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ESTIMATION OF RESIDUAL STRESS IN CYLINDER HEAD

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ABSTRACT−Residual stresses are introduced in aluminum cylinder head during quenching at the end of the T6 heat treatment process. Tensile residual stress resulted from quenching is detrimental to fatigue behavior of a cylinder head when it is overlapped with stresses of engine operation load. Quenching simulation has been performed to assess the distribution of residual stress in the cylinder head. Analysis revealed that in-homogeneous temperature distribution led to high tensile residual stress at the foot of the long intake port, where high stresses of engine operation load are expected. Measurements of residual stress have been followed and compared with the calculated results. Results successfully proved that high tensile residual stress, which was large enough to accelerate fatigue failure of the cylinder head, are formed during quenching process at the end of heat treatment at the same critical position. Effect of quenching parameters on the distribution of residual stress in cylinder head has been investigated by choosing different combination of heat treatment parameters. It was demonstrated that changes of quenching parameters led to more homogeneous temperature distribution during cooling and could reduce tensile residual stress at the critical region of the cylinder head used in this study.

KEY WORDS : Residual stress, Cylinder head, Quenching, Heat treatment, Quenching parameter

1. INTRODUCTION

Due to the emission regulation and effective fuel consumption, HSDI(high speed direct injection) diesel engines with common rail systems are prevail in the market (Monaghan, 2000). Because HSDI diesel cylinder heads are loaded at the maximum ignition pressure of up to 160 bar, high cycle fatigue cracks occur frequently. High cycle fatigue cracks in the water jacket area can be predicted by using adequate CAE methods, in which only operating load conditions are considered (Kim and Chang, 2003; Steiner *et al.*, 2001). Since the properties of cylinder heads are influenced by their complete thermal and mechanical history, however, preloading conditions representing the manufacturing process as well as operating load condition must be considered.

Residual stress is introduced in mechanical components during manufacturing processes. The manufacturing process for aluminum cylinder heads is composed of casting and heat treatment. A typical heat treatment process for cylinder heads includes the three steps: solution heat treatment, quenching and aging. Since the part is heated up to only a few degrees below solidus temperature in the solution heat treatment, it can be assumed that residual stress caused by the casting process is all released after solution heat treatment (Maassen, 2001). Following quenching process, which is necessary to prevent the diffusion of the solute elements to the grain boundary in the cylinder heads, cools cylinder heads in-homogeneously and introduces high residual stress in the parts. The residual stress formed during the quenching process is only slightly reduced by the aging process (Gundlach, 1994). Taking residual stress into account will change the value of the mean stress and influence the fatigue life of the mechanical component (Gong *et al.*, 2001). Generally, tensile stress is detrimental to the component, while compressive one improves the fatigue behavior of materials.

A large number of studies have been performed on the mechanisms for formation of the residual stress during quenching process and the numerical analysis of the residual stress during quenching process has been well understood (Todinov, 1998; 1999; Boley and Weiner, 1960; Fletcher, 1989). Although relatively large number of work has been done on the residual stress in the mechanical components, there are only a few works related to the formation of residual stress in cylinder head during quenching process. Auburtin (Auburtin and

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Morin, 2003) carried out numerical approach for the heat treatment of cylinder head and Maassen (2001) demonstrated that tensile residual stress formed inside water jacket during quenching process could reduce fatigue life of cylinder head by performing numerical analysis.

In the present study, residual stress formed in cylinder head during quenching process is assessed by analysis and experimental measurements were performed to estimate the magnitude of the residual stress in cylinder head. Modifications of quenching process parameters are also investigated to affect the size of the tensile residual stress at the critical area in the cylinder heads used in this study.

2. QUENCHING SIMULATION

The quenching process of T6 heat treatment for aluminum cylinder head was simulated under the following assumptions.

- All residual stress caused by the casting process is released after solution heat treatment.
- Aging process is ignored.

During quenching process after solution heat treatment, sudden changes of temperature field occur in cylinder head. Calculations of the residual stress during quenching process without phase transformation are comprehensively studied (Boley and Weiner, 1960; Fletcher, 1989). The thermal strain caused by temperature differences can be found from coefficient of thermal expansion as following equation,

$$\varepsilon^{th} = \alpha \cdot \Delta T \tag{1}$$

where α is coefficient of thermal expansion. Determination of temperature distribution during quenching is governed by the Fourier's heat conduction equation,

$$\frac{\partial}{\partial x_1}\left(k\frac{\partial T}{\partial x_1}\right)+\frac{\partial}{\partial x_2}\left(k\frac{\partial T}{\partial x_2}\right)+\frac{\partial}{\partial x_3}\left(k\frac{\partial T}{\partial x_3}\right)=\rho c\frac{\partial T}{\partial t} \tag{2}$$

where k, ρ, c are the thermal conductivity, density and specific heat, respectively (Bonollo and Odorizzi, 2001). This governing differential equation can be solved using finite control volume method (Hattel *et al.*, 1998). The geometry of the un-machined diesel cylinder head was imported and enmeshed with finite control volumes. The commercial MAGMASOFT® code was used to simulate the process.

