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Effect of Ageing on the Tribological Behavior of Inconel 690 Using Taguchi's Method

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Abstract Many of our modern technologies in the present day require materials with different combinations of properties that can be used for various applications. One such material is the Inconel 690 possessing various properties like high strength at elevated temperature, toughness, resistance to degradation in corrosive or oxidizing environment, etc. The present work is mainly focused on the study of Tribological properties of Inconel 690 at As Forged condition and at ageing conditions of 725°C for 4 hours respectively. The influences of process parameters like normal load, sliding distance and sliding velocity on the wear loss was studied using pin-on-disc apparatus. The experiments show that normal load is the most significant factor that influencing the wear loss. The work concluded that the combination of parameters that yields to minimum wear loss is not affected by ageing of the Inconel specimen to 725°C.

Keywords Inconel, Wear, S/N ratio

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 which possess an extraordinary combination of properties like high temperature strength, toughness and resistance to the degradation in corrosive or oxidizing environment are called super alloys. Basically super alloys are divided into three categories: cobalt based, nickel based and iron nickel based alloys. 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. It can also endure the sulfidation which takes place at high temperatures. 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. An outstanding resistance to oxidizing chemicals and to high-temperature oxidizing gases is obtained by the substantial chromium content in the alloy. With the high level of nickel, the alloy exhibits resistance to stress-corrosion cracking in chloride-containing environments and to sodium hydroxide solution.

The investigation on the diverse characteristics such as cutting force, temperature, surface roughness, wear and surface integrity etc., of nickel based super alloys was carried out by a lot of researchers. Out of these different characteristics, the prediction of wear was studied by many researchers using Taguchi's Design of experiments and Artificial Neural Network (ANN). They heat treatment process for the test specimen was conducted in two steps; solution annealing (at high temperature) and thermal treatment (at low temperature) to obtain a change in their microstructure. Observations of microstructure indicated that the temperature and duration of solution annealing affect the grain size of Inconel 690 [1]. The examination on the wear properties of Inconel 690 steam generator tubes in various environmental conditions like temperature variation, air environment and water environment to determine the occurrence of reciprocating sliding wear, with the aid of SEM analysis confirmed that the wear loss variation with temperature was due to the formation of oxide layers on worn surfaces [2]. The identification of iron rich Tribological oxide layers formation under the higher loads resulted to be the prime reason of decrease in the wear rate of Nickel Titanium alloys [3]. The sliding and fretting wear tests of thermal treated Inconel 690 has better wear resistance than high temperature mill annealed Inconel 600

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and that the wear and tear due to stick-slip has a very strong effect on the fretting wear behavior of the steam generator tubes [4]. 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 [5]. The conventional sliding tests performed using a pin-on-disk apparatus to compare the test result observed that frictional force was mainly due to the normal loads and vibrating amplitudes and coefficients of friction decreases with the increase in the normal loads and reduction of vibrating amplitudes. Hence Inconel 690 can result in lesser friction forces and also exhibits less wear resistance than Inconel 600 in room temperature water [6].

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 material has high mechanical strength and can be readily formed, machined and welded. Table 1 gives the chemical composition of As forged Inconel 690.

The wear behavior of As Forged and aged samples of Inconel 690 were tested using the Wear and Friction Monitor DUCOM TR-201C Pin-on-Disc Machine. ASTM G99 Standards were followed for the test and the samples were cut to a length of 30 mm each. 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. Table 2 shows the control factors and levels used in the experiment.

3. Experimentation

The Taguchi technique is one of the powerful designs of experiments tool for the acquisition of data in a controlled way and to analyze the influence of process variables over some specific variable which is an unknown function of these process variables [7]. It efficiently obtains the combinations of optimum factor level to achieve a minimum standard deviation (variation) while the mean is kept on the target. It is also a most efficient problem solving tool that updates or improves the performance of the product or process design and system with a sufficient experimental data [8]. This type of approach to experimentation helps in providing an orderly way to collect, analyze, interpret data that satisfies the objectives of the study. The advantage of using this method is that all parameters are varied and at the same time the effect of the performance and their interactions can be learnt simultaneously.

4. Results & Discussion

The experimental wear test results were analyzed using the Taguchi's Design of Experiments method and main effect and interaction plots were made use to investigate the influence of different process parameters on the wear loss. The popular software MINITAB 14 was made use to statistically analyze the wear study experiments. The wear test results of As Forged Inconel 690 and Inconel aged at 725°C according to Taguchi's set of experiments are given in Table 3. The experimental results are then transformed into S/N ratios. Wear loss of as forged Inconel 690 and aged Inconel 690 was conducted for 27 test runs according to Taguchi's design of experiments.

