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Influence of a Liquid on the Deformation Behavior of Porous Nickel and Titanium under Compression

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Abstract. The deformation behavior of capillary porous (CP) Ni and CP Ti is examined under uniaxial compression in air, water, and ethanol. CP metals contained inert liquids such as H₂O and C₂H₅OH are used as the heat pipes' active elements in space applications. The samples for mechanical testing were isostatic compacting and vacuum annealing (porosity of 60%). Uniaxial compression tests were carried out in the air, water, and ethanol in Shimadzu AG-50K XD (traverse rate 0.1 mm/min). It was shown that CP Ni and CP Ti exhibit the ductile deformation behavior in all cases, which is inherent to Ni and Ti. The ethanol environment induces the increase of the compression strength and the total deformation in both materials compared to deformation behavior in air and water. Therefore, a heat pipe's failure containing CP Ni and CP Ti matrixes and ethanol as the working body is caused rather by manufacturing defects, but not the structural materials' intrinsic properties.

1. Introduction

The capillary porous (CP) metals are an essential part of the heat pipes (HPs), which are used in heat dissipation systems in space applications [1]. A heat-transfer liquid circulates inside a CP metallic structure, providing heat transfer from microchips in a vacuum [2]. Porosity, chemical inert to a heat-transfer liquid, and density are the critical parameters for CP metallic devices [1,3] Besides, their strength properties play an essential role in the durability of HPs as technical systems [4]. Therefore the study of the deformation behavior of CP metals in heat-transfer liquids is actual [1, 5].

There are two channels of the influence of the environment on the strength properties of a material. The first one is the interaction of atoms with the surface, while the second is the penetration of the environmental atoms into a material through structural defects [6]. Porosity may be considered as the intrinsic property of CP metals, where a metallic matrix contains pores [7]. The deformation behavior of CP metals under uniaxial compression in inert liquid media is the subject of this paper. CP Ni and CP Ti having a porosity up to 60% are the model materials in this work, whereas water and ethanol are the model heat-transfer liquids [4]. These materials are used in HPs as capillary pumps for heat-transfer fluid in the modern space apparatus [8].

The deformation behavior of CP materials depends on both at the stage of their machining in the manufacture of the HP evaporator and during operation in space flight conditions, including vibration effects at various stages of the comic apparatus flight [1]. However, the mechanical properties of such complex objects have practically not been studied, although, for the successful application of such materials in technology, information on their strength, plasticity, and elastic modulus is required [7]. Therefore, this work aims to study these CP materials' mechanical behavior, including their interaction in some inert liquids.

2. Experimental

The workpieces of CP Ni and CP Ti were prepared using the isostatic compacting of powders, including the vacuum annealing at 700°C for 2 hours. The microstructures of CP Ni and CP Ti possessed a porosity



of 60% in the initial state are shown in figure 1,2. The hollow diamond drill with an inner diameter of 5 mm was used to manufacture the mechanical testing samples. The samples have the shape of a cylinder with a diameter of 5mm and a height of 3 mm The uniaxial compression testing was carried out on Shimadzu AG-50K XD machine (traverse rate 0.1 mm/min) in air, in water, and ethanol. Ten samples were used for testing in every environment. Stress-strain curves were built for every sample, and their mechanical characteristics were determined with the help of Trapezium™ software. Back surfaces of every sample were documented by the metallographic means before and after deformation.

