Numerical Investigation to Predict the Effective Quench Medium for Aluminum Workpieces

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Abstract— Quenching medium employed for the surface hardening of the finished parts has high influence on the micro-structural changes in the material. The time temperature data obtained experimentally or by using lumped system analysis has a constraint due to the difference in heat transfer coefficient for a particular set of quenchant material combination. A numerical heat transfer analysis is carried on an Aluminum work piece with different quench media viz. air and inert gases like argon, helium, nitrogen and hydrogen. Gas quenching resulted in uniform cooling of which Hydrogen and Helium show more cooling rate.

Keywords— gas quenching, heat transfer coefficient, lumped system, transient heat transfer.

I. INTRODUCTION

Wear resistance of finished components is often achieved by using various quench hardening techniques viz. induction hardening (automobile parts), carburizing (gears), nitriding (bushings) flame hardening (shafts) and cyaniding (screws). The quenching medium (quenchant) used for this process has greater influence on the micro-structural changes a work piece material undergoes during the quench time. Rapid quenching may sometimes lead to undesirable distortions in the work pieces. Experimental investigation to find the material-quenchant combination is time consuming and often have to be repeated for every new material-quenchant combination. Hence, a numerical investigation helps in selecting the work piece of any shape and quenchant at various conditions (liquid/gas). Numerical investigation is also environmental friendly, as the quenchant cannot be re-used after conducting an experiment.

Lumped heat capacity method was used by Arif Suginato et al. [1] to determine the temperature dependent heat transfer coefficient. With water as quenchant 'h' obtained by this method was 3000 W/mK^2. Three stages of quenching, nucleate boiling, film boiling and vapor blanket stage were observed by Ramesh et al. [2] while highest heat transfer coefficients were observed during nucleate boiling of Aluminum alloy work piece by Bowang Xiao et al. [3].

For mineral oils and polymer quenchants the heat transfer coefficient was observed as high as 500 W/m^2K and 3200 W/m^2K respectively by Buczek et al.[4]. Present authors have studied the heat transfer during quenching by generating a numerical model [5]. The model is shown in Fig. 1(a) and the isotherms in the work piece of 40 mm square is shown in Fig. 1 (b). High heat transfer coefficients obtained from the simulations are in comparison with the earlier studies [3,4] validating the model. Variation in temperature in the initial quench time results into non-uniform micro-structure in the work piece which eventually lead to non-uniform properties. However, various gas quenching techniques are also used in the industry to obtain uniform microstructures and there by uniform properties in the entire work piece. Paul et al. [7] explored the gas quenching phenomenon and observed an improvements in the cooling rate by using Helium as the quenchant. Thibaud and Udo [8] numerically investigated the flow of air through the quenching chamber with a batch of helical gears for homogeneous quenching rate.

The present investigation, however deals with the heat transfer analysis of a 40 mm Aluminum work piece of square cross-section in various quench mediums viz. air, argon, hydrogen, helium and nitrogen. This analysis is done to predict the best quenchant for an aluminum work piece.

II. NUMERICAL MODEL

Authors have developed the model and used to predict the time temperature data for various sizes and shapes of the aluminum alloy [5]. The domain for simulation consists of a solid surrounded equally by a fluid (Fig. 1(a)). Solid is initially at a temperature of 400 ^oC (673 K) and the surrounding fluid is at 27 ^oC (300 K). Outer surface of the solid is coupled to the inner layer of the fluid domain. The fluid domain outer layer is at atmospheric pressure and temperature conditions. The assumptions and boundary conditions are similar mentioned in the earlier study by the authors [5]. A pressure outlet condition is imposed on the boundaries of the fluid domain. An O-grid mesh is generated with 0.9 quality. Grid independency has been performed comparing the center line temperatures. Conjugate heat transfer is employed by coupling the solid and fluid domains by interface surfaces. Properties of the Aluminum alloy used in the model are given in Table 1 blow. Equation used in the model are given below.

