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U. Esgin, D. Özyürek, and H. Kaya


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An Investigation of Wear Behaviors of Different Monel Alloys Produced by Powder Metallurgy

U. Esgin[1], D. Özyürek[1] and H. Kaya[2, a)]

[1]*Karabük University, Technology Faculty, Department of Manufacturing Engineering / Karabuk*
[2]*Kocaeli University, Asim Kocabiyik Vocational School of Higher Education, Department of Machine / Kocaeli*
[a)]*Corresponding author: hasan.kaya@kocaeli.edu.tr*

Abstract. In the present study, wear behaviors of Monel 400, Monel 404, Monel R-405 and Monel K-500 alloys produced by Powder Metallurgy (P/M) method were investigated. These compounds prepared from elemental powders were cold-pressed (600 MPa) and then, sintered at 1150°C for 2 hours and cooled down to the room temperature in furnace environment. Monel alloys produced by the P/M method were characterized through scanning electron microscope (SEM+EDS), X-ray diffraction (XRD), hardness and density measurements. In wear tests, standard pin-on-disk type device was used. Specimens produced within four different Monel Alloys were tested under $1ms^{-1}$ sliding speed, under three different loads (20N, 30N and 40N) and five different sliding distances (400-2000 m). The results show that Monel Alloys have γ matrix and that $Al_{0,9}Ni_{4,22}$ intermetallic phase was formed in the structure. Also, the highest hardness value was measured with the Monel K-500 alloy. In wear tests, the maximum weight loss according to the sliding distance, was observed in Monel 400 and Monel 404 alloys while the minimum weight loss was achieved by the Monel K-500 alloy.

Keywords: Monel 400; Monel 404; Monel R-405; K-500 alloy; Powder metallurgy; Wear behaviors.
PACS:81.40.Pq

INTRODUCTION

Monel alloys which have come to prominence because of their high resistance, melting temperature, and corrosion resistance contain Ni (63-67% wt.) and Cu (30-33% wt.) at high proportions. Due to the high corrosion resistance, they are preferred at manufacturing of components used in corrosive environments such as valves, pumps, marine industry and chemical binders, aerospace industry, machinery industry and defense industry in several sectors [1-5]. Monel 400 alloy is a single-phased, corrosion-resistant alloy, which can only be hardened through cold processing and can be used within a wide temperature range (-200/+230 °C) [6,7]. Due to the high Cu content in structure, Monel 404 alloy presents superior soldering characteristic. Thus, it is preferred for applications in electric and electronic applications. Since characteristics of the Monel R–405 alloy are similar to those of the Monel 400 alloy, they can be used in similar purposes. Applied processes and the mechanical properties are the same with Monel 400 alloy in general. Besides, machinability, wear and corrosion resistances are higher than that of Monel 400 alloy. Monel K-500 alloy is a Ni-based age hardenable alloy that contains small amount of Fe together with Cu.

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Monel K-500 has the general structural characteristics of other Monel alloys except for addition of 3% Al and 8% Ti for the formation of Ni_3(Al, Ti) aging solutions. Resistance of the Monel K-500 against sea water and many other chemical and acid-gas environments is higher compared to other Monel Alloys. It can maintain the mechanical properties from sub-zero temperatures to 480 °C temperature [8-12]. Because the Monel alloy is widely used for different purposes, there are many studies on the mechanical properties and corrosion behavior of these alloys. But there is lack of studies examining the wear behavior exhibited under the same conditions of different Monel alloy. Therefore, this study investigates the microstructure characteristics and wears behaviors of the Monel 400, Monel 404, R-405 and K-500 alloys produced by powder metallurgy method.

MATERIALS and METHOD

In this study, four different monel alloys (Monel 400, Monel 404, Monel R-405 and Monel K-500) were produced from elemental powders by P/M method. Chemical compositions of the produced alloys are given in Table 1. The supplied elemental powders were weighted (% wt.) in a scale having a precision of 1/10000 and mixed with Turbula Shaker Mixer (T2F Gleen Mills) at 67 rpm for 60 minutes to produce the compositions given in table 1. Mixed powders were cold pressed (600 MPa) as Ø12 x 6-7 mm. compacts. The preformed green compacts were sintered under 10^{-6} millibar vacuum at 1150°C for 2-hours with 4°C/min. heating speed and were cooled down to room temperature in the furnace.

