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Mechanical Strengthening and Microstructural Evolutions of Ni-B Based Hardfacing Alloys Influenced by Titanium Additions

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Abstract: The microstructure and mechanical behaviour of Ni-B binary alloys have been enhanced in this study by varied titanium additions. The alloys investigated were chosen from the nickel-rich region of the Ni-B-Ti system. The microstructure of the alloys was examined using Optical Microscope (OM) and Scanning Electron Microscope (SEM) equipped with Energy Dispersive X-ray Analyzer (EDXA). The addition of titanium led to the formation of various complex phases and a ternary phase τ was observed in the study. The addition of titanium to the Ni-B alloys was found to enhance the mechanical properties of the ternary alloys. Microhardness value of the alloys was observed to increase from 216.2 HV with zero Ti in Ni-B alloys to 1530.7 HV in alloys with 11 wt. % Ti. The stiffness of the alloys was also found to increase as deduced from elastic modulus value of 513.77 to 1046.51 N/m^2 in Alloys C. Remarkable improvement in physical properties of the Ni-based ternary alloys is due to the formation of various hard boride phases and grain size reduction occasioned by the increase in titanium content.

Keywords: Ni-B Alloys, Ti Addition, Microstructure, Microhardness, Ternary Alloy, Stiffness

1. Introduction

Due to the inability of materials to meet the need of engineers, surface treatments of materials become pertinent for their optimum performance. Thus, recently the problem of wear, abrasion, hot corrosion as well as poor hardness and poor stiffness of materials have been addressed by surface treatments and hardfacing techniques [1-6]. Hardfacing is a metalworking process where harder or tougher material is applied to a base metal. It generally takes the form of specialized electrodes for arc welding or filler rod for oxyacetylene. Hardfacing technique involves the preparation and application of hard alloy coatings on surface of materials. These alloys usually contain several hard phases (borides, carbides and silicides) made up of titanium, chromium, vanadium etc. and non-metals like boron, carbon and silicon. Though nickel, cobalt or iron can be used as the base material for these alloys, nickel is often chosen because of its self-fluxing properties at high temperature [3, 7-8]. The distribution of the borides, carbides and silicides in the nickel matrix are the major source of the wear, hot corrosion, abrasive resistance as well as enhanced hardness and stiffness of the alloys.

In the study of phase transitions in some nickel-rich nickel-boron-titanium hard alloys, Ajao [9] reported the microstructure of Ni-B-Ti alloys and the crystallographic orientation relationships between nickel and the boride phases. Solid-state transformation of the ternary phase was observed in his study. Recently, Viega et al. [10] reported the properties and applications of titanium alloys. It was concluded that titanium alloys are practically applicable in aerospace, automotive and biomedical industries; thanks to their outstanding properties. Studies have also shown that titanium, chromium, vanadium enhances the wear, abrasion and hot corrosion resistance; and increases the hardness, stiffness and high temperature compressive strength of alloys containing boron through the formation of hard boride phases [11-14]. It has been reported that boron depresses the melting point of the base alloy mixture and plays a critical role in self-fluxing properties [15]. Recently, An et al. [16] reported the interfacial structure and mechanical properties of surface iron-nickel alloying layer in pure iron fabricated by surface mechanical attrition alloy treatment (SMAAT). A refined Fe/Ni alloy layer of about 50µm was prepared on pure iron, and it was reported that intermetallic/alloy phases were formed and the diffusion activation energy was reduced; the formed alloy reduces fatigue wear effect and improve friction and wear properties to a large extent. In some other studies, eutectoid transformation of some phases in nickel-based hard alloys have been reported [9, 11, 17, 18].