A. **Equations used in the simulations:**

Continuity equation

$\partial\rho/\partial t + \partial(\rho u_i)/\partial x_i=0$ (1)

Energy conservation equation:

$\partial (\rho C_p T)/\partial t +\partial (\rho C_p u_i T)/ \partial x_i= (\partial/\partial x_i)(K(\partial T/\partial x_i))$ (2)

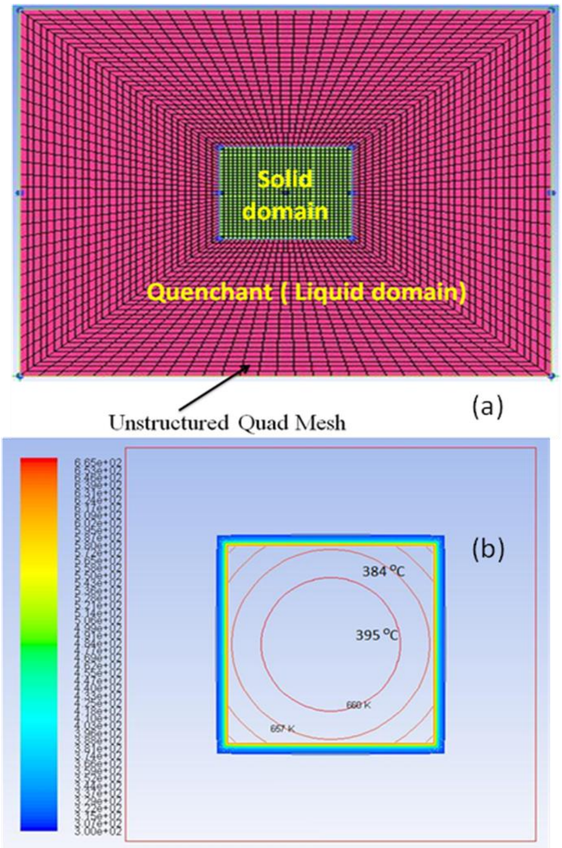

Fig. 1. (a) Enlarged view of the computational domain (b) Isotherms obtained by quenching in water at 0.3 s [5].

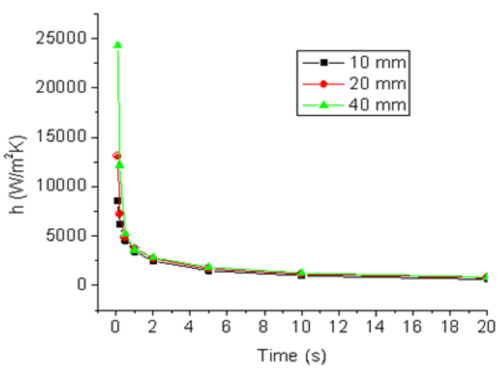

Fig. 2 Heat transfer Coefficient during water quenching [5]

Table1. Properties of Al alloy used in the model

Designation	Parameters	Values
ρ	Density	2719 kgm^{-3}
Cp	Specific heat	871 $Jkg^{-1}K^{-1}$
k	Thermal conductivity	202.4 W/mK

III. RESULTS AND DISCUSSIONS

Fig. 3 (a - e) shows the isotherms in the computational domain obtained for various quenchant mediums Argon, Hydrogen, Helium, Nitrogen and Air respectively at 0.3 s after quenching. The corresponding isotherms when the quenchant is water is shown in Fig. 1(b). The operating conditions of water, air and gases are taken as same i.e at 300 K and atmospheric pressure. Isotherms present at different temperatures in case of water quenching are observed to be absent when the quenching medium is either air or gas. It is clearly evident from Fig. 3(a-e) that the cooling in the work piece is uniform. The temperature in the work piece is deduced from the simulations for every time step (60 s).

Fig. 4 (a) shows the isotherms present in the domain after one hour of quench time for a nitrogen quenchant. It is clearly evident from the figure that the heat diffusion in to the quenchant has increased with time. But the temperature of the work piece is 670 K. A difference of only 3 °C has been achieved after a quench time of one hour. Hence, simulations have been performed for quench time 6 hours. Table 2 gives the temperature of the work piece after 1 hr and after 6 hrs.

Table 2. Temperature of the work piece after 1 and 6 hrs

Quenchant	Temperature (deg. C) after 1 hr	Temperature (deg. C) after 6 hrs	% Reduction in Temperature after 6 hrs
Air	339	326	18.5
Argon	357	347	13.25
Nitrogen	329	326	18.5
Helium	278	275	31.25
Hydrogen	273	271	32.25

Temperature of the work piece has been observed to reduce more with Hydrogen as quenchant. The order of cooling by the gases is Hydrogen; Helium; Nitrogen; Argon and Air for a quench time of one hour. But the effect of the quench gases has changed within 6 hours. It is interesting to observe that the temperature of the work piece quenched in air and nitrogen after 6 hrs is same. Work piece temperature with quenchant as Helium and Hydrogen are also nearly same after 6 hrs.