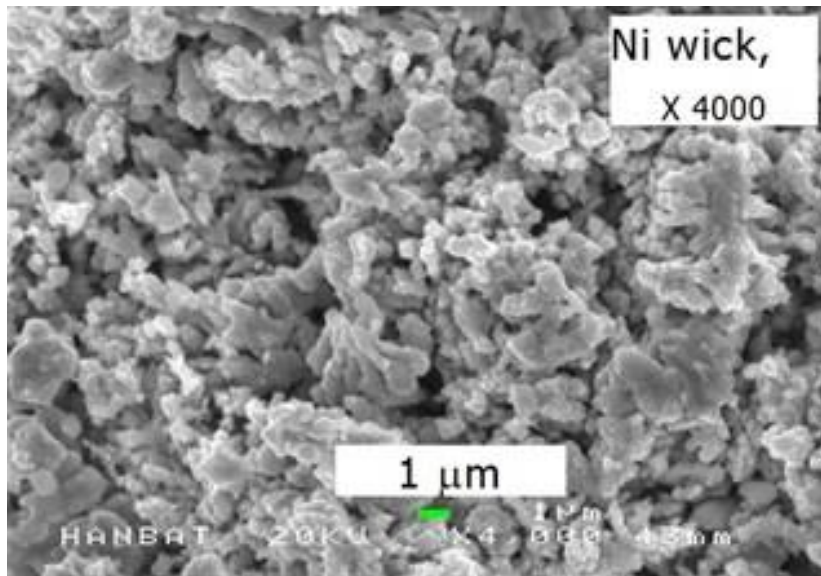


Figure 1. The microstructure of CP Ni (SEM).

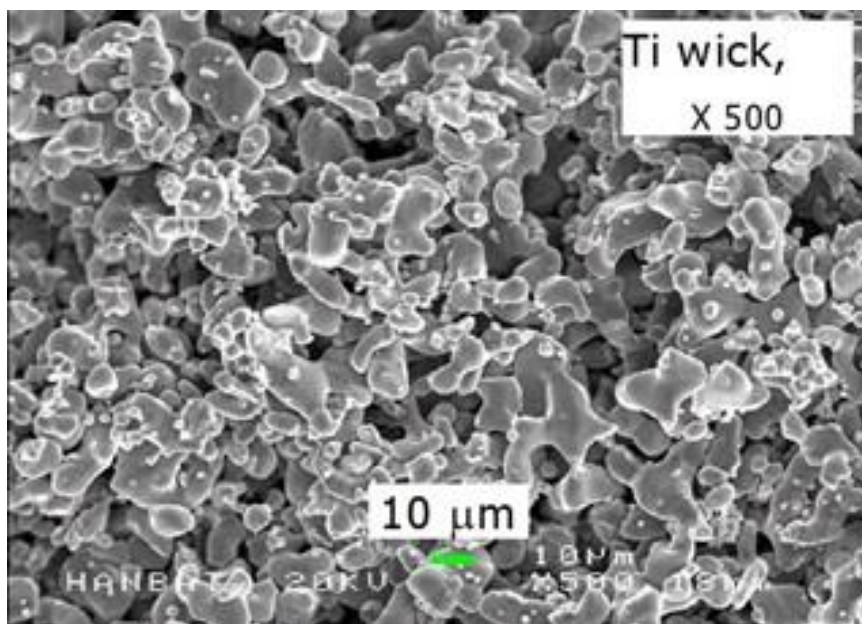


Figure 2. The microstructure of CP Ti (SEM).

3. Results

The stress-strain curves of CP Ni and CP Ti under compression in different environments are shown in figure 3, while their mechanical properties are given in table 1.