In order to calculate the temperature field during quenching, the following process parameters were applied.

- Furnace temperature for solution heat treatment: 535°C
- Temperature of the quenchant (water): 60°C

The cooling condition at outer and inner boundaries of the cylinder head were simulated by applying different, temperature dependent heat transfer coefficients, individually (Figure 1). The core, defined as a heat sink with an extremely high heat capacity, was created for the definition of inner boundary and temperature dependent heat transfer coefficient was applied between cylinder head and core (Figure 2). In order to determine heat transfer coefficients, experiments were performed to record temperature histories at several locations by embedded thermocouples during quenching process. With the initial temperature dependent heat transfer coefficients, time histories of temperatures in cylinder head were simulated and compared with time histories of temperatures measured by thermocouples. Optimization of heat transfer coefficients was performed until the simulated time histories of temperatures match the measured ones.

For the calculation of residual stresses the calculated temperatures were applied as an external load on the elements. Because yielding occurs much easily at high temperature, thermal contraction of the rapid cooling region leads to plastic deformation at high temperature state. Elastic stress in slow cooling region is eliminated

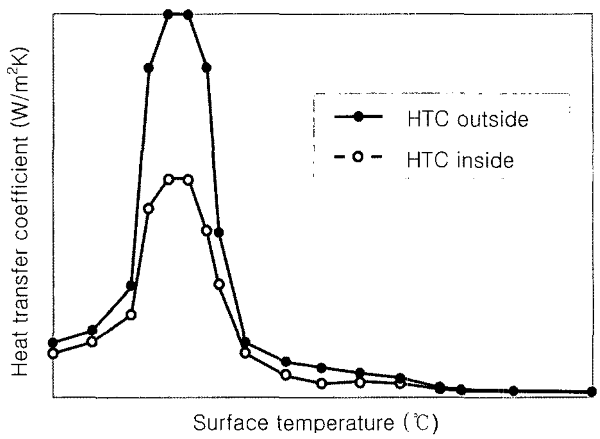

Figure 1. Definitions of heat transfer coefficients for inner and outer boundaries of cylinder head.

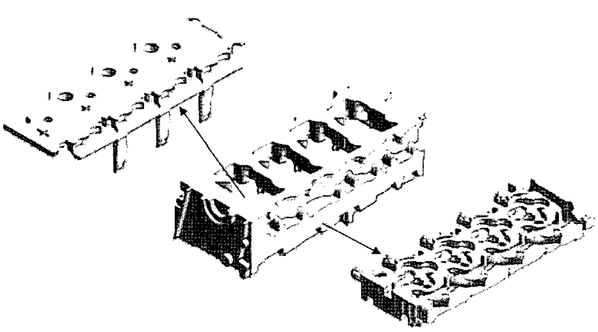

Figure 2. Cores created for the definition of inner area of cylinder head.

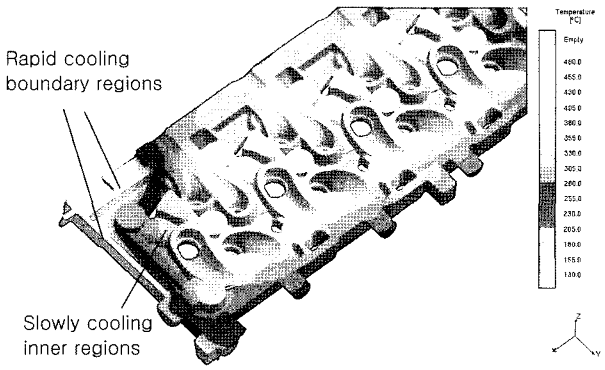

Figure 3. Temperature distributions of cylinder head after 30 seconds of quenching.

with further cooling, but contraction is hindered by rapid cooling region, in which permanent deformation occurred by yielding. Therefore, compressive residual stress is developed in the rapid cooling region and tensile residual stress is in the slow cooling region at room temperature state. Temperature distribution after 30 seconds shows that the regions such as the foot of the long intake port, where materials are aggregated densely, are cooled slowly (Figure 3). This in-homogeneous temperature distribution leads to high tensile residual stress at the foot of the long intake port. Figure 4 shows the maximum principal residual stress distribution and its direction after cooling. The calculated residual stress at the foot of the long intake port indicated level of 130 MPa in tension. This level of tensile residual stress is large enough to accelerate fatigue failure of the cylinder head.

