Fatigue Analysis of Ladle Shell and Prediction of Lining Thickness

Lichuan Ning1,2, Yuanmin Xie1,2 and Ruyi Ma1,2,a
1 Hubei Key Laboratory of Mechanical Transmission and Manufacturing Engineering, Wuhan University of Science and Technology, Wuhan, China
2 Key Laboratory of Metallurgical Equipment and Control Technology Ministry of Education, Wuhan University of Science and Technology, Wuhan, China
a982463279@qq.com

Abstract. The fatigue analysis of steel cladding and prediction method of lining thickness have been studied. The traditional empirical estimates and operational adjustments are not accurate enough. The finite element strength analysis and fatigue analysis of ladle cladding are carried out. A prediction model for the thickness of ladle lining is established. A BP neural network life prediction model is proposed. Then the model is used to solve the problem. The service life of ladle lining is predicted. The actual use of ladle lining is more accurately understood. The service life of ladle lining is increased and the service life of ladle is prolonged.

1. Introduction
The longevity performance of ladle has always been a hot topic for research scholars and the research work has also done a lot. The service life of the ladle is mainly composed of two aspects, which includes the service life of ladle lining and the service life of ladle. Due to the long service life of the steel cladding, the general life of the steel cladding is about 20-30 years. Therefore, the main service life of the ladle is mainly related to the service life of the ladle lining. Although the steel cladding has a long service life, it is still necessary to study the steel cladding and analyze it to extend the life of the cladding of the ladle. The current research work, the calculation of the service life of the ladle lining is still based on empirical estimation and operational adjustment and the actual use of ladle lining can not be understood accurately. Therefore, it is urgent to find a prediction model to predict the service life of the ladle lining. The actual use of the lining of the ladle can be understood accurately. It is no longer the traditional experience of estimating and adjusting operation to barely predict the life of ladle lining. The service life of the lining of the ladle can be improved greatly.

2. Fatigue analysis of steel cladding
A common cause of structural failure is fatigue, which can lead to damage associated with repeated loading, such as gears that rotate for long periods of time, impellers, and the like. An object is subject to varying degrees of fatigue damage under long-term service conditions and complex conditions. What may happen if the fatigue damage is small is that the part is damaged. In the case of severe fatigue damage, an accident may occur, which may cause the safety of life and property. In order to study the expected fatigue of the part at the design stage, the fatigue analysis of the part is analyzed by finite element method and material mechanics.
The fatigue test is carried out by using a conventional ladle. Under a given external force ratio $A$, different stresses $S$ are applied, fatigue tests are performed, and the corresponding life $N$ is recorded. The S-N curve is shown in Figure 1 below.

![Figure 1. S-N Curve](image)

As can be seen from Figure 1, the life is reduced as the stress increases with a certain stress ratio.

2.1. Damage tolerance method

The damage tolerance method is mainly based on the theory of fracture mechanics, and its fracture formula is used. The premise is that the part has a small crack at the beginning. Due to the complexity of the fatigue phenomenon, many scholars have proposed fatigue analysis methods such as energy method and stress field strength method based on a large number of experiments. Figure 2 shows a flow chart of the part fatigue analysis.

![Figure 2. Life analysis flow chart](image)

It can be seen from the block diagram shown in Figure 2 that corresponding ladle situation needs to be found when the stress condition of the parts is analyzed. It is necessary to find the combined force of the self-gravity and the external pulling force of the ladle. The position where the maximum and minimum stress of the ladle stress and the stress are concentrated, and the analysis of the stress and strain at the weakest part of the ladle structure is the basis for fatigue analysis. However, because the parts in actual life are different, there are simple and complicated, and the results calculated by the approximate formula of the literature are quite different from the values of empirical theoretical values and common sense of life.

Metal fatigue damage can be divided into three stages: Micro crack growth stage; Macro crack growth stage; Instantaneous fracture stage.

The maximum stress of the steel cladding occurs at the root of the trunnion. Since the fatigue life of the steel cladding is not infinite life, it can be converted according to formula (1):

$$ N = N_0 / K^m $$

(1)

The values of $K$ and $N_0, m$ can be found in the mechanical design manual. Finally, the minimum life of the ladle can be calculated by formula (1):
In summary, based on the fatigue analysis of the steel cladding, it can be found that the life of the steel cladding can be used for several decades. The key research of the life analysis of the ladle is the life study of the ladle lining, and the study between the lining and the life of the ladle. The law of mutual influence, which has an important guiding role in the prediction of the life of the ladle.

2.2. Fatigue analysis of ladle based on finite element
Fatigue analysis was performed in the Workbench based on the results of the ladle thermal stress analysis. The results of the thermal stress analysis of the ladle are loaded into the fatigue analysis as a boundary condition, then the result analysis is added, and finally the analysis is performed.

The Life contour shows the number of cycles due to fatigue until failure. The BiaxialityIndication stress biaxial contour is used to determine the local stress state, and the biaxial indication is the ratio of the smaller to the larger principal stress. Therefore, the local area of the uniaxial stress has a B value of 0, a pure shear of -1, and a biaxiality of 1. Fatigue Sensitivity shows that the life, damage or safety factor of a component varies with the load in the critical region. The Rainflow array shows that the damage occurred at a low stress amplitude.