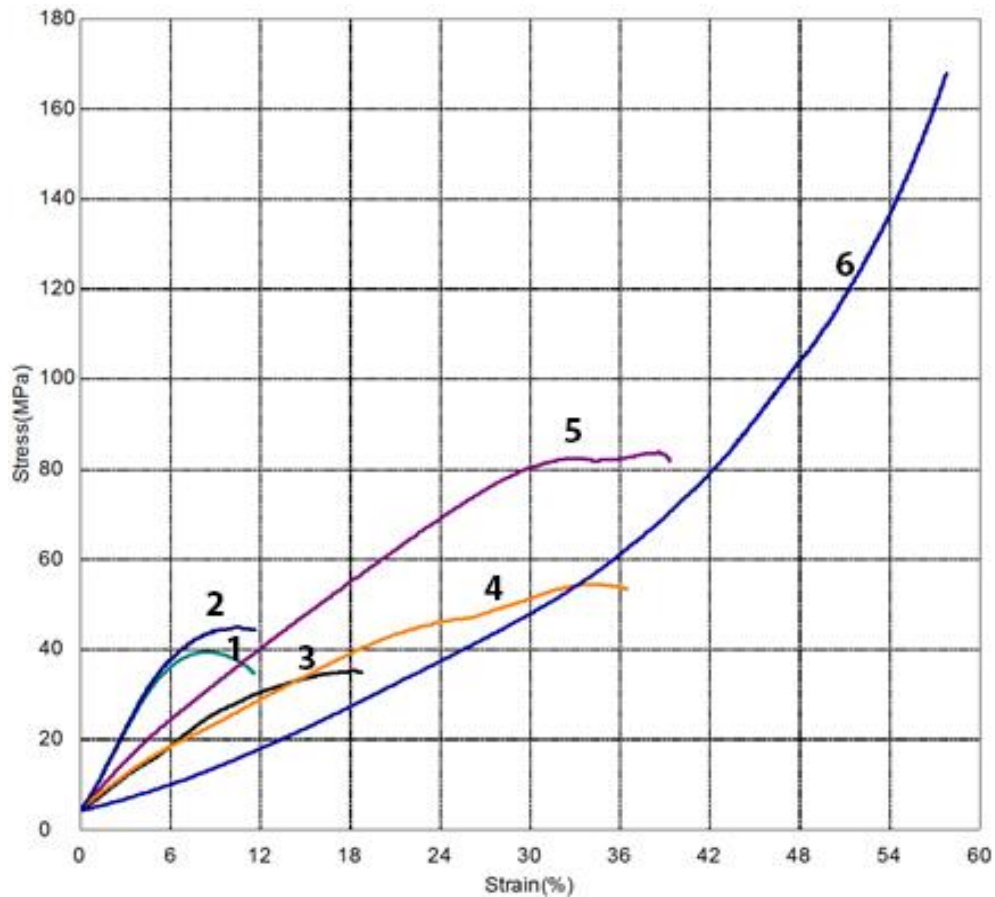


Figure 3. Uniaxial compression of CP Ni (1 - air; 2 - water; 3 - ethanol) and CP Ti (4 - air; 5 - water; 6 - ethanol).

Table 1. Mechanical properties of porous titanium and porous nickel under uniaxial compression in air, water, and ethanol.

Material	Elastic module E, MPa	Tensile strength, MPa	Deformation to failure δ , %
On Air			
Ni	500 ± 50	35 ± 3	10 ± 1
Ti	300 ± 10	55 ± 3	30 ± 5
In Water			
Ni	700 ± 150	33 ± 1	10 ± 2
Ti	300 ± 50	85 ± 15	35 ± 3
In Ethanol			
Ni	200 ± 100	37 ± 7	20 ± 1
Ti	250 ± 50	>165	>55

Both materials exhibit ductile deformation behavior, which is intrinsic to an FCC-metal and an HCP-metal, respectively [9,10]. The CP Ni curve's inclination angles on the initial stage of deformation are the same for testing in air and water, while this parameter for ethanol is less than two times. Indeed, the elastic moduli of CP Ni strongly depend on the environments. The total plasticity and the compression strength of CP Ni in air and water are also the same. The total plasticity of CP Ni compressed in ethanol is two times higher than in air and water, but the compression strength is similar to testing in air and water. The inclination of stress-strain curves and the compression strength of CP Ti in air and water are different, despite their total plasticities are similar. The less inclination of the curve occurs under compression of CP Ti in ethanol, which exhibits the highest total plasticity and the highest compression strength. The elastic moduli of CP Ti are similar for all environments.

The CP Ni and CP Ti samples for compression testing in the initial state are shown in figure 4a and figure 5a, respectively. Both of them possess rough surfaces, whose morphologies are presented in figures 1 and 2. No visible defects, such as notches and large pores, were observed on their surfaces. In other words, the samples did not contain macroscopic stress concentrators, which could induce the failure of a sample.

Under compression in air, the cracks in CP Ni appeared on the samples' cylindric surface. No cracking was observed on surfaces contacted with the testing machine plates (figure 4b). The cracks were directed along the compression axis, while their length was about the sample's height (figure 4c). The testing in water did not change the character of cracking of CP Ni. Cracks appeared on the cylindric surface only (figure 4d,e). Similar behavior took place under compression in ethanol while the samples' surfaces, which contacted the plates, began intensively separated on the tiny pieces near the edges (figure 4f).