Table 1. Chemical composition of Monel alloys.

Alloy	Element (weight %)							
	Cu	Ni	Si	Fe	Mn	C	Al	Ti
Monel 400	31,7	63	0,5	2,45	2	0,3	-	0,05
Monel 404	47,1	52	0,1	0,5	0,1	0,15	0,05	-
Monel R-405	31	63	0,5	2,5	2	0,3	-	-
Monel K-500	28,75	63	0,5	2	1,5	0,25	3,15	0,85

After the sintered samples were prepared using the standard metallographic processes, all the samples were etched in 50 ml glycerol, 20 ml HCl and 10 ml HNO_3 solution for 5-10 minutes and prepared for characterization studies. Samples were then characterized using scanning electron microscope (SEM+EDS), X-ray diffraction (XRD), hardness (HV) and density measurements (according to Archimedes' principles). Shimadzu brand device was used for hardness measurements and the main value of five measurements was calculated to determine the hardness value. Pin-on-disc type standard test apparatus was used for wear tests according to the ASTM-G99-05 standard**.** Prior to the wear test, sample surfaces were prepared with 1200-grid sandpaper and polished using 6 µm diamond paste. So, the same surface quality was achieved for each sample. Wear tests were carried out under three different loads (20 N, 30 N and 40 N), for five different sliding distances 400 m, 800 m, 1200 m, 1600 m and 2000 m) at 1 ms^{-1} sliding speed. The abrasive disc and samples surfaces were cleaned with acetone before the wear tests. The worn samples were weighted at a high

precision scale and weight losses were determined. After the wear tests, the worn surfaces were examined by SEM.

RESULTS AND DISCUSSION

Microstructural Characterization

After the sintering process, the SEM images of the Monel alloys (Monel 400, Monel 404, Monel R-405 and Monel K-500) produced by P/M method are given in Figure 1 and EDS results are given in Table 2.

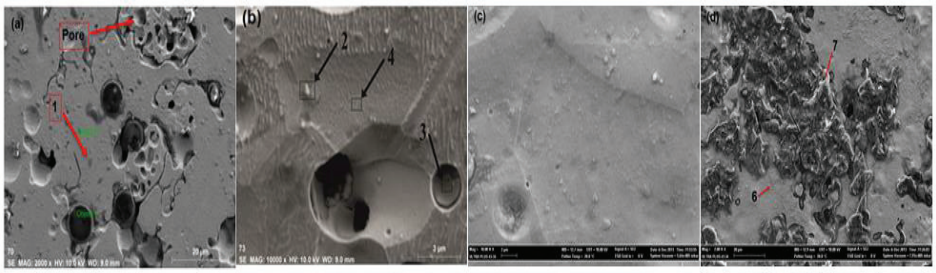

Figure 1. SEM images of Monel alloys: a) Monel 400, b) Monel 404, c) Monel R-405 and d) Monel K-500.

Table 2. EDS analysis results of the Monel alloys.

Figure	Location	Element (weight %)								
		C	O	Al	Si	Mg	Mn	Fe	Ni	Cu
1.a	1.	4,2	3,67	0,51	0,51	-	3,42	1,88	48,51	37,81
1.b	2.	-	-	16,85	5,12	8	-	-	23,78	44,01
1.b	3.	-	-	29,76	0,66	0,3	-	-	16,75	31,4
1.b	4.	2,59	1,7	0,51	1,16	-	-	-	36,67	57,38
1.d	5.	45,2	25,24	7,5	4,67	-	-	9,57	23,78	-
1.d	6.	3,45	1,64	0,7	0,7	-	-	-	60,08	33,42

According to the SEM images in Figure 1, it can be observed that pores formed in the structure following the sintering process are mostly within the grains. Additionally, there are spherical dark regions in Monel 400 (a) alloy. In the SEM images of the Monel 404 alloy, it was understood that the amount of pores is decreased compared to (b) Monel 400 alloy. In the SEM images of the Monel K-500 alloy (d), Ni and Cu-rich phase can be seen as irregular and dark regions. Oxide formations around the dark phase (white regions) (5) can also be observed from the EDS results presented in Table 2. As can be seen from the Figure 1.b, EDS analysis of the 3rd and 4th regions revealed that the structure is Ni and Al-rich. In Figure 3.d, C and O-rich structure can be observed (7). XRD results of the Monel alloys are given in Figure 2.

