The influence of phase transformation hardening on continuous laser processing of notches for fracture splitting of a C70S6 connecting rod

S Q Kou, Y Gao\(^1\) and Z Shi
Roll Forging Research Institute, Jilin University, Changchun 130022, China

Email: Gaoyan_ly@126.com

Abstract. The dynamic process of local material microstructure and hardness of continuous laser grooving for fracture splitting of a C70S6 connecting rod was studied. According to the phase transformation characteristics of C70S6 steel during laser processing, the coupling calculation between the transient temperature field and phase transformation process of continuous laser grooving was carried out, and then the phase transformation process and phase compositions in the heat affected zone (HAZ) was obtained. The research results showed that the HAZ was composed of martensite and pearlite as well as residual austenite after continuous laser grooving, and the generation of the martensite in the HAZ is beneficial to the subsequent splitting process; meanwhile, the hardening effect of continuous laser grooving is remarkable on the HAZ, and the requirement for the cutting tool and technique used at the subsequent machining process for the fine boring of the big end hole should be higher.

1. Introduction
The advanced fracture splitting technology for the splitting parts such as engine connecting rod has developed rapidly in recent years with high-precision, high-quality, high-efficiency, low-cost and other significant advantages. The principle of fracture splitting process is that the initial fracture source with a certain geometry size, which is the fracture splitting notch, is processed at the predetermined splitting position, then normal stress perpendicular to predetermined fracture surface is applied, and the parts was separated by brittle fracture along the initial fracture source under the condition that there is almost no plastic deformation. The principal means for pre-processing a fracture splitting notch includes laser cutting, wire-electrode cutting and mechanical cutting. Among these cutting techniques, laser grooving has many advantages such as high heating and cooling speed, no tool wear, narrow heat affected zone and others, and it has developed rapidly in grooving for fracture splitting. At present, Nd:YAG pulsed laser grooving for fracture splitting has been widely concerned and applied [1-3], but pulse laser grooving is a repetitive process of laser drilling, fracture splitting notch is actually made up of a series of blind holes, the blind holes distribution is influenced by the laser and processing parameters and then affects the quality of the subsequent splitting process. Therefore, the quality control of pulsed laser grooving is quite complicated. Continuous Nd:YAG laser is one of the lasers used commonly in the industry. The phase transformation hardening generated during laser processing has a great effect on the subsequent splitting and machining process, meanwhile, the sharp and complex changes of the temperature and phase transformation during grooving, which is limited by the material factors and processing factors, are difficult to measure by the experimental method. Therefore, the numerical simulation of continuous laser grooving for fracture splitting of a C70S6
connecting rod was studied in this research, and the coupling calculation between the three-dimensional transient temperature field and phase transformation process was carried out with SYSWELD which has been applied in the other processing fields except for the welding [4, 5]. The influence of the microstructure and hardness in the HAZ around the fracture splitting notch on the quality of the subsequent splitting process was analyzed, and then the feasibility of the new laser source used in the fracture splitting production of connecting rod was explored for evaluating and optimizing the continuous laser grooving technique for fracture splitting.

2. Theoretical basis
Continuous laser grooving is a complexly physical interaction process between laser and materials, and it is a thermal cutting technology for the processing purpose that fracture splitting notch is obtained with required dimension at the appropriate location of the workpiece.

2.1. Heat conduction equation of continuous laser grooving for fracture splitting
Heat conduction differential equation of three dimensional transient temperature field of continuous laser grooving in the coordinate system is shown as follows:

\[ \rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} (k \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (k \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z} (k \frac{\partial T}{\partial z}) + Q \]  

(1)

Where \( T \) is temperature which is a function of coordinates and time; \( k \) is the material thermal conductivity; \( \rho \) is the material density; \( c \) is the material specific heat; \( Q \) is the intensity of internal heat source; \( t \) is time for heat transfer.