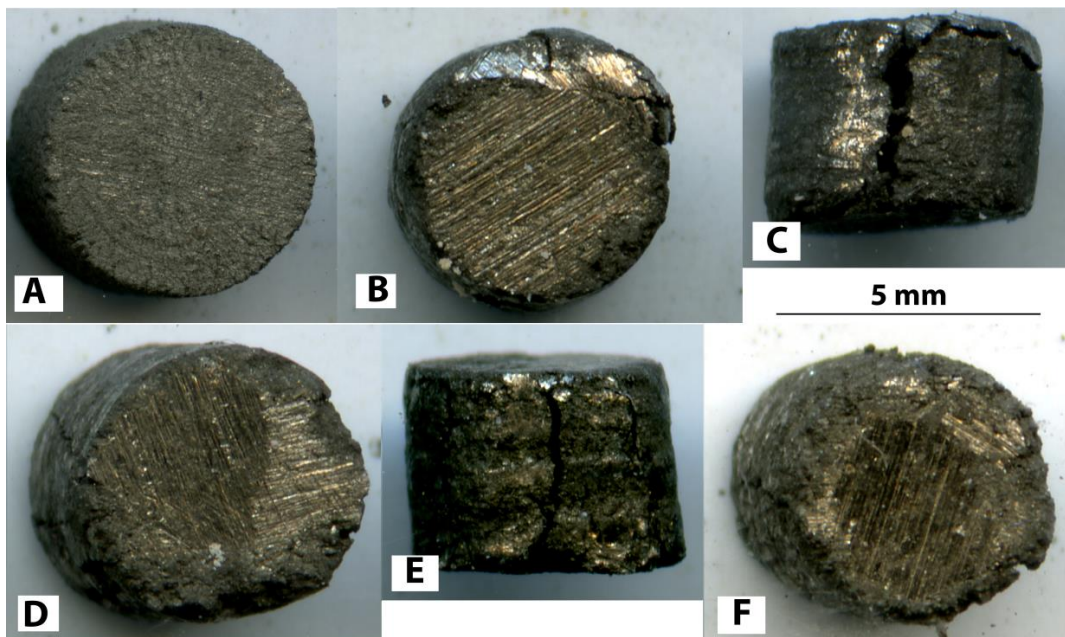


Figure 4. Samples of CP Ni for mechanical testing: a – initial state; b, c – testing on air; d, e – testing in water; f – testing in ethanol.

There were cracks in both cylindric and contact surfaces of the CP Ti samples compressed in the air. The cracks on the contact surface advanced along the circle, which radius is close sample's diameter (figure 5b). The cracks on the cylindric surface had an almost rectilinear profile and were inclined to the sample's compression axis (figure 5c). It should be noted that initially cylindric surface was transformed into a barrel form under compression of the CP Ti in the air. The fracture behavior of CP Ti under compression in water was similar to that described above (figure 5d,e). Under compression in ethanol, CP Ti samples were separated into tiny parts (figure 5f). However, the cracks moved on the concentric trajectories were sometimes observed on the samples' contact surfaces.

