Mechanical Properties of Tungsten Fiber Reinforced Ti-6A1-4V Alloy by HIP Fabrication

S.Y. SON[*1], S. NISHIDA[*2], N. HATTORI[*2], K. HAYASHI[*2] and K. NAKANO[*3]

[*1] Graduate school of Saga University, Dept. of Mechanical Engineeting,
Honjo-machi 1, Saga City, 840-8502, JAPAN
[*2] Saga University, Dept. of Mechanical Engineering
[*3] Takata Engineering Ltd. Co., Kitakyushu 808-0143, JAPAN

ABSTRACT

Tungsten short fiber reinforced Ti-6Al-4V alloy (W/Ti-6A1-4V) was processed by Hot Isostatic Pressing (HlP) and it's mechanical properties were investigated and compared with those of conventional Ti-6Al-4V alloy and HlP treated Ti-6Al-4V.

According to the results in the present study, the average hardness of diffusion phase between fibers and Ti-6Al-4V matrix shows a value of about 20-30% higher than that of the conventional Ti-6Al-4V and also the hardness value increased with an increase in the volume fraction of tungsten fibers. The tensile strength of the composite material was about 15% higher than that of the conventional Ti-6Al-4V.

However, the fatigue limit of the composite materials was unexpectedly deteriorated in comparison with that of the conventional ones. The deterioration of the fatigue limit could be attributed to the defects in the microstructure of the composites such as clustering of fibers, micro-cracks and porosity.

KEYWORDS

Tungsten Fiber Reinforced Ti-6Al-4V Alloy, HlP Fabrication, Hardness number, Tensile Strength, Fatigue Limits, Defects

1. INTRODUCTION

Metal-matrix composites (MMCs) have been continuously developed to provide a mutual solution between an advanced property and cost saving. Several kinds of MMCs containing particles, whiskers or fibers as reinforcements have been increasingly employed in industry where specialized properties of materials with extremely high fatigue limits, high stiffness and low coefficient of thermal expansion, etc. are demanded [1,2,3].

Conventional Ti-6Al-4V alloy is widely employed in several engineering applications and the MMCs using this alloy for the matrix have been studied and expected to be one of the most currently advanced materials [4,5]. Most research on Ti-based MMCs has concentrated on ceramic reinforcement composites whose fabrication is expensive and complicated. Recently, tungsten (W) fiber, which possesses high a melting point and excellent mechanical strength has been attempted to be used as an alternative metallic reinforcement in developing a new type of W/Ti-6Al-4V MMC.

The subject of this paper is to investigate the mechanical and fatigue properties of a tungsten fiber reinforced Ti-6Al-4V (W/ Ti-6Al-4V) processed by a powder metallurgy method employing HIP, following by a secondary treatment using free forging and rotary swaging.

2. EXPERIMENTAL PROCEDURE

2.1 Materials and specimen

Table 1. Chemical compositions of Ti-6Al-4V alloy

Al	V	Fe	O	C	N	H
6.14	3.93	0.17	0.19	0.011	0.014	0.009

mass%

Table 2. Tensile strength and aspect ratio of W fiber

Fiber diameter d (μ m)	Tensile strength σ_B (MPa)	Aspect ratio l*/d		
		Max.	Min.	Ave.
20	3430	135	7.0	47.9

*l: Fiber length, d: Fiber diameter

Table 3. Specimens and fiber contents by HIP conditions and second process

Materials	HIP	Second process	Volume fraction of W fiber (vol.%)
Con.*	-	-	0
H1-9	1	FF	9
H2-0	2	RS	0
H2-6			6
H2-9			9
H2-12			12

FF: free forging, RS: rotary swaging
Con.* : conventional Ti-6AL-4V

Table 4. Results of Vickers hardness test

Materials	Average	Surface*	Core*	Matrix**	Interface**
Con.	316.9	320.5	313.2	-	-
H1-9	446.0	457.1	435.0	394.0	464.3
H2-0	-	334.3	345.0	-	-
H2-6	381.0	410.0	373.0	359.5	424.6
H2-9	405.5	421.3	379.9	382.2	453.5
H2-12	418.2	431.3	396.0	406.0	437.5