However, the percentage reduction in work piece temperature is less with Argon as the quenchant. Hydrogen shows the highest reduction in temperature for a quench time of 6 hrs as well as at one hour as discussed earlier.

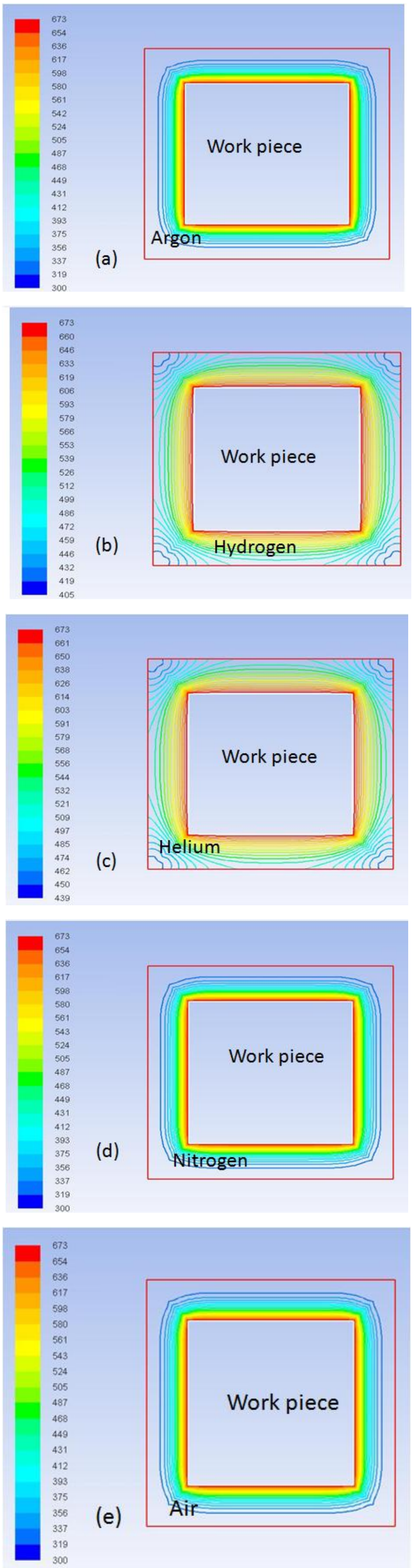

Fig. 3 Isotherms at 0.3 s after quench in (a) Argon (b) Hydrogen (c) Helium (d) Nitrogen and (e) Air.

Fig. 5 shows the time-temperature history of the work piece from one hour to 6 hrs of quench time. It has been observed that reduction in work piece temperature is negligible after 2 hours of quench time. The quench time of one hour has been observed as important to achieve the required micro-structural changes there by the required material properties. There is a large amount of data available about the micro-structure attained by a material at a given quench rate. The time-temperature history obtained from the simulations can be correlated with that data to predict the microstructure attained by the work piece at a given quench time. The analysis can be repeated by changing the solid material properties to obtain the required temperature history for the material - quenchant combination .