3. MEASUREMENT OF RESIDUAL STRESS

Dissection method has been used to measure the residual stress in cylinder heads. Since the access to water jacket area of cylinder head is limited, an opening, through which installations of gage and wire could be made, was necessary. A practicably small window was cut at the front of the cylinder head (Figure 5(a)). Knowing the direction of the maximum principal residual stress from simulation, a strain gage was aligned in the direction of maximum principal residual stress. Figure 5(b) shows the strain gage attached at the foot of the long intake port.

A large part of cylinder head were cut by sawing, and then succeeding removal of the part was performed until the small parent part with the strain gage was remained (Figure 6). The surface area of the specimen at the final cutting was arranged small that the strain on the surface becomes precise measurement of residual deformation. Careful consideration of the cutting position was given to fulfill St. Venants' condition so that the machining stresses at the edge might be neglected (SAE Information

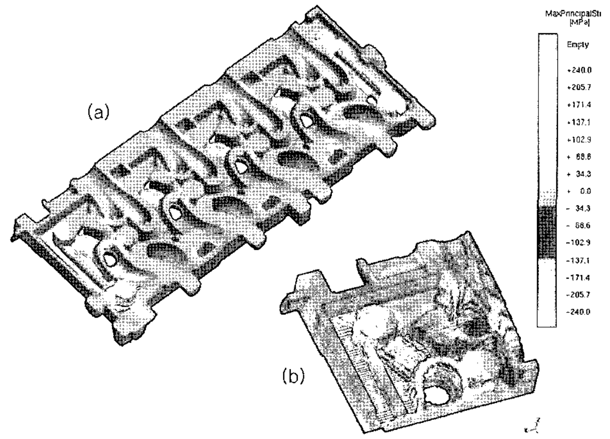

Figure 4. Distribution of maximum principal residual stress: (a) contour; (b) arrow plot.

Report, 1965). Initial reading of the strain gage before parting out was recorded to obtain the reference value of the strain and the final reading was obtained when the cylinder head was reduced to its final dimension. From these values, the residual stress, the parting-out stress, was obtained in the specimen using Hooke's law,

$$\sigma = E\varepsilon \tag{3}$$

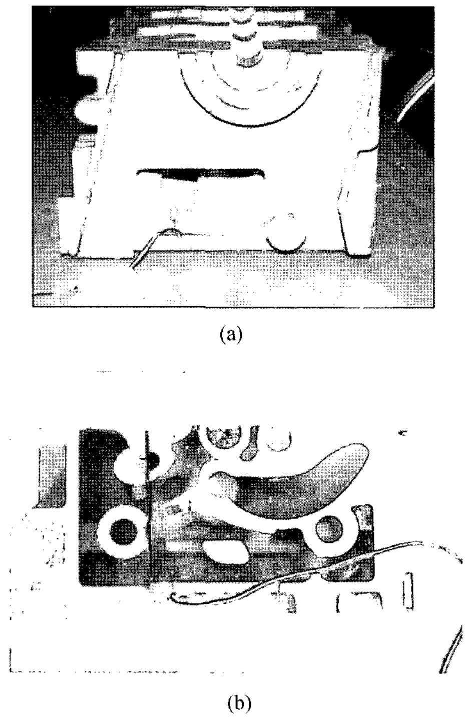

Figure 5. Installation of strain gage in cylinder head: (a) an opening made for installation of strain gage; (b) strain gage attached at the foot of the long intake port.

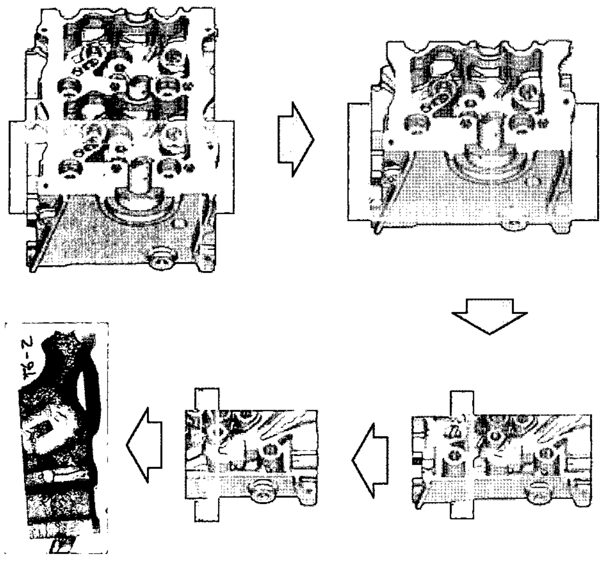

Figure 6. Parting out procedure for measurement of residual stress.

where E is Young's modulus of aluminum (70 GPa) and ε is measured strain.

