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NiTi shape memory alloy: physical and tribological characterization

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Abstract:

The current research work focuses on the mechanical and tribological behavior of an NiTi shape memory alloy (SMA) processed with the help of powder metallurgy. SMAs have found applications in the medical, space and aerospace industries with usage in the manufacturing of microelectromechanicals (MEMS) and as actuators in the electronic industry. The wear behavior of a material greatly affects its performance. The wear behavior of an SMA can be determined with the help of the dry abrasion test. The increase in binder content and rotational speed at a constant load increases the wear rate of SMA alloys. The coefficient of friction decreases with the usage of alloys. A decrease in density has been found, as well as porosity, with the increasing content of binder in the alloy. Density decreases from 6.7 to 5.1 g/cm³ while porosity decreases from 57 to 23% with increased binder content. Scanning electron microscopy (SEM) and X-ray diffraction has been used for the investigation of surface morphology and phases present in the alloy.

Keywords: alloy, density, friction, NiTi, porosity, wear

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1 Introduction

NiTi alloys due to their shape memory effects have found abundant usage in engineering as well as in the biomedical field [1]. Shape memory alloys (SMAs) due to their superelasticity is a well-known alloy in various applications [2]. It is used in orthopedic, cardiovascular and orthodontic, surgical instruments, and in neurosurgery [3]. In every application when these SMAs come in contact with some other material, wear takes place. Due to technological development the size of instruments is becoming smaller, as a result the laboratory has changed due to this miniaturization [4]. Hence, a minute amount of wear plays a crucial role in the appropriate functioning of equipment [5]. Thus wear of SMA also plays an important role in the applications of these alloys. Wear behavior is directly linked with numerous mechanical properties [6]. NiTi alloy manufactured by powder metallurgy when used during sintering of calcium prevented the formation of secondary phases [7]. Reinforcement of carbon nanotubes (CNTs) improved the mechanical properties with an increase in thermal hysteresis and a decrease in friction coefficient with a small effect on the shape memory characteristics of NiTi alloys [8], [9]. Both micro- as well macro-hardness of NiTi alloys increased by reinforcing the alloy with Al₂O₃ due to which NiTi₂ and Ni₃Ti phases were formed, having high hardness as compared to martensite and austenite [10]; furthermore, the wear resistance of NiTi alloy reinforced with Al₂O₃ increased. NiTi alloy with oxide film showed better corrosion and wear resistance [9]. In a corrosive environment the NiTi alloy with oxide film showed better wear resistance than that of NiTi alloy without oxide film (saliva) and it has been found that wear rate increases in the presence of artificial saliva. After the surface mechanical attrition treatment of NiTi alloy both wear and coefficient of friction decreased due to the formation of ultrafine grain consisting of nano-crystalline and submicrometer grain in the surface layer produced [11]. NiTi alloy was used for coating on steel alloys to improve their cavitation erosion resistance [12]. NiTi alloy coated with TiN coating enhanced the osteoblasts growth on its substrate [13]. The plasma source ion implantation technique also increases the wear and pitting corrosion resistance of these SMAs. Oxygen-ion implantation techniques showed better results than the plasma source ion implantation technique for improving the wear and corrosion resistance of NiTi alloys [14].

The physical properties of SMA vary with variation in composition and type of binder. A porous structure is produced because the binder present in green compact evaporates at the time of sintering which reduces the strength of the material due to decrease in the modulus of elasticity. The formation of this porous structure has found various applications in medical field [15], [16].

Hence, in the current research, the physical properties of the NiTi alloy with various amounts of organic binder have been studied. An increase in the porosity of SMA can be obtained by increasing the amount of

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organic binder. Dry abrasion wear of Ni51.2Ti50.8 was evaluated at various rotation speeds (i.e. 200, 250 and 300 rpm) by using a dry abrasion test rig. The percentage of binder varies from 3% to 12% by weight at an equivalent loss of both powder particles. Wear behavior and friction coefficients of NiTi SMA were compared. The micro-structures of the surfaces were also evaluated for its wear behavior.