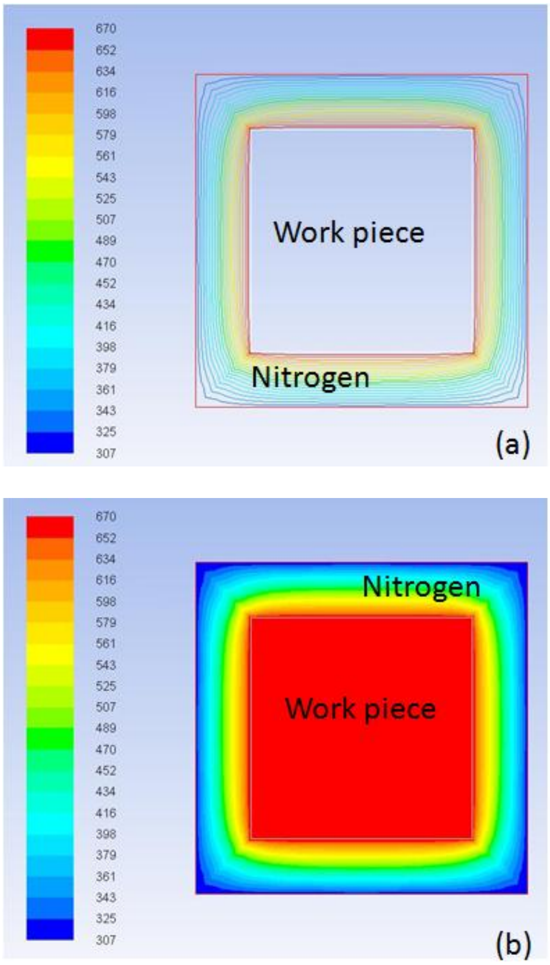

Fig. 4 (a) Isotherms (b) Temperature contours in the domain when the work piece (40 mm) quenched in Nitrogen after 1 hour.

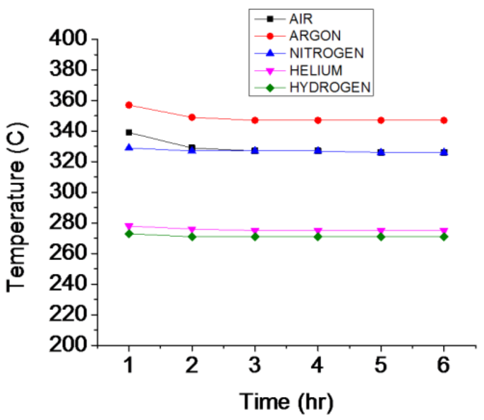

Fig.5 Time-Temperature history of the work piece in various quenchant media.

Paul et al.[6] observed that the heat transfer coefficients for liquid/gas quench medium in vacuum chambers show increase in value for higher pressures. He gas at 20 bar pressure has shown highest heat transfer coefficient of 2700 w/m2K. Hence, the work has been extended to see the effect of pressure/ velocity on temperature of the work piece. Fig. 6 below shows the temperature contours of 40 mm Aluminum work piece at 10 s.

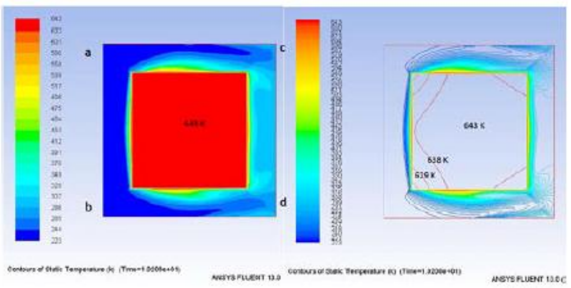

Fig. 6 (a) Temperature contours at 10 s (b) Temperature gradients in the work piece

Simulations are performed using Hydrogen gas entering the domain at ab and leaving at cd. Hydrogen gas at 223 K with a pressure of 20 Pa is sent for cooling. A 30 0C difference in temperature is observed. A small temperature gradient also is observed as the gas is sent from only one direction. This clearly indicates that the gas sent with higher pressures can achieve improved cooling rates than still quenching. The work can further be improved to check the optimum pressure required to achieve the required cooling rates. Experimentation can be avoided and the present numerical model can be employed to predict the required parameter.

IV. CONCLUSIONS

A 2D numerical model is employed to simulate the quenching of Aluminum work piece in air and gases Argon, Nitrogen, Hydrogen and Helium. Conjugate heat transfer has been imposed by coupling the solid and fluid regions with an interface boundary. The conclusions from the analysis are given below:

- Water as quenchant causes rapid cooling and temperature gradient during initial quench time in the work piece.
- Quenching by air or gas helps in obtaining uniform temperature distribution there by uniform material properties.
- Hydrogen quenching gives higher cooling rate during the initial one hour of the quench time.
- The order of decrease in cooling rate obtained with gas quenching for an aluminum work piece is is Hydrogen; Helium; Nitrogen; Argon and Air.
- % reduction of the work piece temperature after 6 hrs of quench time is same for air and nitrogen. Hydrogen and helium also show nearly equal % reduction where as argon shows lowest cooling rate.
- Hydrogen or helium can be used for an effective gas quenching of an aluminum work piece.
- As the analysis is done for still quenching, better cooling rates can be obtained when the gas is sent at higher pressures.
- Gas at lower temperatures and higher pressures can improve the cooling rates and obtain the uniform cooling throughout the work piece.

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