Ni-B alloy coatings possess remarkable properties like high wear resistance, high hardness and attractive corrosion and abrasive resistance properties [19, 20-22]. Also, Ni-B coatings have properties which include: lubricity, uniform thickness, attractive ductility, anti-bacterial property, good electrical properties, low porosity, superior electromagnetic and bonding [23-28]. Because of these attractive properties, interests in Ni-B based alloys continue to grow in different area and have been applied practically in many highly technological industries such as petroleum, automobile, nuclear, aerospace, computer, optics, textile, food, etc. industries [29-34]. In some other instances, Ni-Cr-B-C group is taken as the primary composition of nickel-based alloys. Different alloy elements lead to different degrees of hardness. Nickel alloys also resist wear and corrosion well, and are cheaper than cobalt alloys. Controlled amounts of carbide powders such as tungsten carbide, chromium carbide and niobium carbide, have been added to Co and Ni-based alloys. These have shown to improve the physical properties of the hardfacing layer, also exhibit an enhanced performance in high-temperature environments [35-37]. Titanium possesses high hardness, specific strength, low thermal conductivity, relatively low density, high reactivity with a variety of elements and good corrosion resistance, among other attractive properties [38-41]. Titanium is known to be a very important additive in Ni-B based binary and ternary superalloys for wear resistance applications due to its formation of TiB_2-Ni compacts and coatings [42-45]. As a result of these unique properties of titanium, it is important to study the addition of titanium with Ni-B alloys for improved performance. To the best of the knowledge of the authors, not much studies have been carried out on Ti additions in Ni-B system and few reports are currently available on the influence of titanium on physical properties of Ni-B alloys [46, 47]. The foregoing thereby stimulates the interest in the present study. The aim of the work was to prepare Ni-based ternary alloy with varied additions Ti additions using electric furnace melting, and hence determine the effect of titanium additions on the microstructure and the mechanical properties of the alloy samples.

2. Materials and Methods

2.1. Preparation of the Alloys

A binary control sample of Ni-10B was prepared separately, and the ternary Ni-B-Ti alloys at different compositions of titanium (2-11 wt. %). The components of the alloy samples were pure nickel and binary Ni-B containing 10 wt. % B and pure titanium (99.99% pure). The components of each alloy were accurately weighed and melted in an electric furnace. Shown in Figure 1 is the equilibrium phase diagram for the Ni-B-Ti system by Schobel and Stadelmaier [48] and the positions of the alloys studied are identified. The chemical compositions of the alloys are presented in Table 1.

2.2. Characterization of the Alloys

Metallographic observation of the alloys was done by optical and scanning electron microscopes equipped with energy dispersive X-ray analysis system. Etching of the samples were done before SEM analysis. The etchant consists of 5g $FeCl_3$+10ml HCl dissolved in 50ml H_2O. Micro-hardness tests were performed on the alloys at the Engineering Development Institute (EMDI), Akure, Nigeria, while compression tests were performed on the alloys with the use of the Instron machine at Centre for Energy Research and Development (CERD), Obafemi Awolowo University, Ile-Ife, Nigeria.

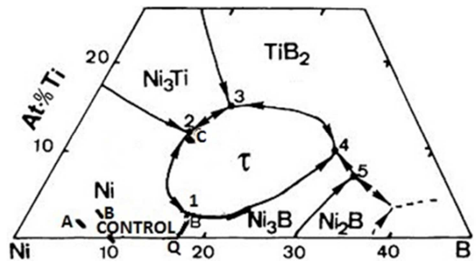

Figure 1. *The liquidus projection of the Ni-B-Ti ternary system [48].*

Table 1. *Chemical compositions (wt. %) of the alloys.*

Sample	Chemical compositions (wt. %)		
	Ni	B	Ti
Control	90	10	-
Alloy A	93	5	2
Alloy B	91	6	3
Alloy C	82	7	11

3. Results and Discussion

3.1. Microstructure of the Alloys

The scanning electron and optical micrographs of the control sample are shown in Figures 2a and 2b respectively. The primary Ni (α) phases can be seen bounded by strips of Ni-Ni_3B phases. However, a drastic change in the microstructure can be observed for the Ni-B alloys containing Ti additions. For Alloy A with 2 wt. % Ti addition and quenched from the liquidus, the primary phase observed in both SEM and optical microscope images is the block-like Ni(α) phase shown in Figures 3a and 3b. This phase was surrounded by wider binary eutectic phase Ni-Ni_3B. The quenched Alloy B with 3 wt. % Ti shows clearly the presence of the binary eutectic Ni-Ni_3B as the primary phase (Figures 4c and 4d). The primary Ni-Ni_3B phase is surrounded by Ni_3B phase. Meanwhile, the elemental compositions of the identified phases in the microstructures were analyzed with EDXA and the results shown in spectra images, Figures 4a, 4b and 4c for Ni (α), Ni-Ni_3B and Ni_3B respectively. It should be noted that though the elemental composition of the analyzed phases in the control sample is similar to that of Alloys A and B with titanium content, the primary phase observed in the morphology was the Ni(α) phase (Figures 2a and 2b). The absence of Ti in the analyzed phases of Alloy A and B might be due to the fact the Ti content was below the detection limit. However, due to the microstructural changes observed, we can therefore imply that the additions of titanium have influence on the phase transformations of the alloys, which encouraged a shift from the hypoeutectic to the hypereutectic region during quenching in air. Similar observation has been reported by Ajao [9] in his study of Ni-B-V ternary system.