2.2. Phase transformation theory in continuous laser grooving
Material microstructures and properties around fracture splitting notch could affect the fracture mode, the splitting force and the quality of fracture splitting processing; moreover, they could be predicted by analyzing the phase transformation in the heating stage and cooling stage of continuous laser grooving.

2.2.1. Characteristics of phase transformation in continuous laser grooving and related assumptions
During the continuous laser grooving, phase transformation could inevitably occur due to the rapid increase and decrease of material temperature. The phase transformation process during laser grooving is very similar with the one during quenching; materials would undergo the heating and cooling process accompanied by the transformation from the material microstructures at room temperature into the austenite and martensite. But because the speed of heating and cooling is very high during continuous laser grooving, the evolution of material phase transformation becomes very complex.

C70S6 steel is the typical materials in the fracture splitting connecting rod. Based on the phase transformation characteristic of C70S6 steel and the actual situation of laser grooving, the following hypotheses can be made for the phase transformation research: (1) the original microstructures of C70S6 steel is pearlite at room temperature, and therefore a portion of material microstructures at room temperature could be transformed into austenite; (2) the material temperature must be higher than the critical austenite transformation temperature in the heating stage; (3) the cooling speed of austenite must be over a certain critical value in the cooling stage; (4) the austenite must be cooled below the critical martensite transformation temperature which is namely \( M_s \).

2.2.2. The calculation of phase transformation amount
There is diffusive phase transformation and non-diffusive phase transformation in the whole process of continuous laser grooving for fracture splitting, the transformation from pearlite into austenite belongs to the diffusive type, and the transformation from austenite into martensite belongs to the non-diffusive type.

For the diffusive phase transformation, the relationship between the phase transformation amount and isothermal transformation is described in Avrami equation [6], as is shown in equation (2).
\[ V = 1 - \exp(-Bt^n) \]  
\[ (2) \]

Where \( V \) is transformation amount; \( t \) is isothermal time; \( B \) and \( n \) are the dynamic parameters related to temperature, material composition and austenitizing coefficient.

For non-diffusive phase transformation, Koistinen and Marburger empirical formulas provide the basis for describing transformation from austenite into martensite [7], as is shown in equation (3).

\[ V = 1 - \exp[\alpha(M_S - T)] \]  
\[ (3) \]

Where \( V \) is the transformation amount; \( M_S \) is the martensite transformation temperature; \( T \) is the instantaneous temperature; \( \alpha \) is the parameter which reflects the speed of martensite phase transformation, and \( \alpha \) for steel is set to 0.011 in general.

3. Finite element modeling

The outer contour curve of engine connecting rod is more complex and the fracture splitting notch is located at the inside of the crankshaft hole of the connecting rod big end, as is shown in Figure 1(a). Based on the symmetry of the crankshaft hole, the laser heat source and the fracture splitting notch, the connecting rod big end was simplified to be a rectangle for simplifying the calculation and half of the rectangle along the symmetrical plane of the fracture splitting notch was selected for modeling, as is shown in Figure 1(b).

Temperature varies rapidly during continuous laser grooving. Therefore, the changes of material thermophysical parameters with temperature should be considered in the calculation. But for C70S6 steel, its physical properties at high temperature are quite difficult to measure accurately due to the limitation of experimental conditions and the lack of critical data, and the non-linear processing of connecting rod material properties is a difficult issue for the numerical simulation. In this research, the thermophysical parameters of 70 steel whose carbon content is similar to that of C70S6 steel was used for numerical calculation. In addition, martensite transformation temperature of steel C70S6 was 271°C based on the calculation formula of martensite transformation temperature for the pure austenitizing materials [8].

