Journal of Manufacturing Engineering, September 2019, Vol. 14, Issue. 3, pp 129-133

INVESTIGATION OF WEAR BEHAVIOR OF AS FORGED INCONEL 690 SUPER ALLOY USING ARTIFICIAL NEURAL NETWORKS

https://doi.org/10.37255/jme.v4i3pp129-133

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ABSTRACT

The present study aims to study the wear properties of as forged Inconel 690. The dry sliding wear behavior of as forged Inconel 690 is studied in accordance with ASTM standards G99 i.e. dry sliding on pin on disc wear test apparatus. Three wear parameters namely normal load, sliding distance and sliding velocity were considered in this study. The experiments for wear loss have been conducted as per Taguchi Design of experiments. An L27 Orthogonal array was employed for this purpose. The wear loss obtained for As Forged Inconel 690 is predicted by the Neural Network Toolbox of MATLAB R2015a using the Levenberg-Marquardt (trainlm) algorithm which trains the feed forward neural network having 3-6-1 (three input neurons, six hidden neurons in the single hidden layer and one output neuron). Experimental data sets from obtained from L27 Orthogonal array have been utilized to develop ANN. The results concluded that error for wear loss of As Forged Inconel 690 lies within 10% between experimental data and neural network prediction.

Keywords: *Inconel 690, Taguchi and Artificial neural networks.*

1. Introduction

The evolution of super alloys is mainly due to the significant development in gas turbines. Today in many industries metallic alloys are been used at high temperatures and corrosion-resistant applications. Moreover, the service temperature even goes above 0.7 of the melting point of the metallic alloys frequently for some applications. Such metallic alloys with an exceptional combination of high temperature strength, toughness and resistance to degradation in corrosive or oxidizing environment are called super alloys [1]. Basically, super alloys are divided into three categories: nickel based, cobalt based and iron-nickel based alloys.

The composition of nickel-based super alloys is varied depending on the properties required. Besides nickel, the alloys generally contain 10-20% of Chromium, up to 8% of Aluminum along with Titanium and 5-10% of Cobalt. Boron, Zirconium and Carbon are also included in small amounts. Nickel based super alloys are generally classified into two categories: wrought and cast. Wrought are those that are able to forge or roll into the rods, sheets or turbine discs. Also, they have a high strength up to 870°C and they are also characterized by good fracture toughness. Cast alloys exhibit sufficient creep strength at elevated temperatures up to 0.8 of their absolute melting point, but they have limited toughness [2, 3, 4].

Also, nickel based super alloys are classified according to the process of their manufacturing as conventionally cast (CC), mechanically alloyed (MA), dispersion oxide strengthened (DOS), prepared by powder metallurgy (PM) and directionally solidified (DS). One of the new nickel based super alloy having excellent resistance to corrosion and elevated temperatures is Inconel 690. The high chromium nickel content gives the alloy an excellent resistance to various corrosive aqueous media and high-temperature applications. Owing to its anticorrosive properties, the Inconel 690 possesses strong metallurgical stability which permits it to retain structural integrity in various applications. Furthermore Inconel 690 has high strength, excellent metallurgical stability and also favorable fabrication conditions.

A few studies relevant to current investigation have been presented below. Jin-Ki Hong et al. [5] explained the microstructural effects on the fretting wear of Inconel 690 by heat treating the specimens by solution annealing (at high temperature) and thermal treatment (at low temperature) in a view to change in their microstructure. The study brought to light those larger grain carbides and coarse carbides along the grain boundaries have higher resistance to wear. Jin-Ki Hong et al. [6] examined on the wear properties of Inconel

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690 steam generator tubes in various environmental conditions, with the aid of SEM analysis. They confirmed that the wear loss variation with temperature was due to the formation of oxide layers on worn surfaces. Abedini et al. [7] studied the effect of normal load and sliding distance on the dry sliding wear behavior of NiTi alloys at room temperature. They identified that iron rich Tribological oxide layers formation under the higher loads could be the prime reason of decrease in the wear rate of Nickel Titanium alloys. Banker et al. [8] studied the dry sliding wear behavior of Inconel 600 employing Taguchi's L_{27} orthogonal array. It was noted that wear rate was independent of the apparent contact area and conclusion was drawn that Inconel 600 had 17% higher wear resistance when compared to Inconel 690 at loads varying from 2.5 N to 12.5 N. Ramesh et al. [9] attempted to study the influence of parameters viz. applied load, speed and sliding distance on the dry sliding wear of mild steel specimens coated with Inconel 718. They built a mathematical and neural network models for predicting wear within the domain knowledge and the outputs of both the models were compared by confirmation tests. The results were found to be formidable. Kumar et al. [10] modeled & predicted the parameters affecting wear behavior of Inconel 800 by using Taguchi's methodology and Artificial Neural Network. The prediction of wear characteristics using ANN cleared that, a three layer feed-forward network offered better performance value over the two-layer feed forward network. It was also concluded that error predicted for different models was less than 15%. Based on the literature cited above, the present study is one such attempt to study effect of process parameters on the wear behavior of As Forged Inconel 690 using Taguchi's design of experiments methodology and predict the results obtained through Artificial Neural Network.