A distinct and complete evolution in the microstructure can be observed for Alloy C containing 11 wt. % Ti as shown in SEM and optical images (Figures 6a and 6b). The effect of the Ti addition can be deduced from the total transformation with the grain size and widespread distributions by the formed phases. The primary phase formed as solidification began was the τ phase. This phase was followed by the crystallization of Ni-Ni3B-τ ternary eutectic. These phases are shown in the SEM (Figure 6a) and OM (Figure 6b) images for Alloy C. Figures 7c and 7d shows the EDXA spectra for the main τ and Ni-Ni_3B-τ phases. It should be emphasized that for the alloys without the Ti addition, the primary phase observed on the microstructure was the Ni (α) phase. While the addition of titanium to this Ni-B binary led to the formation of other hard phases, which effect reflected most in this work at the at highest Ti addition of 11 wt. %.

Another very important observation is the evolution of the grain size and distribution in the alloys. The size of the grains making up the alloy microstructure is observed to reduce with the addition of the titanium to the Ni-B binary alloy. The control alloy is observed to be constituted of relatively larger grain of primary Ni (α) phase bounded by Ni-Ni_3B phases. Studies have shown that grain size reduction usually have positive impact on the mechanical or generally the physical properties of the metal matrix alloys or ceramic composites, while grain growth during sintering or alloying process does have detrimental effect. Thus, the more reduced the grain size during material processing, the better the structural properties such as hardness, wear, corrosion etc. In this work, reduction in grain size of the phases was achieved with Ti addition, and it is indicated that the Ti enhanced the physical properties of Alloy A, B and C.

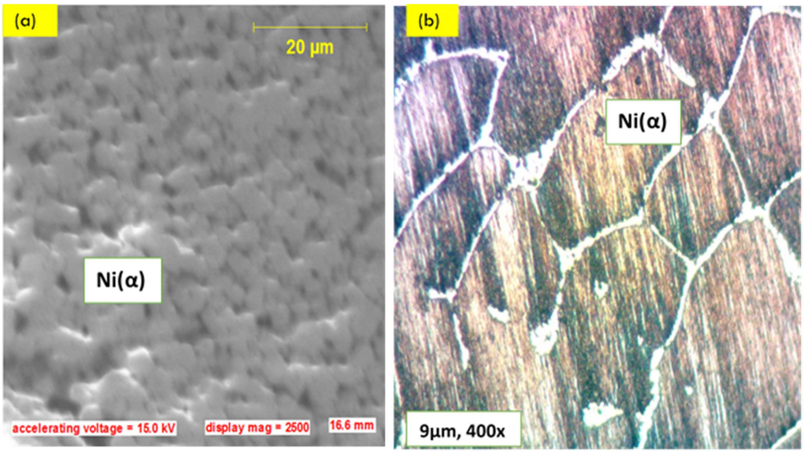

Figure 2. *Micrographs of Quenched Control Sample (Ni-10B-0Ti). (a) SEM and (b) optical microscope.*

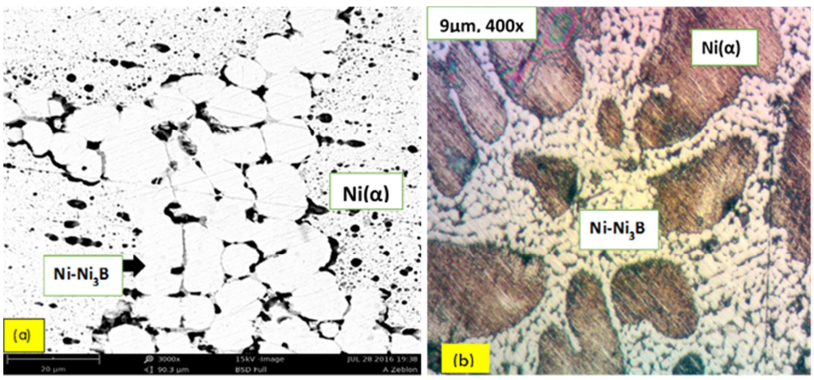

Figure 3. *Micrographs of Alloy A containing 2 wt. % Ti. (a) SEM and (b) optical microscopy.*