For laser grooving for fracture splitting, the required ratio of depth to width of fracture splitting notch is larger, which shows that heat flow of laser heat source imposes great influence in the thickness direction of the workpiece; therefore, 3D gauss conical heat source model was used in numerical computation. The mathematical expression of 3D gauss conical heat source is shown as follows.

\[ q(r,z) = \frac{9\pi Pe^3}{\pi H(e^3 - 1)(e^3 + r_0^2 + r_1^2)} \exp\left(-\frac{3r_0^2}{r_0^2}\right) \]  
\[ (4) \]

\[ r_0(z) = r_e - (r_e - r_i)(z_e - z)/(z_e - z_i) \]  
\[ (5) \]

Where \( r_e \) and \( r_i \) is heat flux distribution radius of the upper and lower surfaces of heat source.
respectively; \(z_u\) and \(z_l\) is \(z\) coordinate of the upper and lower surfaces of heat source respectively; \(r_0\) is the heat flux distribution radius on the plane of \(z\) coordinate; \(P\) is laser output power; \(\eta\), which is affected only by the laser and the material surface status in this research, is effective power coefficient; \(H\) is the heat source depth.

In order to guarantee the authenticity and accuracy of the numerical computation, the laser heat source model was checked by means of the heat checking function in SYSWELD software and the experiment result of continuous laser grooving of engine crankcase bearing block [9]. L3020 continuous laser numeric control machine of TRUMP Laser GmbH + Co.KG Company was used in the experiment. The output power \((P)\) was 1kW, the cutting speed \((v)\) was 25mm/s and the defocusing amount \((\Delta f)\) was 0mm. The notch width was 0.522mm and the notch depth was 1.06mm. Under the condition of the same parameters, the simulation of continuous laser grooving was carried out, the temperature field result is shown in Figure 2, and the effective absorption rate of materials for laser energy was set to 0.5.

![Figure 2. The simulation result of continuous laser grooving.](image)

4. Phase transformation analysis

When the output power \((P)\) is 400W, the cutting speed \((v)\) is 30mm/s, the spot radius \((r)\) is 0.06mm and the \(\Delta f\) is 0mm, the temperature distribution of continuous laser grooving is shown in Figure 3. Continuous laser grooving is a physical process which contains laser melting material or even gasifying material, and high-speed airflow blowing the molten material. Therefore, the isotherm of material melting-point temperature can be as the notch contour line to calculate the dimension of fracture splitting notch, and the notch depth was 0.64mm. The notch depth under the above condition meets the required depth range from 0.45mm-0.7mm in practical production, and then the phase transformation process under the condition of the same parameter combinations was analyzed.

![Figure 3. The dimension of the fracture splitting notch.](image)
In the subsequent splitting process, fracture started at the root of fracture splitting notch. Therefore, this research focused on the phase transformation process and the final phase composition in the HAZ of the notch root. Due to the fact that the notch depth was 0.64mm, point E shown in Figure 4 was selected on the cross section where is 1mm away from the fracture splitting notch starting position, the $z$ coordinate of point E is -0.66mm, and the phase transformation process at point E during grooving was analyzed.

![Figure 4. The cross section of fracture splitting notch.](image)

During continuous laser grooving, the relationship curve of the content of each phase composition with temperature at point E is shown in Figure 5. When time is close to 0.02s, temperature begins to rise rapidly. When laser processing time is 0.021s, temperature rises to about 750º C and reaches the critical austenite transformation temperature (Ac1), then pearlite begins to transform into austenite. When time is close to 0.025s, temperature reaches the highest value.

![Figure 5. The relationship between the temperature and phase transformation of point E.](image)

Afterwards, temperature at point E begins to decrease rapidly, when temperature is lower than the Ac1, pearlite stops transforming into austenite. Meanwhile, still 42% of pearlite does not transform into austenite, the main reason for which is that temperature changes quickly, the residence time at
high temperature is too short, and a part of the pearlite cannot transform into austenite in time. Then, temperature at point E continues to decrease, when laser processing time is 0.052s, temperature decreases to 270°C or so, namely Ms. In addition, it can be seen that the cooling speed at point E is very high in the temperature curve. Therefore, the requirements for the transformation temperature and cooling speed of martensite phase transformation are met, and martensite phase transformation would happen at point E. Subsequently, austenite transforms into martensite constantly until time is 0.25s, namely when temperature is below 100°C, the martensite phase transformation is basically completed, and the martensite content is no longer increased. Finally, there is still a small amount of retained austenite in the region of point E. The ultimate phase compositions at point E are described as follows: martensite accounts for 52%, pearlite accounts for 42% and retained austenite accounts for 6%, which show that the solid-state phase transformation zone consists of a large number of pearlite and martensite as well as a small amount of residual austenite after laser grooving.