Ladle life analysis is closely related to thermal insulation properties, light weight, and thermomechanical stress of ladle. The thermal insulation performance and light weight performance of the ladle are only the discussion and research on the longevity of the ladle from the side, which reduce the minimum temperature of the steel cladding and the thermomechanical stress of the ladle. Thereby the service life of the ladle is extended. This is just one aspect of life analysis. The steel cladding strength analysis and fatigue analysis are carried out above, and the minimum life is calculated according to the formula.

3. Ladle lining thickness prediction model
According to the neural network, the thickness of the ladle lining is predicted. This provides some theoretical basis for the life prediction of the ladle, which is of great significance for extending the life of the ladle. A neural network can be thought of as a directed graph. Figure 3 shows the structure of a single layer sensor.

![Figure 3. Single layer perceptron structure](image)

3.1. Structure of BP neural network
A BP neural network is a network of multiple hidden layers with the ability to handle linear indivisible problems. BP neural networks are generally multi-layered, and another concept associated with them is Multi-Layer Perceptron (MLP). MLP has several hidden layers in addition to the input and output layers. MLP emphasizes that neural networks are structurally composed of multiple layers. BP neural network emphasizes the learning algorithm of network using error back propagation. In most cases,
MLP n uses the error back propagation algorithm for weight adjustment. The BP neural network has the following characteristics:

1. BP neural network consists of multiple layers, with layers connected completely, with no connections between neurons in the same layer. Multi-layer network design allows the BP network to extract more information from the input and perform more complex tasks.

2. The transfer function of BP neural network must be different. Therefore, the transfer function of the sensor, the binary function is not useful here. BP neural networks typically use a second linear function as a transfer function. The Sigmoid function is further divided into a Log-Sigmoid function and a Tan-Sigmoid function depending on whether the output value contains a negative value. A simple Log-Sigmoid function can be determined by:

\[ f(x) = \frac{1}{1 + e^{-x}} \]  

(2)

3. Learning is performed using the Back-Propagation Algorithm. The BP neural network prediction model design steps are shown in Figure 4.

4. Model solving

4.1. Network structure design

The model takes the thickness of each layer of the ladle of each set of data as input, and the thickness of the composite insulation layer as the output. Through analysis, it is determined that the number of nodes in the input layer of the ladle lining analysis is 5, and the number of nodes in the output layer is 1.

A prediction model is built using a three-layer, multi-input, single-output BP network with a hidden layer. The following empirical formula is used to refer to the number of hidden layer neurons:

\[ l = \sqrt{n + m + a} \]  

(3)

Where n is 5, m is 4, and a is an integer between 1 and 10. According to the above formula, the number of neurons can be calculated as 3-12. As shown in Figure 5.
4.2. Model implementation

The specific implementation steps of the prediction model are as follows:

- Normalize the training sample data and input it into the network. After setting the parameters, the network starts to train.

The traditional method is only based on “experience estimation & operational adjustment” to meet the current social development needs. Here only the data is simulated to predict the thickness of the ladle composite insulation layer. Follow-up can experiment with real data, which can accurately estimate the thickness of the ladle insulation layer and effectively extend the service life of the ladle.

The life of the ladle lining mainly affects the service life of the ladle. The design and layout of the ladle working layer uses the same material as the ladle. And the masonry working layer increases the service life of the ladle composite structure to achieve uniform loss. Optimized design of the ladle structure can effectively reduce the thermal stress of the ladle. From the previous ladle strength analysis and fatigue analysis, it can be known that the reduction of the thermal stress of the ladle can effectively extend the service life of the ladle. Optimize and compare the material of each layer of the ladle, which can improve the performance and strength of castables and effectively extend the lining life of the ladle. The curvature of the ladle is improved to reduce the erosion rate of the impact zone, which can also effectively extend the service life of the ladle. From the masonry method to study the life of the ladle, the setting of the ladle lining expansion joint can effectively extend the life of the ladle. Setting a 2 mm expansion joint size can effectively reduce the thermo-mechanical stress of the ladle and extend the life of the ladle bushing. Reducing the refining rate and refining treatment time, optimizing the production organization and strengthening the management of the ladle online cycle are important ways to reduce the hot flaking of the ladle lining and speed up the turnover to improve the life of the ladle lining.

5. Conclusion

The life of the ladle is mainly composed of two parts, one is the lining life of the ladle, and the other is the life of the ladle of the ladle, mainly related to the lining life of the ladle. In this paper, the strength
analysis and fatigue analysis of the ladle of the ladle are first carried out. The results show that the life of the ladle is longer than that of the ladle, and the life of the liner is particularly important. Therefore, a BP neural network life prediction model is proposed to predict the service life of the ladle lining, which can accurately understand the actual use of the lining of the ladle. It is no longer as precise as traditional empirical estimation and operational adjustments, which can greatly improve the life of the lining of the ladle. Institutional management of the ladle's masonry, production management, and post-maintenance and maintenance can extend the service life of the ladle.

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