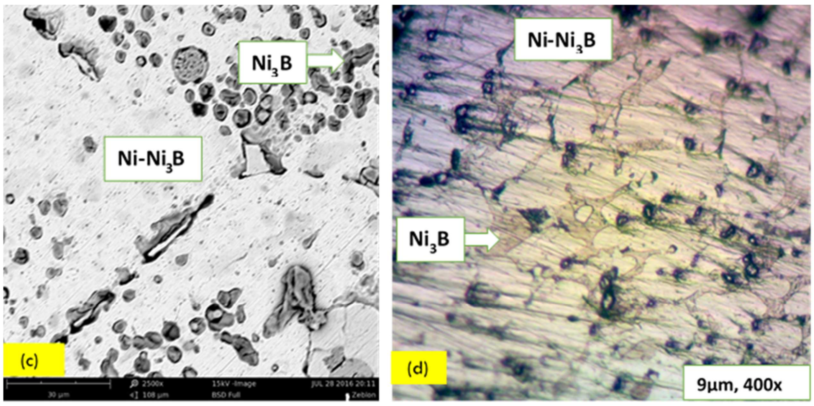

Figure 4. *Micrographs of Alloy B containing 3wt. % Ti. (c) SEM and (d) optical microscope.*

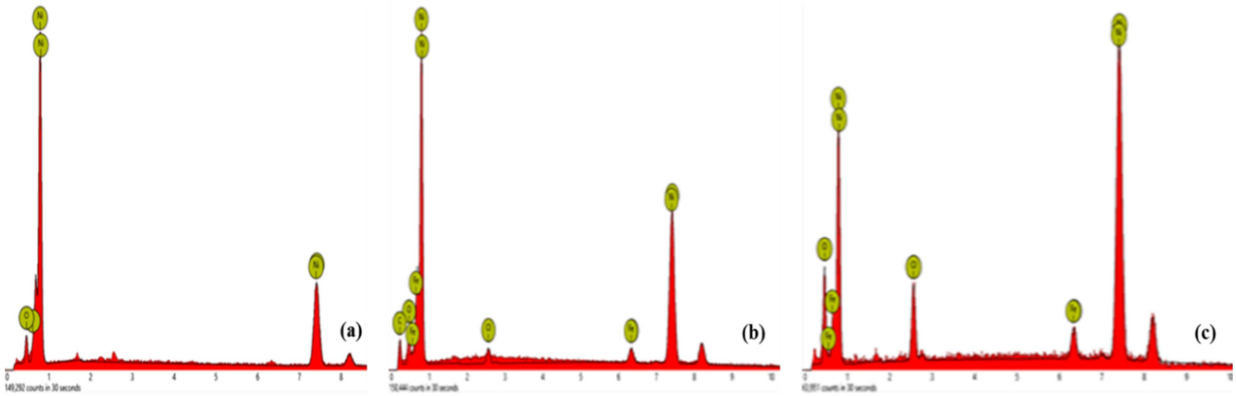

Figure 5. *EDX analyses spectra of (a) Ni (α), (b) Ni-Ni₃B and (c) Ni₃B phases identified on Alloys A and B.*

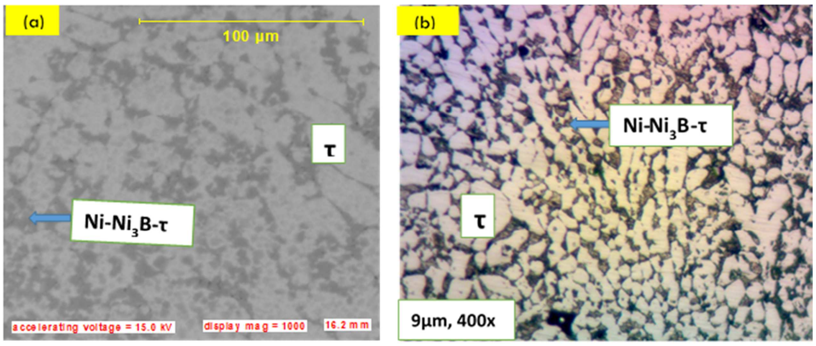

Figure 6. *Micrographs of Alloy C containing 11wt. % Ti (a) SEM and (b) Optical microscopy.*

