investigated sample was a block made of ST37 steel, (100 x 100 x 40) mm in size containing notches of different dimensions as depicted in **Fig.13**. The experiments presented in this paper focus on the notch with 2.2 mm depth. A 20W laser beam is used to scan over the notch and the thermal distribution on the surface is captured by an IR camera. We did two set of experiments with same laser power but different scanning speed 1mm/s and 10mm/s. In both case we carried our experiments where metal surface is in room temperature.

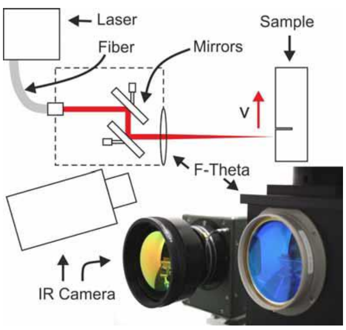

Fig. 12. *Experimental schematic*

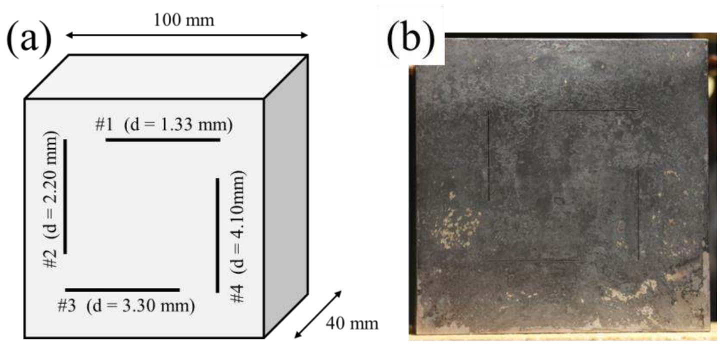

Fig. 13. *(a) Scheme of the specimen 0.2 mm in width.*
(b) Photograph of the specimen made of ST37 steel.

10.21611/qirt.2016.092

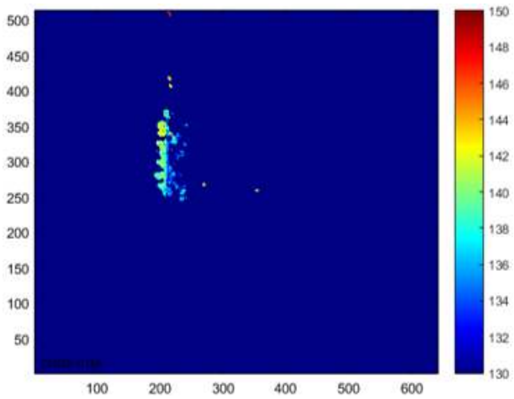

Fig. 13. Processed experimental data (20W and 1mm/s)

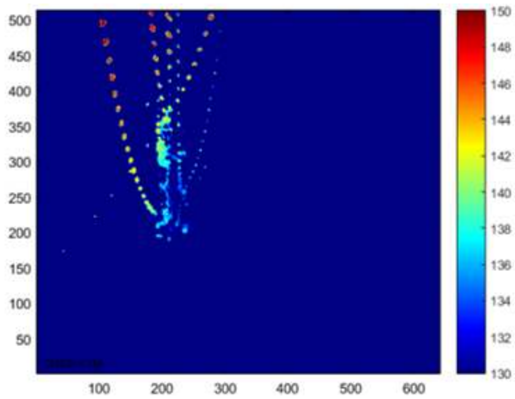

Fig. 14 Processed experimental data (20W and 10mm/s)

Fig.14 and **Fig 15** shows the processed image of the experimental data where the clear identification of notch due to heat blockage is obtained. But compared to modeling results in experimental data has some difficulties like emissivity variation with in the surface, surface irregularities, since we are using high power laser which may lead to micro level material removal and production of fumes etc. all this will affect the thermogram. So that we need to consider all these difficulties while processing to get better vicinity of the crack.

4. CONCLUSION

A Modeling study of in-line laser thermography for crack detection at various surface temperature is carried out. And a promising model for laser thermography is achieved using Comsol Multiphysics. The thermal contrast is decreasing with increase in surface temperature of the sample but the decrease in thermal contrast is very small. Only 15% decrease in thermal contrast is noted when the surface temperature raised from 300K to 600K. This shows that the crack detection capabilities of laser thermography even at elevated temperature. Since algorithm gave a compromising crack detection in both experimental data and FEM simulations, which justify proposed algorithm can be applicable in future applications for an online testing and monitoring at elevated temperature. The potential of this method can be efficiently examined and allows to develop laser thermography to a powerful and reliable NDT technique.

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10.21611/qirt.2016.092

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