2. Materials and Methods

Inconel 690 is a nickel-chromium based alloy that is well suitable for elevated temperature applications. The high chromium nickel content gives the alloy an excellent resistance to various corrosive aqueous media and high-temperature applications that require resistance to heat and corrosion. The composition is shown in Table 1. For this project the as forged material of Inconel 690 rods of 8mm diameter is cut using a cutter, to a length of 30mm as per the ASTM G99 standards and then the edges were grinded using grinding machine. Later the test surface was flattened using a lathe machine.

Table 1 Composition of As Forged Inconel 690

S.No	Element	%
1	**Ni**	59.909
2	**Cr**	30.08
3	**Fe**	9.15
4	**C**	0.002
5	**Si**	0.16
6	**Mn**	0.17
7	**S**	0.002
8	**Cu**	0.011
9	**P**	0.007
10	**Ti**	0.31
11	**Al**	0.153
12	**Mo**	0.019
13	**Co**	0.027

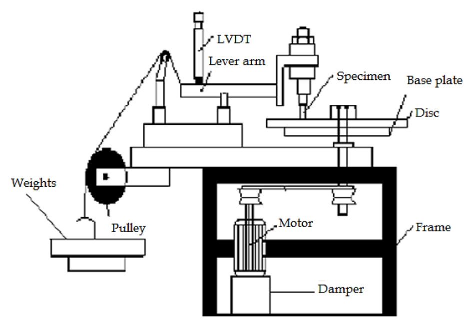

Fig. 1 Schematic representation of pin on disc wear test machine.

The specimens were separated into 27 specimens for accommodating Taguchi's design of experiment methodology [11, 12, 13, 14 15 and 16]. The wear behavior of As Forged Inconel 690 was tested using the wear and friction monitor DUCOM TR-201C Pin-on-Disc machine (Fig. 1). The track radius of 120 mm was set and the specimen was held stationary while the disc is rotating with a normal force applied through a lever mechanism.

3. Experimental Procedure

The operational condition under which the wear study of Inconel 690 was carried out is given in Table 2 at room temperature. Three parameters namely normal load, sliding distance and sliding velocity were considered in this study accordance with L27 (313) orthogonal array design.

Table 2 Control factors and their levels

Control Factor	Level I	II	III	Units
Normal Load	20	40	60	N
Sliding Distance	400	800	1200	m
Sliding Velocity	2	4	6	m/s

3.1 Artificial Neural Network

Artificial neural network (ANN) is a modeling approach successfully applied in modeling of many biological systems [9]. They are capable of dealing with multiple independent (input) and dependent (output) variables simultaneously without prior information about their functional relationship. The wear loss of As Forged Inconel 690 is predicted by the Neural Network Toolbox of MATLAB R2015a using a Levenberg-Marquardt (trainlm) algorithm [17] which trains the neural network having 3-6-1 (three input neurons, six hidden neurons in the single hidden layer and one output neuron) (Fig. 2). Experimental data consisting of 27 datasets has been utilized to develop ANN so that it understands the correlation between the input and output.

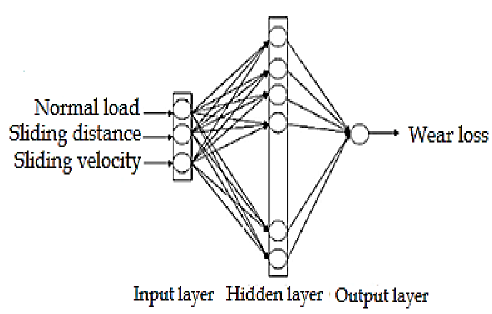

Fig. 2 Neural network architecture.

4. Results and discussions

The experimental wear test results for As Forged Inconel 690 were conducted using the L27 based Taguchi's Design of Experiments method. The validation of wear loss was done by using neural network tool in MATLAB 15. The wear test results of As Forged Inconel 690 according to Taguchi's set of experiments are given in Table 4.1.

Table 3 Test condition with output results for As Forged Inconel 690 using L_{27} array.