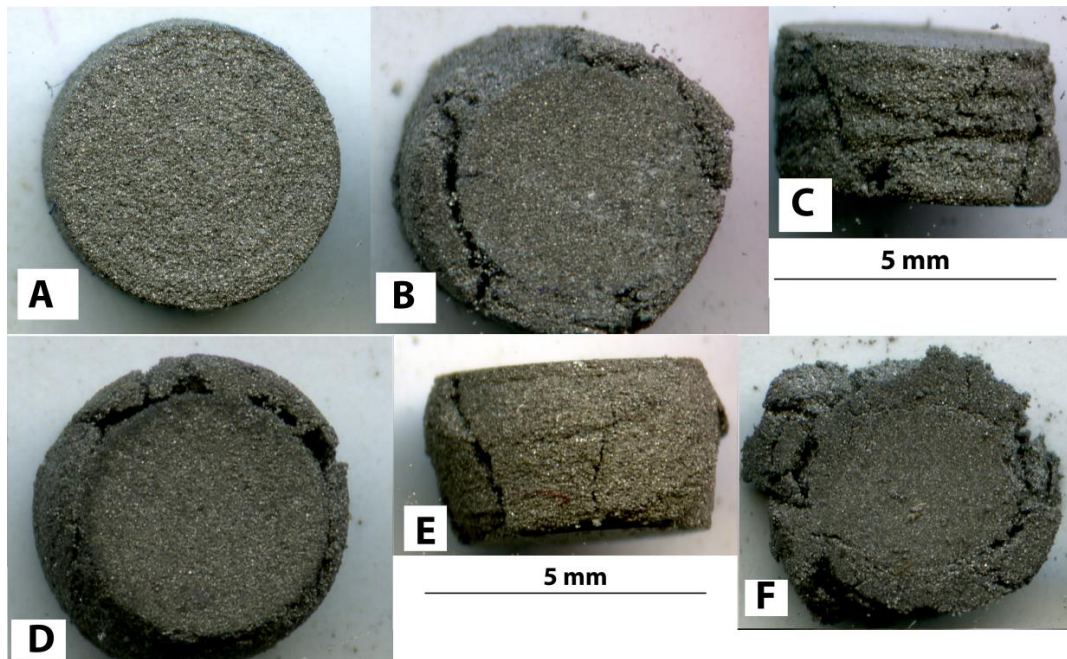


Figure 5. Samples of CP Ti for mechanical testing: a – initial state; b, c – testing on air; d, e – testing in water; f – testing in ethanol.

4. Discussion

As was expected, CP FCC-metal of Ni exhibits high work-hardening but low plasticity compared to CP HCP-metal of Ti [9,10]. A liquid environment does not change this trend independently from the mechanical properties of an inert liquid [1,7]. Water does not influence the behavior of CP Ni compared to its behavior in the air. On the contrary, CP Ti's work-hardening in water increases compared to testing in air, while CP Ti's plasticities in air and water are the same. The fracture behavior of CP Ni in the air is similar to its fracture behavior in water. A similar picture takes place in CP Ti tested in the air and water. The work-hardening decreases, while the plasticity increases in ethanol in both CP metals. Their fracture behavior in ethanol is also the same. It may be concluded that both CP metals behave like ductile solid independently from an environment [7]. However, their plastic properties rise considerably under testing in ethanol.

The presence of water causes the difference between the mechanical properties of CP Ti in water and air. Water flows into the pores of the metallic matrix and, hence, changes its elastic properties. As a result, the work-hardening of CP Ti increases. The same scenario can occur in CP Ni; however, this effect did not observe due to FCC-metal CP Ni's high strengthening.

The penetration of ethanol into the CP metallic matrix's pores leads to considerable growth of both metals' plasticity. Hence, ethanol does not induce the rising of elastic properties of the porous matrix. Its lower viscosity compared to water is the cause of this effect. It may be supposed that the capillary

effect plays the dominant role in the behavior of CP Ni and CP Ti under compression in an inert liquid. Simultaneously, the capillary effect could prevent the flow of a liquid inside the porous matrix. Therefore, the heat-transferer in the heat pipe should possess low viscosity compared to water for CP Ni and CP Ti matrixes [1,4].

The feature of CP Ni and CP Ti's deformation behavior under compression in inert liquids is its ductile character. It means that the brittle crack growth should be suppressed in both materials despite considerable deformation before the failure and their porous morphology [11]. Considering that CP Ni and CP Ti do not embrittle by ethanol and water, the failure of a heat pipe with Ni or Ti matrix is caused rather by manufacturing defects, but not the structural materials' intrinsic properties [7,10].

5. Conclusion

CP Ni and CP Ti exhibit the ductile deformation behavior in all cases, which is inherent to Ni and Ti. The ethanol environment induces the increase of the compression strength and the total deformation in both materials compared to deformation behavior in air and water. Therefore, a heat pipe's failure containing CP Ni and CP Ti matrixes and ethanol as the working body is caused rather by manufacturing defects, but not the structural materials' intrinsic properties

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