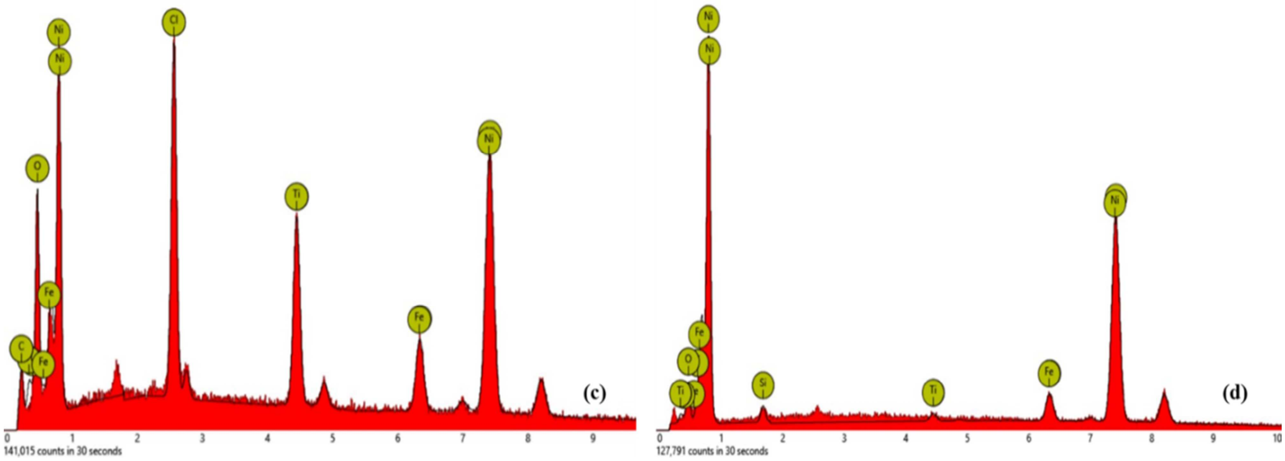

Figure 7. *EDX analyses spectra of the (c) τ phase and (d) Ni-Ni₃B-τ phase in Alloy C.*

3.2. Microhardness of the Alloys

The hardness values of the alloys are presented in Table 2. A plot of the hardness values of the alloys as a function of the titanium contents is shown in Figure 8. It can be seen that the hardness values increased as the titanium contents increased. Experimental results indicated that the microhardness of Ni-B alloy samples with Ti additions had higher hardness values compared to the control alloy Ni-10B. Similar observations has been reported in literatures [46, 49]. The very high microhardness exhibited by Alloy C (11 wt. % Ti) is a result of large amount of Ti elemental powder that was well dispersed within the Ni-based ternary resulting in increased volume fraction of hard boride phases known for high hardness. The wide gap between the microhardness values of the alloys is as a result of the wide difference in concentrations of titanium additions in the ternary alloy samples. Also, the introduction of Ti in Ni-B binary matrix enhances its mechanical properties by the suppression of grain growth during melting and recrystallization, which led to the propagation of the fine-grained microstructure of intermetallic boride phases such as Ni3B, Ni-Ni3B-τ, τ and Ni3B [50].

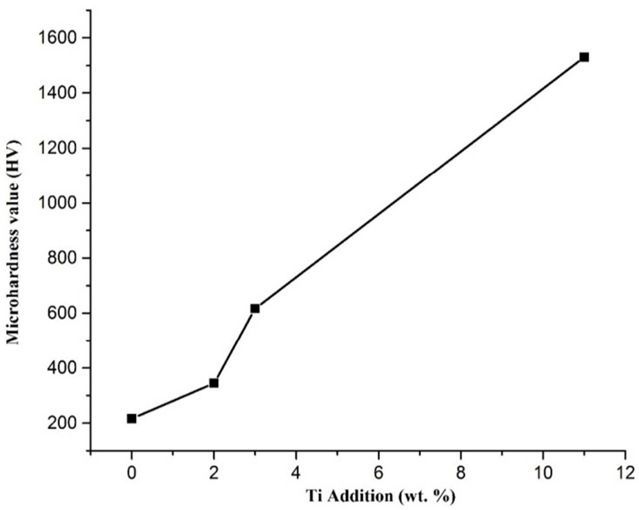

Figure 8. *Average hardness values of the alloys as a function of the titanium contents.*

