Numerical Thermal Stress Analysis of Ceramic Tile Grout Removal Process

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ABSTRACT

Tiled surfaces provide a good resistance to corrosion and are extremely cleanable. However, grouted joints are the weak point. Their physical properties are far inferior from those of the tiles themselves. Decontamination and reuse of tiled surfaces have always been costly activities. It is very difficult to remove this type of grout conventionally. A single stage laser based process for the application of grout material removal between commercial tiles using a 1.5 kW high power diode laser (HPDL) has been developed at UMIST.

In this paper the 3D numerical modelling to simulate the laser grout removal of a ceramic tile and its backing layer and adjacent grout was carried out. Thermal stress analysis by the finite element method using the ADINA package was used to predict removal behaviour of the grout and its integrity with the tile and backing layer. The temperature profile over the depth and width of the tile was studied for a range of laser power from 60 to 180 W with various speeds of progress rates applied to the top of the grout along the centre-line of a symmetrical section of tiles. Finally the numerical results were compared with existing experimental results of the laser processing for grout removal materials.

INTRODUCTION

Epoxy grout materials, which are used to fill the gap between ceramic tiles, can be contaminated by harmful substances over the years. Their removal will be required in decommissioning and refurbishment of buildings and other constructions to maintain their appearance as well as to extend their life span. The majority of removal processes employed for architectural materials involve mechanical noise and production of large amounts of dust. The potential of the high power laser as an effective tool for processing of architectural materials has been recognised by a number of authors [1-4]. High power diode laser (HPDL) is a useful tool for the removal of epoxy grout materials and cutting of the non-metallic materials. The advantages of this method are excellent controllability, compactness with relatively low power requirement and virtually very long tool life.

In this paper, a 3-dimensional (3D) Finite Element (FE) thermal stress analysis model is formulated for the ceramic tile grout removal process. The boundary conditions such as conductivity, radiation and conduction are formulated. Then the temperature profile over the depth and width of the tile is studied using ADINA and its associated graphics facilities briefly will be described. The laser power ranged from 200 to 900 W/cm^2 with various speeds of progress rates applied to the top of the grout along the central symmetrical line of the tile. Finally the numerical results are compared with existing experimental results of the laser processing for epoxy grout removal.

3D THERMAL STRESS FINITE ELEMENT MODEL

Mathematical modelling for the tile, backing and grout is necessary to fully understand the behaviour of laser removed grout tiled surfaces (LRGTS) on a large-scale to determine the structural limits of LRGTS. LRGTS will be subjected to a series of stresses such as structural movements caused by thermal or moisture expansion. Therefore the LRGTS structure must be flexible enough to withstand the loads imposed during the life cycle.

Another major point in LRGTS is the laser removal process itself. High temperatures and stresses are generated during the operation. A transient analysis of the process shows the temperature and stress distribution at different stages of the process. This contributes to the optimisation of the process by indicating the peak temperatures and stresses, which in turn, indicate possible modifications that must be made to the removal process.

The laser removal process presents some aspects that can be very difficult to model, including multiple phases of the materials. The grouting material goes through three different phases during removal. Heating of the materials involved is non-linear, which greatly complicates the resolution of the temperature and stress distribution. The evaluation of these stresses is an essential element to determine the limits of LRGTS. However, working on the principle that the heat developed during laser firing, directly generates the stresses, only the primary heat transfer will be investigated.

FORMULATION OF THE MODEL

The boundary conditions of a 3D model, such as conductivity, radiation and conduction are formulated as follows:

Heat transfer equations

The concise summary of the theoretical formulation basis of the finite element computer program is described for the analysis of the heat transfer. For heat transfer in a body of tile and other materials, we assume that the materials of the body, obey Fourier's law of heat conduction (i.e. [5]). In the principal axis directions x, y, and z the equation will be as:

$$q_x = -k_x \frac{\partial\theta}{\partial x};\ q_y = -\kappa_y \frac{\partial\theta}{\partial y};\ q_z = -\kappa_z \frac{\partial\theta}{\partial z} \qquad (1)$$

in which θ is temperature and q_x, q_y and q_z and k_x, k_y and k_z are the heat fluxes per unit area and the thermal conductivities in principal axis x, y and z directions. The minus sign indicates the physical fact that a positive heat flux along direction '*x*' is given by a drop in temperature θ in that direction ($\partial\theta/\partial x<0$) and similar for other directions.

Equilibrium of heat flow in the interior of the body thus gives

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial\theta}{\partial x}\right) + \frac{\partial}{\partial y}\left(\kappa_y \frac{\partial\theta}{\partial y}\right) + \frac{\partial}{\partial z}\left(\kappa_z \frac{\partial\theta}{\partial z}\right) = -q^B \qquad (2)$$

in which q^B is the rate of heat generated per unit volume.