The above-mentioned microstructures in the HAZ kept consistent with the expected results in application. The generation of martensite, with which material plasticity is decreased and brittleness is increased, is beneficial to brittle fracture in fracture splitting processing. And then splitting force is reduced effectively, plastic deformation during fracture splitting processing is decreased, and fracture defects are reduced, which is also the main reason why laser grooving replaced mechanical broaching and wire cutting. Moreover, microstructures in the HAZ would be removed in the finish-boring of the big end hole of connecting rod subsequently, which can ensure the requirement of microstructures and properties in the final product of connecting rod.

5. Hardness distribution

The hardness and martensite distribution around the notch is shown in Figure 6 after the continuous laser grooving is completed. It can be seen that the material hardness from the notch to the base metal trends to decrease, which shows that the materials hardness in the HAZ has been improved significantly after grooving. The main reason is that the hardness is directly related to the final phase composition when the material chemical composition remains the same. The martensite leads to the material hardness increase, the hardness decreased with the martensite content from the notch surface to the base metal, and the base metal hardness is not affected due to the fact that laser energy has little effect on the matrix microstructure.

![Figure 6. The hardness and martensite distribution.](image)

The hardness distribution along the depth direction of CD line in Figure 1(b) is investigated, and the hardness curve at the CD line is shown in Figure 7. The corresponding material hardness decreases sharply from 680HV to the base metal hardness when the Z coordinate decreases from -0.64mm to -0.70mm, materials hardness at the point E is about 560HV, and the matrix hardness remains the same.
6. Discussions
Based on the above analysis, the cutting position could be hardened locally by continuous laser, the generation of the martensite in the HAZ increases the material yield strength and reduces the fracture toughness KIC, which makes brittle fracture easier to implement for decreasing the cracking strength and reducing the cracking defects effectively. However, it should be noted that the hardening effect of continuous laser grooving is remarkable for the high carbon micro-alloy non-quenched and tempered forged steel C70S6 of connecting rod material for fracture splitting, materials hardness in the HAZ is larger than the doubled matrix hardness after grooving. After the connecting rod is separated and the bolts are assembled, the fine boring of the big end hole would be done. Therefore, the requirement for the cutting tool and technique used at the subsequent machining process is higher. The tool cuts from the base metal with lower hardness to the narrow high hardness zone at a certain speed, the cutting edge of cutting tool will remain under the impact force, then the “Cutter breakage” or “Cutter relieving” phenomenon could appear easily and the wear of cutting tool becomes severe. The cutting tool with higher hardness should be chosen in subsequent processing, and the problem, such as the size of the feed rate and spindle rotating speed, should be taken into account in the machining process.

7. Conclusions
In this paper, continuous laser was used in grooving for fracture splitting of a C70S6 connecting rod, the phase transformation process during grooving and the hardening effect was studied. Based on the actual physical process of laser processing, the coupling analysis between the three-dimensional transient temperature field and phase transformation process of continuous laser grooving for fracture splitting was carried out, and then the phase transformation process and phase compositions in the HAZ was obtained. The HAZ was constituted by pearlite, martensite and retained austenite after continuous laser grooving; the generation of the martensite in the HAZ is beneficial to the subsequent fracture splitting processing. The hardening effect of continuous laser grooving is remarkable for the HAZ of the fracture splitting notch, and the material hardness in the HAZ can be up to 680HV, which increases the difficulty of the subsequent machining and the requirement for the cutting tool.

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