The effect of the control parameters on the wear loss for as forged and aged Inconel is graphically shown in the Figs.1(a) and 2(b) respectively. From these both figures and considering the possible interaction between the parameters we can conclude that the combination of 20N, 400m and 2m/s gives the minimum wear loss. However the wear loss yielded for aged Inconel specimen was found to be higher when compared to as forged Inconel specimen. This may be due to the solution treating of the specimen at 1040°C and water quenching before the actual ageing process. Moreover solution treatment entraps the internal stresses leading to softening effect.

Table 1. Composition of As Forged Inconel 690

Element	Ni	Cr	Fe	C	Si	Mn	S	Cu	P	Ti	Al	Mo	Co
%	59.909	30.08	9.15	0.002	0.16	0.17	0.002	0.011	0.007	0.31	0.153	0.019	0.027

Table 2. Control factors and levels used in the experiment

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

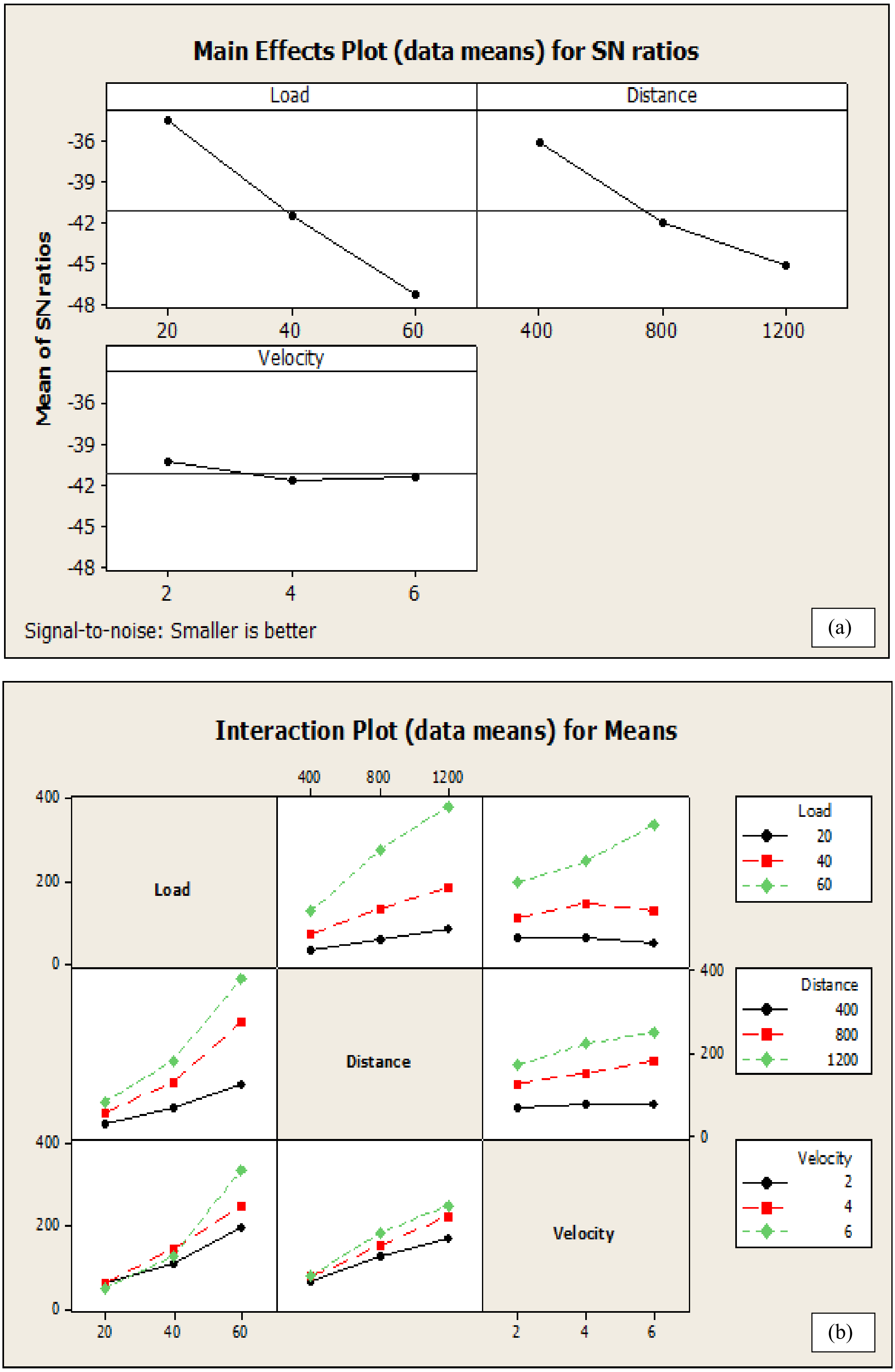

Figure 1. Main effect and Interaction plots for as forged Inconel 690 specimen

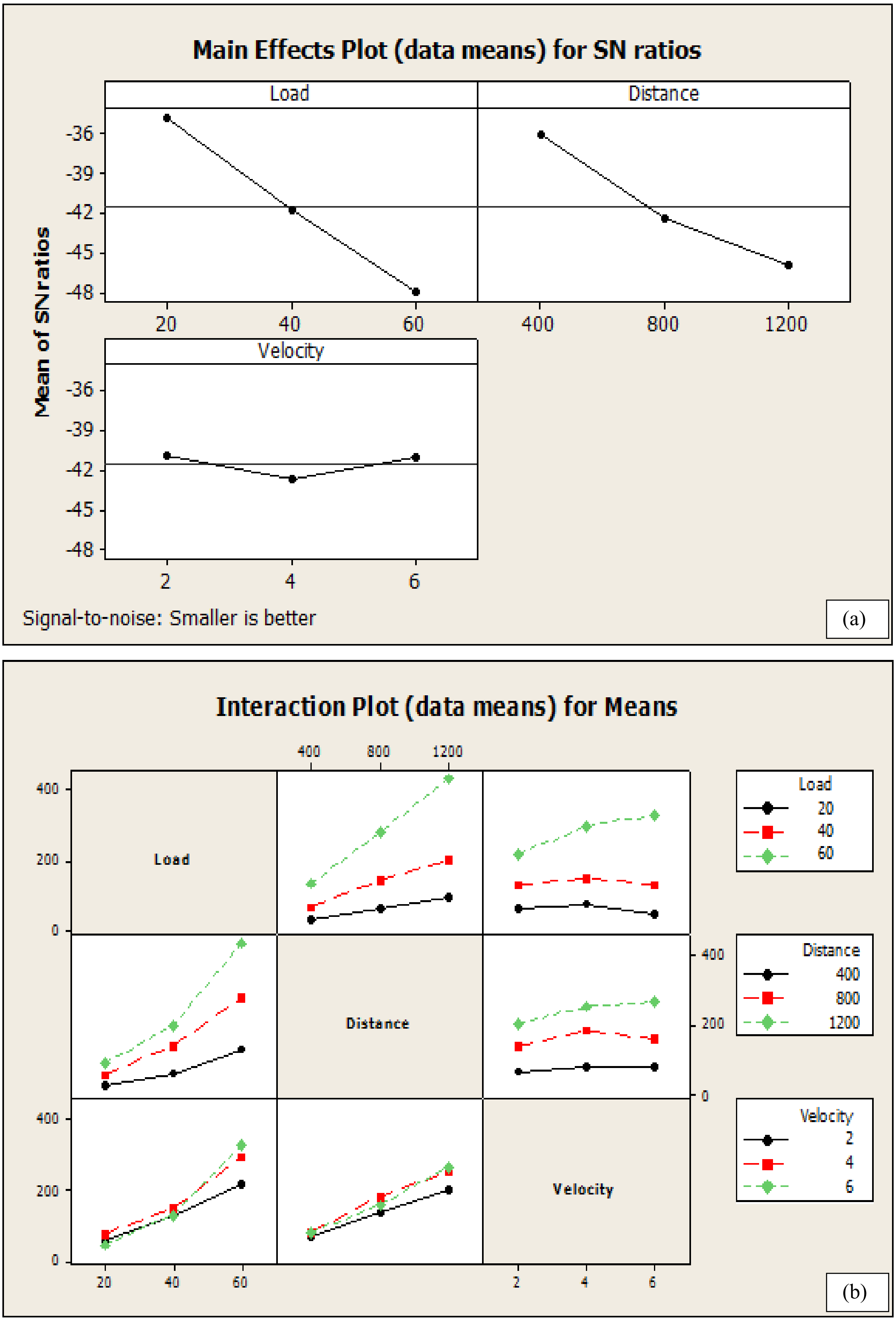

Figure 2. Main effect and Interaction plots for Inconel 690 specimen aged at 725°C