3.3. Stiffness of the Alloys

Stiffness is the rigidity of an object, which is the extent to which it resists deformation in response to an applied force. The stiffness of an alloy is of high significance in various engineering applications, hence the modulus of elasticity is often one of the primary characteristics considered when selecting a material. A high stiffness is required when deflection is detrimental to the design, while a low modulus of elasticity is required when flexibility is necessary. In this work, high hardness of the alloy is desirable. The results obtained from the compressive tests performed on the alloy samples are presented in Table 3. A plot of the variation of elastic moduli with titanium content is shown in Figure 9. The stiffness of the alloys can be deduced from the elastic modulus plot, and it is shown to increase with increase in the titanium content. What this means is that as we add more titanium to the nickel-boron matrix, the matrix becomes stiffer. This is attributed to the formation of harder boride phases and most importantly the reduction in grain sizes of these alloys as we add more titanium to alloys. It may also be attributed to the formation of pockets of titanium boride hard phases in these alloys as we add more titanium.

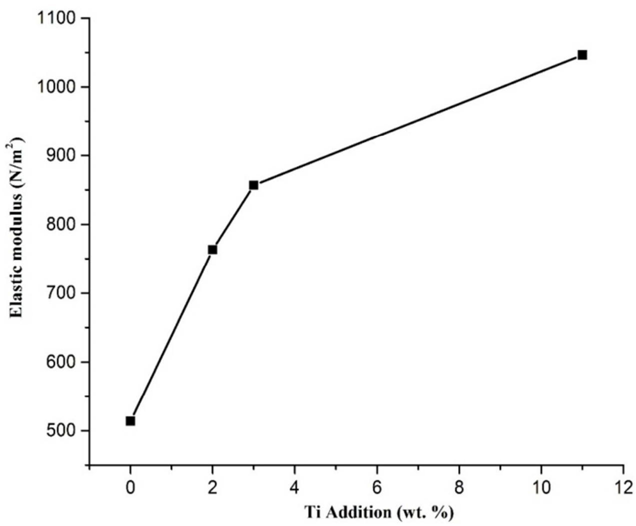

Figure 9. *A plot of the variation of elastic moduli with titanium content in the alloys.*

Table 2. *Average hardness values of the Ni-based alloys investigated.*

Samples	First HV	Second HV	Third HV	Average HV
Control	218.8	212.2	217.5	216.2
Alloy A	339.1	335.1	359.4	344.5
Alloy B	639.4	627.3	583.1	616.6
Alloy C	1675.9	1556.8	1359.5	1530.7

Table 3. *Compressive test results of the alloys investigated.*

Sample	Maximum compressive stress (MPa)	Compressive strain at maximum compressive stress	Elastic modulus (N/m^2)
Control	82.62908	0.16083	513.77
Alloy A	354.18392	0.46412	763.13
Alloy B	185.12663	0.21611	856.63
Alloy G	353.06255	0.33737	1046.51

4. Conclusion

In this study, binary Ni-B and ternary Ni-B-Ti alloys with varied Ti addition were prepared using high temperature furnace melting, while the influence of Ti additions to the Ni-B based ternary alloys have been studied using microstructural, elemental and mechanical characterization techniques. It is observed that addition of Ti to the Ni-B alloys led to the shifting of the alloys from the hypoeutectic to the hypereutectic region during quenching in air. Also, addition of Ti to the Ni-B alloys also led to the formation of hard boride and complex phases as discussed in the text. As show in the microstructure, titanium addition and increase in Ti concentrations induced steady reduction in grain size in the Ni-based alloys with the formation of two major primary phases [Ni (α) and τ] and other binary and ternary eutectic structures, and were identified as contributing to the hardness of the ternary alloys. Increase in addition of Ti to the Ni-B alloys led to corresponding increase in the hardness and stiffness of the alloys.

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