Boundary and initial conditions

In the heat transfer the following boundary conditions can be specified:

Temperature conditions: The temperature can be prescribed at specific points and surfaces of the body, denoted by S_1 in equation

$$\theta|_{S_1} = \theta^e \qquad (3)$$

in which θ^e is the external surface temperature (on surface S_1).

Heat flow conditions: The heat flow input can be prescribed at specific points and surfaces (S_2) in equation

$$\kappa^n \frac{\partial\theta}{\partial n}\Big|_{S_2} = q^S \qquad (4)$$

where k^n is the body thermal conductivity in the direction *n* of the outward normal to the surface, and q^s is the heat flow input to the body across surface S_2.

Convection boundary conditions: Included in equation (4) are convection boundary conditions where

$$q^S = h(\theta^e - \theta^S) \qquad (5)$$

with *h* being the convection coefficient (possibly temperature dependent), θ^e the environmental (external) temperature, and θ^s the body surface temperature.

Radiation boundary conditions: Also specified by equation (4) are the radiation boundary conditions

$$q^S = \lambda(\theta^r - \theta^S) \qquad (6)$$

in which θ^r is the temperature of the external radiation source, and λ is the coefficient given by:

$$\lambda = h^r \left[\left(\theta^r\right)^2 + \left(\theta^s\right)^2 \right] (\theta^r + \theta^s) \qquad (7)$$

in which h^r is determined from the Stefan-Boltzmann constant, the emissivity of the radiant and absorbing materials and the geometric view factors

Phase change: At a solid-liquid interface the latent heat is liberated (or absorbed) at a rate proportional to the volumetric rate of conversion of the material from one phase to the other. This heat must also be balanced by the heat flow from (or to) the phase change "front" and can be considered by Rolph and Bathe, [6].

$$q^f = L_f \rho V_l \qquad (8)$$

in which q^f is the heat flow for changing the phase of material, L_f is the latent heat of fusion or vaporization [J kg^{-1}] per unit weight of material, ρ is material density and V_l is the volume of changed phase material.

RESULTS OF FINITE ELEMENT PROGRAMMING FOR NUMERICAL ANALYSIS

Thermal stress analysis by the 3D finite element method using the ADINA package is carried out to predict installation behaviour of the enamel, grout and its integrity with the tile and backing layer, and analysed the temperature distribution. All above boundary conditions are taken into account.

Geometry of 2D and 3D models

The problem posed by the laser sealing of tile grout is obviously a three dimensional problem. The Figure (1) describes the geometry of the 2D model.

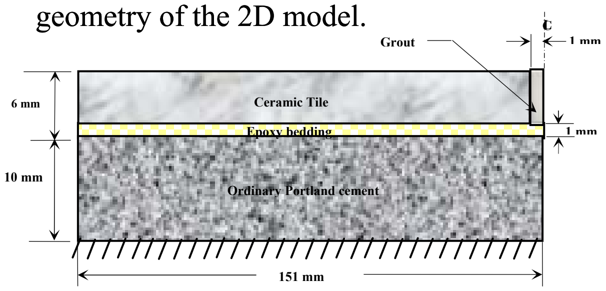

FIGURE 1: Geometry of the 2D model.

Due to the symmetry of the tiled surfaces, only a quarter of a tile set model is required for 3D model of numerical analysis. The sizes of this model in principal axis are X = 22.8 mm, Y = 20.5 mm and Z = 16 mm. The total number of elements and nodes in the model are 588 and 4725 respectively.

Material parameters

The characteristics of the materials for tiling a surface with new enamel glazing which are used for FE numerical analyses are shown in Table (1). Some of these material parameters such as Thermal conductivity, k and Heat Capacity/volume, c are temperature dependents which are not shown in this table.

TABLE 1: Material parameters for FE programming.

Property	Ceramic Tiles	Epoxy Bedding	Ordinary Portland Cement
Thermal conductivity, k (W/m -	**0.75**	**0.346**	**0.29**
Convection Coefficient, h (W/m^2	**7.5**	**3.46**	**2.90**
Thermal Expansion Coefficient,	**8.9×10^{-6}**	**5.0×10^{-6}**	**4.16×10^{-6}**
Heat Capacity/volume, c (kJ/m^3	**1225**	**2213.75**	**1842.3**
Melting Point (°C)	**600**	**550**	
Latent Heat of Fusion L (J/m^3)		**7.92×10^8**	
Hardness (Hv)	**570**		
Softening Point (°C)	**1750**		
Poisson's ratio, n	**0.2**	**0.25**	**0.25**
Young's Modulus, E (N/m^2)	**8.4×10^{10}**	**2.6×10^9**	**8.4×10^{10}**
Density, ρ (kg/m^3)	**1750**	**1750**	**2300**
Emissivity Coefficient, ε	**0.4**	**0.5**	**0.8**

Temperature results

The temperature profile over the depth and width of the tile is studied as shown in Figure (2). The laser power that was used for this figure is 180 W, equivalents to 640 W/cm^2 with speed of 5 mm/s was applied to the top of the enamel along the centre-line of a symmetrical section of tiles. Maximum temperature at the top of grout in the burned phase is 1890 °C as shown in Figure (2).