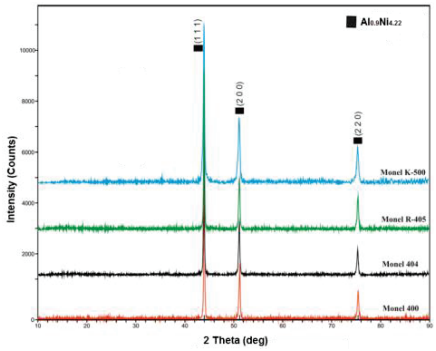

Figure 2. XRD results of the Monel alloys.

Phases occurred in P/M Monel alloys can be seen in the XRD results in Figure 2. After the sintering process, the structure of the PM Monel alloys can be understood that almost the same. Only the peaks of gamma (γ) matrix are obtained for four alloys. Elements are not given in the XRD examinations, because inter-metallic occurred within the structure was scanned rather than elements forming the matrix. Density and hardness changes observed in alloys after the sintering process are given in Figure 3.

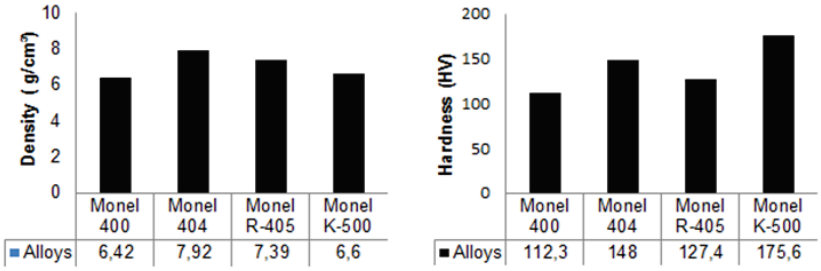

Figure 3. Changes in density and hardness values of various Monel alloys.

It was observed that densities of the Monel alloys sintered at 1150 °C changes due to chemical compositions. It is difficult to achieve 100 % density in the materials the produced by P/M method. This is because of the pores formed in the structure. Theoretical densities of Monel 400, Monel 404, Monel R-405 and Monel K-500 alloys are measured as 73%, 89%, 84%, and 77% respectively. Their hardness measurement results are given in Figure 3 b. According to hardness results, Monel K-500 has the highest hardness value.

WEAR TEST RESULTS

Monel alloys (Monel 400, Monel 404, Monel R-405 and Monel K-500) have been tested under the conditions of 1 ms^{-1} sliding speed, three different loads (20N, 30N and 40N) and five different sliding distance (400 m-2000 m). Weight losses and friction coefficients of the Monel alloys under 20N, 30N and 40N loads and for different sliding distances are given in Figure 4.

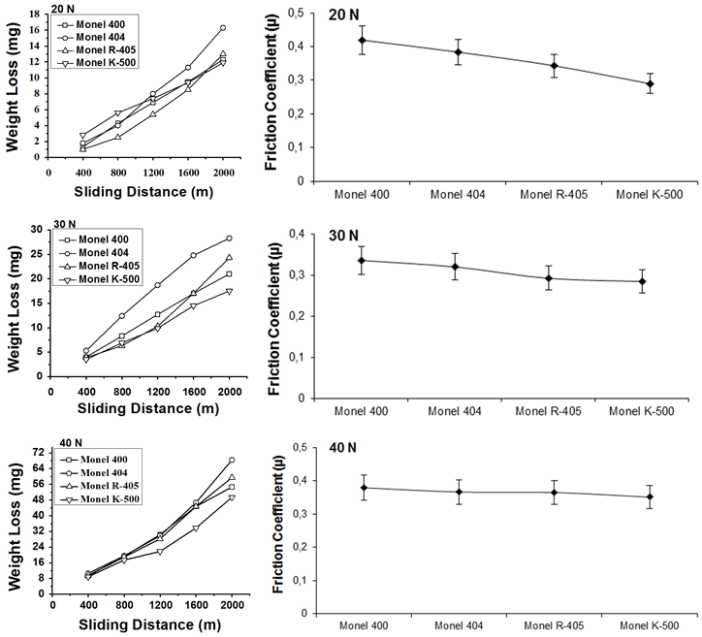

Figure 4. Weight losses and friction coefficients of Monel alloys for different sliding distances under different loads (20N, 30N and 40N).