Sl. No.	Normal Load (N)	Sliding Distance (m)	Sliding Velocity (m/s)	Wear Loss (mg)
1	20	400	2	32.26
2	20	400	4	32.10
3	20	400	6	28.90
4	20	800	2	69.60
5	20	800	4	61.86
6	20	800	6	42.13
7	20	1200	2	82.06
8	20	1200	4	97.76
9	20	1200	6	75.26
10	40	400	2	75.16
11	40	400	4	75.13
12	40	400	6	60.60
13	40	800	2	102.46
14	40	800	4	159.76
15	40	800	6	135.76
16	40	1200	2	159.00
17	40	1200	4	201.46
18	40	1200	6	192.53
19	60	400	2	98.83
20	60	400	4	128.93
21	60	400	6	150.26
22	60	800	2	213.96
23	60	800	4	238.36
24	60	800	6	376.13
25	60	1200	2	279.90
26	60	1200	4	378.23
27	60	1200	6	486.60

Experimental data consists of 27 datasets that are utilized to develop ANN so that it understands the correlation between the input and output. The test and predicted values of wear loss for As Forged Inconel 690 is depicted in Table 4.2. It must be noted that 60% of the experimental data was used for training the neural network model and around 20% is used for validation and testing purpose [17]. The predicted ANN values and the experimental values of wear loss are compared and percentages error between them is calculated as using the Eq. 1.

$$\%Error = \left\{ \frac{[WL(Exp) - WL(ANN)]}{WL(Exp)} \right\} \times 100 \quad (1)$$

Where, WL (Exp) = Experimental value of Wear loss, WL (ANN) = ANN predicted value of Wear loss.

It is evident that the error for wear loss of As Forged Inconel 690 lies within 10% between experimental data and neural network prediction and hence we can conclude that neural network prediction has proceeded in right manner. A regression plot is plotted between the network output and the target is shown in Fig. 3. The tracking of output values with the targets values holds good for the correlation coefficient (R2-value) 0.99528. Also, it shows better match with the experimental data. A performance plot showing the training, validation and test errors is shown in Fig. 4. At iteration 7 best validation performance occurs with mean squared error value of 269.9047. After 7th iteration the test set error and the validation set error will have similar characteristics and there will be no over-fitting occurring. Therefore, validation stops at 13th iteration.

Table 4 Experimental test data and predicted values of ANN for wear loss of As Forged Inconel 690.

Sl. No	Normal Load (N)	Sliding Distance (m)	Sliding Velocity (m/s)	Wear Loss (mg)		Error (%)	Absolute Error (%)
				Exp.	ANN Predicted		
1	20	400	2	32.26	34.588	-7.21	7.21
2	20	400	4	32.1	34.973	-8.95	8.95
3	20	400	6	28.9	26.296	9.01	9.01
4	20	800	2	69.6	68.556	1.5	1.5
5	20	800	4	61.86	63.196	-2.1	2.1
6	20	800	6	42.13	40.605	3.6	3.6
7	20	1200	2	82.06	89.696	-9.3	9.3
8	20	1200	4	97.76	100.193	-2.4	2.4
9	20	1200	6	75.26	74.709	0.73	0.73
10	40	400	2	75.16	74.616	0.68	0.68
11	40	400	4	75.13	73.137	2.65	2.65
12	40	400	6	60.6	61.556	-1.57	1.57
13	40	800	2	102.5	95.783	6.51	6.51
14	40	800	4	159.8	156.307	2.16	2.16
15	40	800	6	135.8	142.215	-4.75	4.75
16	40	1200	2	159	154.429	2.87	2.87
17	40	1200	4	201.5	195.263	3.07	3.07
18	40	1200	6	192.5	202.199	-5.02	5.02
19	60	400	2	98.83	103.77	-4.99	4.99
20	60	400	4	128.9	133.798	-3.77	3.77
21	60	400	6	150.3	150.43	-0.11	0.11
22	60	800	2	214	206.185	3.63	3.63
23	60	800	4	238.4	232.639	2.4	2.4
24	60	800	6	376.1	374.147	0.52	0.52
25	60	1200	2	279.9	272.977	2.47	2.47
26	60	1200	4	378.2	373.511	1.24	1.24
27	60	1200	6	486.6	486.377	0.045	0.045

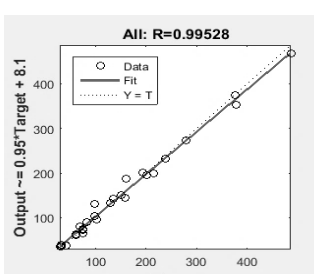

Fig.3 Regression plot using LM algorithm for wear test results of As Forged Inconel 690

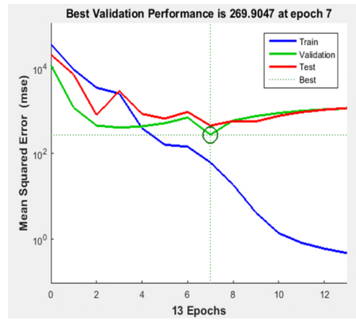

Fig.4 Performance plot using LM algorithm for AS

5. Conclusions

In the present work to analyse wear properties of Inconel 690 have been analysed using ANN. The wear test was conducted using pin on disc apparatus and experimental results for wear loss were determined using the Taguchi based L_{27} Orthogonal array. Load, sliding distance and sliding velocity were selected as input parameters. The comparison between experimental results and ANN results shows a good agreement having a correlation coefficient of $R^2 = 0.99528$. The prediction of wear loss using ANN was validated and the accuracy of result obtained was within 10%. Also, iteration 7 proved to be the best validation performance for wear loss, as it had mean squared error value of 269.9047.

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