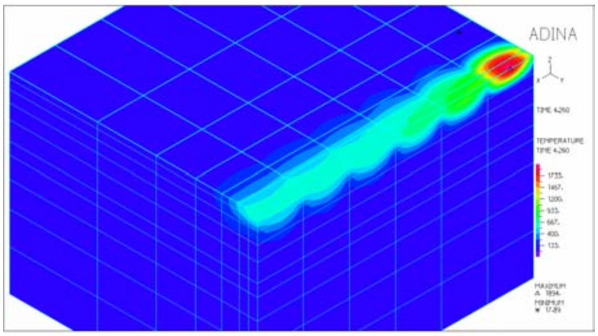

FIGURE 2: Temperature profile over the depth and width of the tile.

Figure (3) shows the temperature contours over the depth and width of the tile during the laser processing at time 3.80 s. The cross sectional profile of the grout surface after experimental laser processing at 180 W with speed of 5 mm/s is also shown in this figure [3]. The experimental and numerical results for the removal depths are in close agreement.

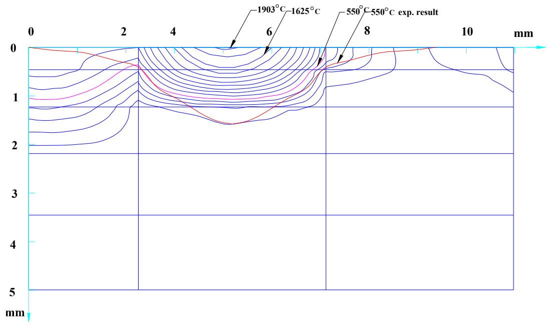

FIGURE 3: Temperature on nodes of vertical symmetry line of the tile.

Stress and strain result of materials

Associated with these temperature differences are stresses. The maximum stress is ZZ Stress on the horizontal lines in the X direction. The minimum predicted stress is about –410 MN/m^2 (that is, compressive), whilst the maximum predicted value is about 390 MN/m^2, in other words, tensile.

The sample results presented in this paper are associated with high temperature differences and hence higher stresses. When the conditions were less severe, no cracking was observed, and this is consistent with the predictions.

CONCLUSION

Grout removal materials process of tiles was numerically modelled and simulated for a 3D mesh using thermal stress analysis. These simulated results were compatible with the experimental results. According to this numerical analysis the removal process as using laser do not damage the tiles or any of the other back layer materials.

On the basis of the 3D finite element simulations performed, it is predicted that suitable process parameters can be set which reduce the risk of cracking due to residual stresses.

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REFERENCES

[1] Minami, K., Li, L., and Schmidt, M.J.J., "Materials Behaviour and Process Characteristics in the Removal of Industrial Cement Tile Grout Using a 1.5 kW Diode Laser"", *E-MRS SYMPOSIUM H*, 2003.

[2] Heshmati, A.A.R., Lane, P., Gale, A.W., Edwards R.E. and Li, L, "Numerical Thermal Stress Analysis of Sealing of Ceramic Tiles", *Computational Mechanics in Engineering in UK, 11th ACME Annual Conference UK*, University of Strathclyde, Glasgow, 2003.

[3] Minami, K., Lawrence, J., Li, L., Edwards, R.E. and Gale, A.W., (2002) "The Removal Industrial Epoxy Grout Using a High Power Diode Laser", *Optics and Lasers in Engineering*, **2002**, Vol. 38, 485-498.

[4] Lawrence, J., Li, L., Edwards, R.E. and Gale, A.W., "Single-stage of Ceramic Tiles by Means of High-Power Diode Laser Radiation", *Journal of Laser Applications*, December **2001**, Vol. 13, No. 6, 222-230.

[5] Carslaw, H.S. and Jaeger, J.C., "Conduction of Heat in Solids", 2nd edition, *Oxford University Press,* **1969**.

[6] Rolph, W.D. and Bathe, K.J., "An Efficient Algorithm for Analysis of Nonlinear Heat Transfer with Phase Changes", *International. Journal of Numerical Methods in Engineering*, **1982**, Vol. 18, 119-134.