According to the weight losses are given in Figure 4, it is observed that weight losses increase by the sliding distance. The results of the wear tests showed that the lowest weight loss is obtained at 20 N load for all Monel alloys tested in this study. Consequently, the highest weight loss was observed in the wear tests with 40 N applied load. When the Monel alloys tested were compared with each other, it is clear that the highest weight loss was from Monel 400 alloy while the lowest weight loss was from Monel K-500. The results of weight loss from Monel alloys are in consistence with the hardness results given in Figure 3. Plastic deformation occurs in the samples during the wear tests as a result of the contact and friction of steel disc and sample surface depending on the loads. During the sliding of the sample on the steel disc (microchips formed by the scratching among two metals) causes cold welding by smearing on surface due to loading and adhesion effect. Furthermore, massive part fractions occur from the samples produced by P/M method. Besides, according to the friction coefficients given in Figure 4, it can be observed that as the amount of load increases, friction coefficient increases as well. While the highest friction coefficient values are obtained with the Monel 400 alloy, the lowest friction coefficient values are obtained with the Monel K-500 alloy. It is also observed that as hardness values of the Monel alloys increase, friction coefficients decreases. The obtained results are supported by some studies carried out previously [13-15]. SEM images of the worn surface of the Monel Alloys under 20 N load at the wear tests are given in Figure 5.

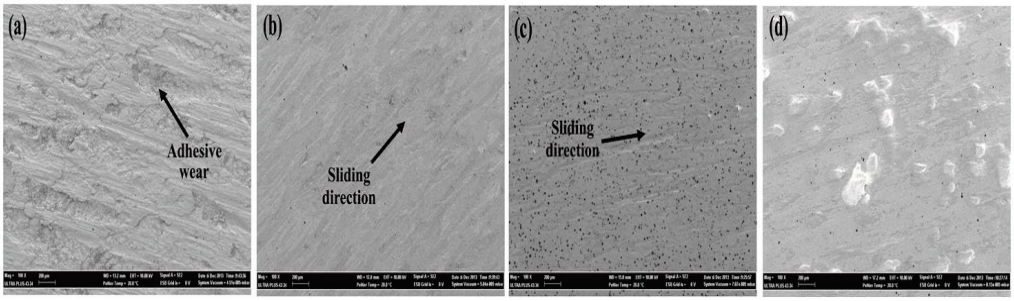

Figure 5. SEM images of worn surfaces of the Monel Alloys tested at 20 N load: a) Monel 400, b) Monel 404, c) Monel R-405 and d) Monel K-500.

According to the SEM images of the Monel alloys given in Figure 5, a plastic deformation can be observed (especially on the worn surface of the Monel 400 alloy). It is understood that smearing occurred as a result of the contact between metal surfaces (Figure 5.a). In the SEM images of worn surfaces of the Monel 404 (b) and Monel R-405 (c) alloys, the direction of sliding can be clearly observed. In generally, although some oxidation took place on worn surfaces, it is understood that adhesive wear mechanism occurred [1, 14, 15].

CONCLUSION

In this study wear behaviors and microstructures of Monel Alloys produced by P/M method were investigated. The below conclusions can be made according to the results of study:

- According to the SEM images, it was determined that pores were formed within the structure and that there were oxidized regions around the phases formed.
- In XRD examinations, peaks belonging to gamma (γ) matrix and $Al_{0,9}Ni_{4,22}$ inter-metallic phase were observed in the Monel alloys.
- The highest density was measured with the Monel 404 alloy while the lowest one was measured with the Monel 400 alloy.
- In the hardness measurements, the highest hardness values were obtained from the Monel K-500 alloy. And the wear tests results gave the lowest weight loss for this alloy as well.
- In wear tests, the lowest friction coefficient values were obtained for the Monel K-500 alloy.
- SEM worn surface images, indicated that the dominant wear mechanism was adhesive wear.

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