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

L27 Tests	Normal Load (N)	Sliding Distance (m)	Sliding Velocity (m/s)	S/N ratio for As Forged Inconel 690	S/N ratio for aged Inconel 690 at 725°C
1	20	400	2	-30.1733	-30.3439
2	20	400	4	-30.1301	-32.2979
3	20	400	6	-29.2180	-26.8721
4	20	800	2	-36.8522	-35.7634
5	20	800	4	-35.8282	-38.0618
6	20	800	6	-32.4918	-32.5596
7	20	1200	2	-38.2826	-39.4069
8	20	1200	4	-39.8032	-40.7803
9	20	1200	6	-37.5313	-37.8374
10	40	400	2	-37.5197	-37.1984
11	40	400	4	-37.5163	-37.3257
12	40	400	6	-35.6495	-34.6639
13	40	800	2	-40.2111	-42.6580
14	40	800	4	-44.0694	-43.7651
15	40	800	6	-42.6554	-43.0885
16	40	1200	2	-44.0279	-45.2609
17	40	1200	4	-46.0838	-46.9216
18	40	1200	6	-45.6900	-45.9215
19	60	400	2	-39.8978	-39.9826
20	60	400	4	-42.2071	-42.4705
21	60	400	6	-43.5369	-44.6447
22	60	800	2	-46.6067	-46.9645
23	60	800	4	-47.5447	-50.1409
24	60	800	6	-51.5068	-49.3625
25	60	1200	2	-48.9401	-50.5043
26	60	1200	4	-51.5551	-52.8043
27	60	1200	6	-53.7434	-54.4750

From the interaction plot in the Fig 1(b) for as forged Inconel specimen it is evident that at constant loading, the wear loss increases with the increase in sliding distance due to more contact between the pin & disc and in turn more heat is generated. This heating up of the material initially at 20N loading gradually increases with the increment in sliding distance and results in more removal of the material. Even at 40N loading and variation of sliding distance, the same material removal pattern is followed. But at 60N loading there is an abrupt increase in the wear loss due to the tearing of the material that is caused by high frictional forces acting on the pin & disc, which results in high amount of heat generation.

The wear loss with respect to constant loading and varying velocity shows that, initially at 20N loading, there is an increment in wear loss when the velocity is varied from 2 m/s to 4 m/s. This is due to the large heat generated at increasing velocity. With further increase in velocity from 4 m/s to 6 m/s, we observe a negative slope due to the burr formation at the end of the material which indicated that the material is malleable. A similar pattern of wear loss occurs at 40N loading. But at 60N loading there is a continuous increment of wear loss because as the sliding velocity increases, there is formation of heat and thus at higher velocities the tearing of the material occurs and the material is lost in terms of small chips. With constant sliding distance and varying load, the wear loss increases with gradual increment in positive slope for 400 m sliding distance. But for 800 m sliding distance, initially when load increases from 20N to 40N the wear loss increases gradually and when load increases from 40N to 60N there is a quick increment of positive slope of wear due to the removal of material caused by heat generation and tearing of the material which in turn is caused by higher loading. A similar pattern of wear loss occurs for 1200 m sliding distance. For constant sliding distances and varying velocity, the wear loss takes a slight linear increment due to less contact of pin & disc at 400 m sliding distance. But when the sliding velocities varies for 800 m and 1200 m sliding distances, the wear loss increases with the increase in sliding velocity because of increase in heat formation at the interface of pin & disc. The pattern of wear loss for constant sliding velocity and varying load shows that, for 2 m/s velocity when load increases from 20 N to 40 N, there is a gradual increment of wear loss and it still increases with increment in load due to the formation of frictional forces. For 4 m/s velocity, the wear loss follows a gradually linear incremental pattern with the increase in load. But for 6 m/s velocity, a small increment of wear loss initially from 20 N to 40 N is observed and when the loading is still increases from 40 N to 60 N the positive slope of wear abruptly increase due to generation of frictional forces.

From the interaction plot in the Figure 2(b) for aged Inconel 690 specimen, it is evident that at constant loading, the wear loss increases with increase in sliding distance due to more contact between the pin & disc and in turn more heat is generated. This heating up of the material initially at 20N loading gradually increases with the increment in sliding distance and results in more removal of the material. Even at 40N loading and variation of sliding distance, the same material removal pattern is followed. But at 60N loading there is an abrupt increase in the wear loss due to the tearing of the material that is caused by high frictional forces acting on the pin & disc and due to the softening effect caused by ageing treatment. Also the large grain size contributes to higher wear loss due to loose packing of the grains.

5. Conclusions

The present work is mainly focused on the study of Tribological properties of Inconel 690 at As Forged condition and at ageing conditions of 725°C for 4 hours respectively. The study is conducted as per Taguchi's design of experiment. Following conclusions are drawn:

- Ageing Heat treatment on Inconel 690 increases the wear loss because it softens the material.
- The normal load was found to be the strongest influencing parameter or factor on the wear loss for both as forged and aged Inconel 690, followed by sliding distance.
- The combination of 20 N, 400 m and 2 m/s gives the minimum wear loss for As Forged and aged specimens.

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