*: HV(1.96N) **: HV(0.049N)

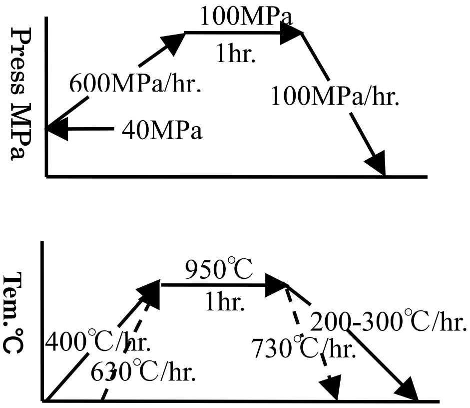
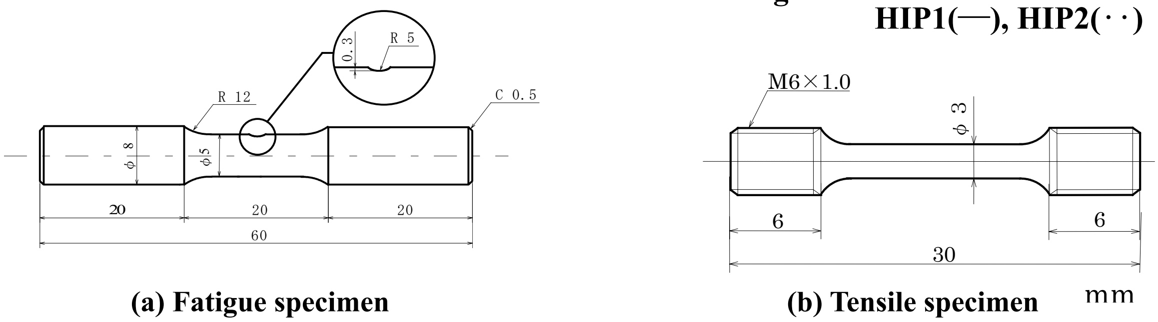


Fig. 1 HIP treatment conditions HIP1(—), HIP2(· ·)



(a) Fatigue specimen **(b) Tensile specimen**

Fig. 2. Shape and dimensions of specimen

Atomized Ti-6Al-4V powder, with grains of an average size of 100μm, and tungsten short fibers were mixed (using a V milling machine, operating at 60 rpm for 0.5hr) and then the composites were processed by HIP[6,7]. Table 1 lists the chemical composition of Ti-6Al-4V alloy and Table 2 lists the tensile strength, density and aspect ratio of W short fiber, respectively.

Two conditions of HIP were used as depicted in Fig. 1. In order to improve the homogeneity of fiber-distribution in the matrix, a secondary process employing free- forging (FF) or rotary swaging (RS) was performed after the HIP process. Table 3 lists the specification of the specimens.

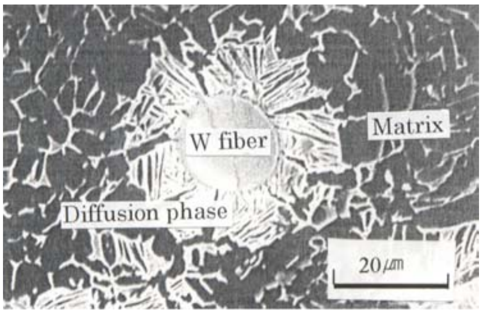
Configurations of tensile and fatigue test specimens are shown in Fig. 2.

2.2 Test procedure

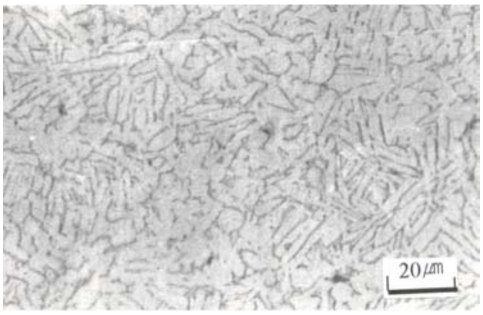
All of specimens were annealed at 600°C for 0.5hr in a vacuum furnace. After annealing, the specimens were mechanically polished with emery paper (#400~3000) then with polishing powder (Al_2O_3/0.1 μm), and then etched with a solution of 10%HF + 20%HNO_3. To assess the effects of the polishing method on the testing results, one additional group of HIP-2 treated specimens was prepared by extensive electro-polishing after mechanically polishing.