Figure 7 demonstrates the residual stresses resulted from heat treatment. Specimens with heat treatment revealed significantly high tensile residual stress at the foot of the long intake port, while specimens without heat treatment showed marginal level of residual stress. The results show, therefore, it is appropriate to assume that residual stress resulted from the casting process is released after solution heat treatment and quenching introduces new residual stress distribution. The residual stresses were 80–91.3 MPa in tension at the surface where strain gage was attached. The measured values showed differences from the calculated, but fitted in the same range of the calculated data. The differences between the calculated values and measured ones are mainly due to the rough divisions of surfaces in cylinder head for different temperature dependent heat transfer coefficients, since rough divisions neglect differences in cooling within the same division. The calculated values would be closer to the measured ones if more divisions of surfaces in cylinder head were made. Other reasons for the differences between the calculated values and measured ones could be found in the measurement procedures. Residual stresses could be underestimated during measurements because parting out process could not be performed close enough to the strain gauge due to the geometric complexity. Cutting out procedure for the installation of gauge in the beginning also could affect the values of residual stresses at the measured location.

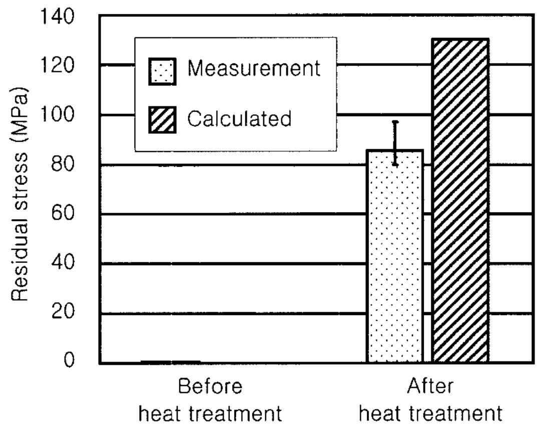

Figure 7. Results of residual stress at the foot of long intake port.

Test results prove that high tensile residual stresses exist at the same location that analysis predicted. Therefore, it can be assured that the heat treatment process can be adequately simulated with the analysis, even though quantitative predictions are limited.

4. EFFECT OF QUENCHING PARAMETERS

The reason for the high tensile residual stress at the gage position is the rapid cooling of the boundary in the first cylinder. In order to reduce residual stress at the gage location, where high stresses of engine operation load are also expected, different combinations of heat treatment parameters are investigated.

- Decrease in temperature of solution heat treatment: 535°C → 520°C
- Increase in temperature of quenchant: 60°C → 90°C
- Change of quenching direction
- Intelligent positioning of the cylinder heads

Figure 8 shows arrangement of cylinder heads in the heat treatment process. Intake side of the cylinder head is positioned downward so that slow cooling region inside water jacket can get better cooling (Figure 8(a)). Front side of cylinder head stands closely to the next cylinder head to reduce the temperature gradient at the fast cooling region (Figure 8(b)).

In analysis with new parameters, the quenching direction is modeled by modifying the temperature dependent heat transfer coefficients. For the definition of quenching direction and positioning of the cylinder heads, two additional cores were defined (Figure 9). For the heat transfer coefficients between cylinder head and the cores of the intake side, the temperature dependent increase is extended to higher temperatures (Figure 10). This leads to an earlier cooling of the intake side. The heat transfer coefficient of the front side is changed to heat transfer coefficient of inside. The other heat transfer coefficients remain unchanged.

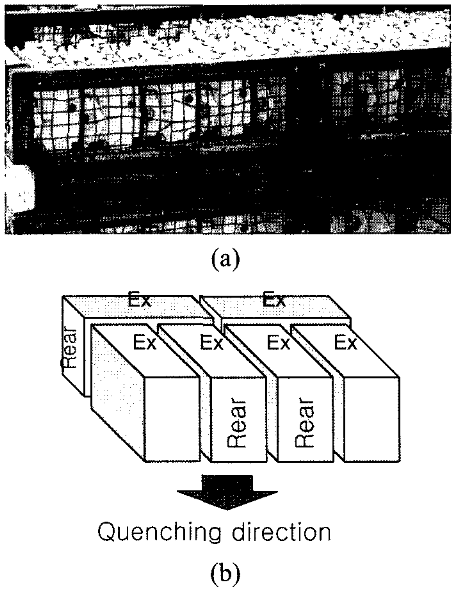

Figure 8. Arrangement of cylinder heads in the heat tre intelligent positioning of cylinder heads.