2 Materials and methods

Ni and Ti elemental powders were taken as the starting materials; their chemical composition is shown in Table 1. For the homogeneous mixing of Ni and Ti elemental powders, they were ball milled in a high-energy planetary ball mill [17], [18]. During ball milling, an organic binder is also added, so that it can be homogeneously mixed with the Ni and Ti elemental powders during the milling process (Kamman Group, Mumbai, India). Various weight percentages (3–15%) of organic binders were used. After 15 h of ball milling, the combined powder is placed in the die for compaction. After compacting the combined powder, the green compact was sintered for 75 min in the furnace at a temperature of 1250 K in the presence of argon gas to avoid oxidation. A dry abrasion test rig (Ducom®, Germany) was used for wear testing in the presence of dry sand at different rotation speeds (i.e. 200, 250, 300 rpm). The evaluations of surface morphology were performed via scanning electron microscopy (SEM) (FESEM with EDX model, Surpa 40 VP with Bruker EDS system, Germany) at a voltage of 15 kV. The density was calculated by mass and volume calculation of the sample. The mass of the sample was measured by the precise weight balance of accuracy at 0.001 g. Porosity can be calculated with the help of equation 1.

Table 1: Chemical composition of nickel and titanium powder.

S. No.	Nickel powder		S. No.	Titanium powder	
	Element	Observation (Wt.%)		Element	Observation (Wt.%)
1	Fe	0.031	1	Ni	0.086
2	Cr	0.024	2	Fe	0.930
3	Co	0.090	3	V	0.341
4	Ni	99.84	4	Mo	0.05
			5	Ti	98.89

$$\% \text{ Porosity} = [1 - d/d_a] * 100 \quad (1)$$

The weight before and after the rotation of the abrasion wheel was considered by an accurate weight balance (Mitutoyo). All the samples were checked for wear characteristics and the SEM determines the surface characteristics, i.e. morphological characteristics on the surface before and after wear experiments.

3 Results and discussion

3.1 Density evaluation

It was found from the measurement that with the increase of content of organic binder from 3 to 15% (by wt.%), the density decreases from 6.7 to 5.1 g/cm³ (Table 2). The volume remains constant with a decrease in mass with increasing content of organic binder. As was evident, the density is the ratio of mass to volume and hence it decreases. Figure 1 shows the variation of density with the content of organic binder.

Table 2: Variation of density with the binder percentage.

S. No.	Binder percentage	Density (g/cm ³)
1	3	6.7
2	6	6.3
3	9	5.8

4	12	5.4
5	15	5.1

Figure 1: Density variation with changes in the organic binder percentage.

3.2 Porosity evaluation and X-ray diffraction (XRD) analysis

Porosity was calculated with the help of equation 1. An increase in porosity was observed with increasing content of organic binder in the green compact (Table 3); this may be due to the lesser density of organic binder as compared to nickel and titanium. The variation of porosity with weight percentage of organic binder is shown in Figure 2. At the time of sintering the organic binder evaporates which resulted in porous SMAs. The results were also confirmed with the SEM micrograph of sintered NiTi alloy. The average pore size increases with the increase of binder percentage. Figure 3A reveals the average pore size of 6 μm , while the pore size in Figure 3B–D is 8, 10 and 12 μm , respectively. Also with the increasing content of organic binder, the number of bigger pores increases significantly. Figure 4 represent the X-ray diffraction (XRD) (Bruker D8 Discover, X-ray source-Cu, 3KW, Germany) analysis of sintered NiTi at different binder percentages. Austenitic NiTi phase (B2); overcomes the occurrence Ni_3Ti phase, NiTi_2 phase and martensitic NiTi phase (B19').

Table 3: Variation of porosity with the binder percentage.

S. No.	Binder percentage	Porosity (%)
1	3	23
2	6	32
3	9	41
4	12	49
5	15	57

Figure 2: Porosity variation with changes in the organic binder percentage.