The Vickers Hardness number was measured in accordance to JIS-Z2244 at the loads of 1.96N and 0.245N, respectively.

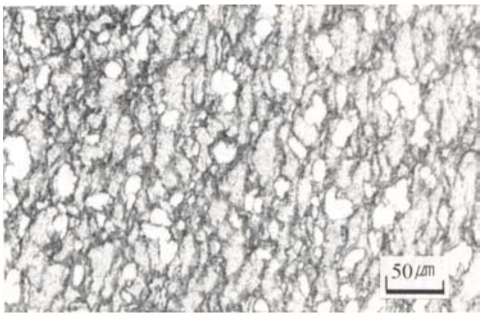
The tensile tests were carried out using a hydraulic universal testing machine（with a capacity of 98kN）and the fatigue tests were conducted by an Ono-type rotating bending machine operating at 3000rpm at room temperature. The surface of the fatigue specimens was monitored by



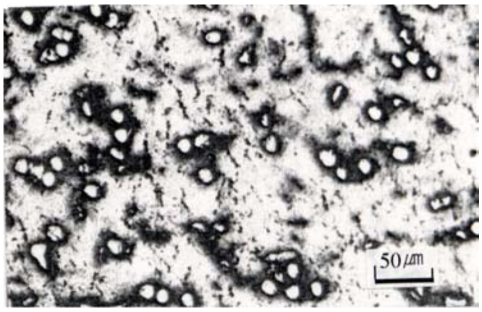
(a) Microstructure of composite



(b) HIP2-0



(c) HIP1-9



(d) HIP2-9

Fig.3 Optical microstructure

Table 5. Tensile strength of W / Ti-6Al-4V

Materials	Tensile strength MPa
Con.	980
H2-0	1088
H2-6	1144
H2-9	1520
H2-12	1288

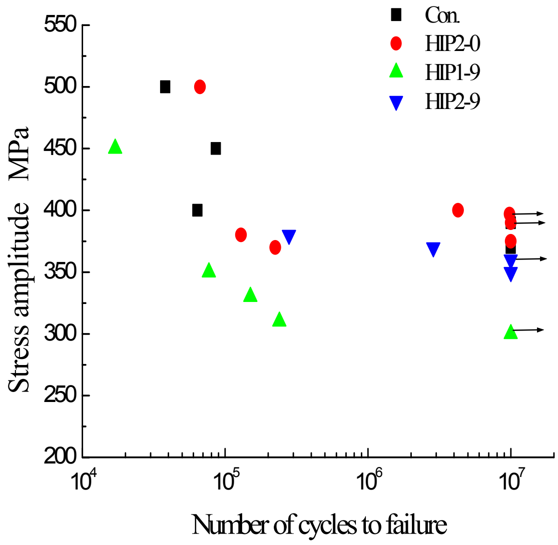


Fig. 4 S-N curves of HIP1 and HIP2 specimens

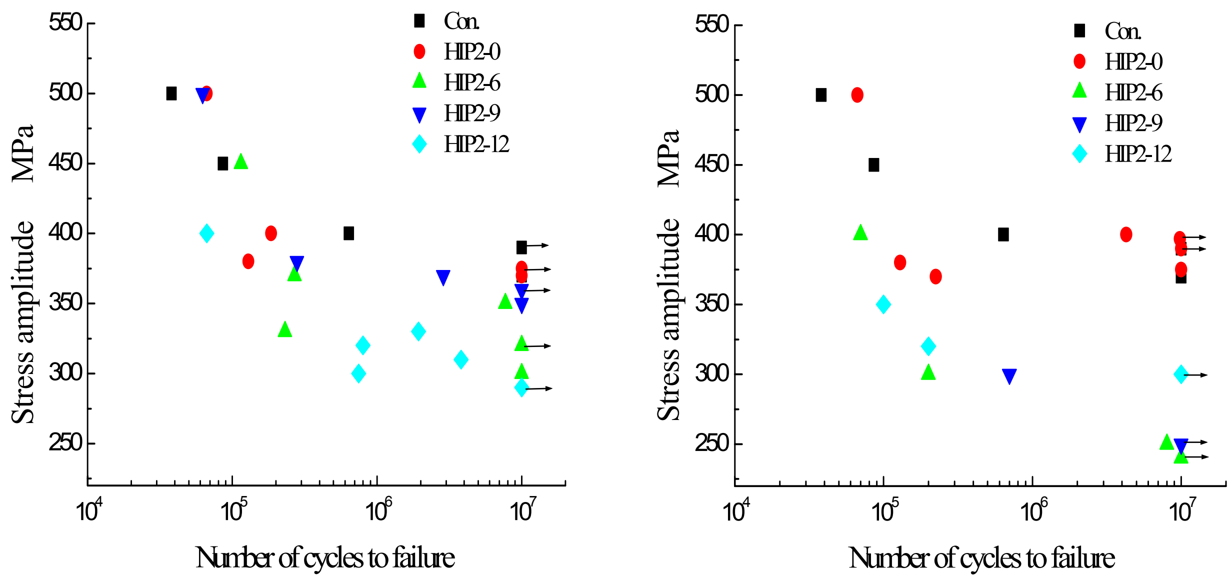
plastic-replica method and the successively taken replicas were observed with an optical microscope. The fracture surface of the tensile and fatigue specimens was investigated using scanning electro microscope (SEM).

3. RESULTS

Fig. 3 shows the microstructure of HIP-Ti-6Al-4V alloy and HIP1-W/Ti-6Al-4V and HIP2-W/Ti-6Al-4V, respectively [Fig.3]. An interphase structure was observed between the fibers and the matrix [Fig.3 (a)]. By EPMA analysis, it is suggested that the interphase could be a diffusion phase in which the W atom diffused into the Ti-6Al-4V matrix. Table 4 lists the result of the hardness test. The hardness number of HIP1 showed higher value than HIP2 by about 12%. The hardness numbers of the diffusion phase in MMCs showed a value by about 20-30% more than that of conventional Ti-6Al-4V alloy. It increased with an increase in volume fraction of W fiber.