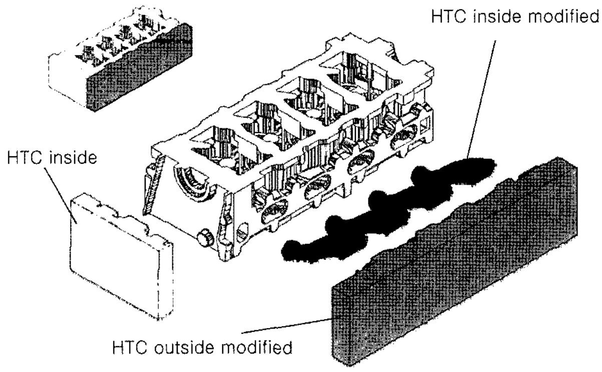

Figure 9. Additional definitions of cores for modified quenching parameters.

Analysis with new parameters showed that increased cooling of the intake side led to much more homogeneous temperature distribution during cooling. The decrease of temperature gradient between inner and outer areas produced much lower residual stress at the foot of the long intake port. Calculation showed that the maximum principal residual stress at the foot of the long intake port was decreased to 36 MPa.

Residual stress measurements were performed on cylinder heads with new heat treatment parameters. Test results indicated significant reduction of tensile residual stresses at the gage location as predicted by analysis. The measured stresses were 14–23 MPa in tension and this reduction of tensile residual stress will be effective to increase fatigue life of the cylinder head (Figure 11).

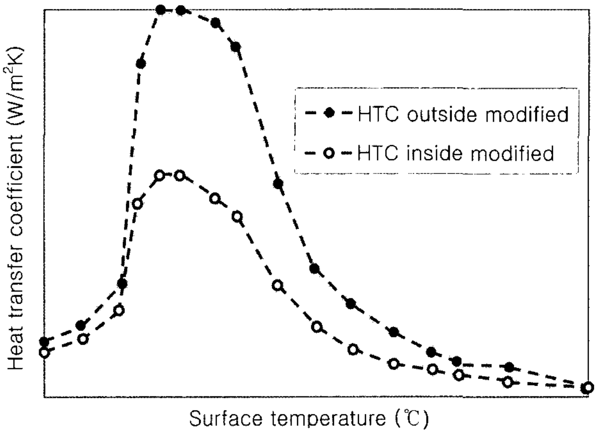

Figure 10. Definitions of heat transfer coefficients for the modified quenching parameters.

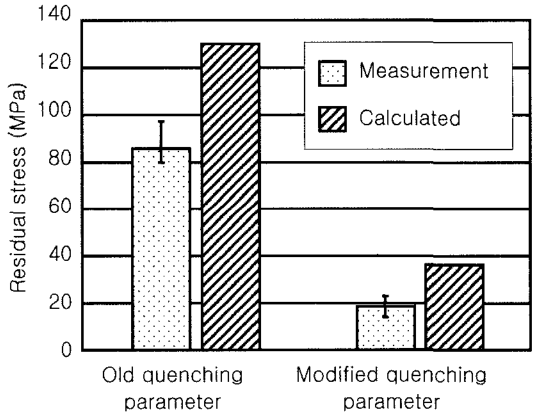

Figure 11. Reduction of tensile residual stress at the gage location with modified quenching parameters.

5. CONCLUSIONS

Quenching simulation of the heat treatment in the cylinder head manufacturing process was performed. Parameters of quenching process were carefully selected to represent current manufacturing process. Results of analysis suggest that high tensile residual stress is present in the region where slow cooling is expected during quenching process. Following measurements of residual stress at the equivalent location confirm the formation of high tensile residual stress at the foot of long intake port during heat treatment. Both simulation and measurement indicate that the residual stress at the gage location is large enough to reduce fatigue life of cylinder head when overlapped with stresses of engine operation load.

Change of quenching parameter has the effect on the distribution of residual stress in cylinder head. Combination of decrease in temperature of solution treatment, increase in temperature of the quenchant and change of cylinder head position in quenching process are expected to reduce residual stress significantly by analysis. Measured data of residual stresses in the cylinder heads, which are heat treated with new quenching parameters, agree qualitatively with analysis.

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