Figure 3: As-sintered NiTi alloy at (A) 3% binder percentage; (B) 6% binder percentage; (C) 9% binder percentage; (D) 15% binder percentage.

Figure 4: X-ray diffraction at (A) 3% binder; (B) 6% binder; (C) 9% binder; (D) 12% binder; (E) 15% binder.

3.3 Wear behavior

It can be observed from the Table 4 that with increase in rotational speed of the abrasion wheel at a constant value of time, the wear rate was found to be increased. This is due to the fact that with the increase in the rotational speed; an increase in the contact time between the sample and abrasion wheel surface increased. Thus, an increase in the slope of wear line can be observed in Figure 5. Hence, at lower value of rotational speed; smaller wear takes place due to adhesive wear. But with the increase of rotational speed; hard intermetallic NiTi particles along with the dry sand occurs in between the abrasion wheel and the sample, which converts the mechanism of wear from adhesive to abrasive wear and a larger wear rate being observed.

Table 4: Wear rate in NiTi alloy.

Dead weight	Actual	Time	Wear NiTi (mg)		
			200 rpm	250 rpm	300 rpm
0.6	4.51	12	0.68	1.05	18
0.9	5.14	24	0.75	1.10	18.8
1.2	5.88	36	0.82	1.18	20.2
1.5	6.23	48	0.90	1.29	20.9
1.8	6.87	60	0.97	1.38	21.4
2.1	7.24	72	1.01	1.45	21.9

Figure 5: Wear behavior of NiTi alloy.

3.4 Microstructural evaluation

The wear images show that the surface of NiTi contains hard particles of nickel and titanium which resulted in a smaller wear rate. The fine grooving is observed in the SEM images (Figure 6A–C). Material eroded by dry sand resulted in the formation of fine grooves in the sample. But, as the rotational speed increases these fine grooves were converted into craters which become considerable (Figure 6B and C) and the main reason for abrasive wear at the increased speed is the material was eroded by dry sand at constant load. Thus, in the NiTi alloy, the worn-out surface are not so imposing; which resulted in the wear resistant properties of SMA. With the increase of the rotational speed of the abrasion wheel all the material was found to be disintegrated and small particles of the sample found along with the sand. When the wheel rotates at maximum speed (i.e. 300 rpm), the surface becomes strange as shown in Figure 6C.

Figure 6: Wear behavior of NiTi alloy (A) at 200 rpm; (B) at 250 rpm; (C) at 300 rpm.

3.5 Coefficient of friction

Figure 7A shows the variation of coefficient of friction with the sliding distance. With increase in sliding distance the coefficient of friction reduces; which may be due to strain hardening of the material. With increased sliding distance, the surface of the material becomes smoother, which results in the decreased coefficient of friction. Figure 7B shows the graphical representation of coefficient of friction with the wheel rotational speed. An increase in coefficient of friction was observed with increased rotational speed; which may be due to heat being generated in the counter-face which, in turn, increases the true contact area as per equation 2.

Figure 7: Coefficient of friction variation in (A) NiTi vs. sliding distance; (B) NiTi vs. rotation speed.

$$\mu = F = A\tau/W \quad (2)$$

where A = true contact area, τ = shear strength and W = normal reaction.

4 Conclusions

1. The density of the NiTi alloy decreases from 6.7 to 5.1 g/cm³ with the increase of organic binder percentage from 3 to 15%.
2. The porosity increases from 23 to 57% with the increase of organic binder percentage from 3 to 15%. SEM micrographs also reveal that with the increase of binder percentage the porosity increases.
3. XRD analysis reveals; that in the sintered NiTi alloy, austenitic NiTi phase (B2) overcomes the intermetallic NiTi₂, Ni₃Ti and the martensitic NiTi (B19') phase.
4. The wear rate increases with an increase in the load and rotational speed of the abrasion wheel.
5. The coefficient of friction reduces slightly in NiTi alloy with sliding distance while it increases with the rotational speed.

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