Table 5 lists the results of the tensile test of HIP2-W/Ti-6Al-4V specimens. The tensile strength of the MMCs showed a higher value in comparison with the tensile strength of the conventional Ti-alloy. It tended to improve with an increase in the volume fraction of the W fibers. The maximum value of the tensile strength in this work was 1520 MPa, which was achieved for the MMC reinforced with 9 vol.% W fibers.

Fig. 4 representatively illustrates the S-N curves of HIP1-9, HIP2-9, HIP2-0and conventional Ti-6Al-4V specimens. The fatigue limit of HIP1-9 and HIP2-9 were lower than that of the conventional Ti-6Al-4V by approximately 25% and 10% respectively. On the contrary HIP2-0



(a) Mechanically polished materials **(b) Electro-polished materials**

Fig.5 S-N curves of HIP-2 specimen to various fiber content ratios

exhibited the same or higher value fatigue limit in comparing with that of the conventional Ti alloy.

Fig. 5 shows some typical S-N curves of HIP2 treated specimens followed by mechanical [Fig.5 (a)] and electro-polishing [Fig.5 (b)]. The fatigue limit of the MMCs was about 40% lower than that of the conventional Ti-6Al-4V specimens. Considering the volume fraction of W-fibers, the fatigue limit decreased in the order of 12,9,6 vol.% for the electro-polished specimens, but it decreased in the order of 9,6,2 vol.% for the mechanically polished ones. Generally, the overall fatigue limits of the mechanically polished specimens were higher.

4. DISCUSSIONS

4.1 W-fibers/matrix diffusion layers and improvement of tensile strength:

According to the foregoing test results, tensile strength of W/Ti-6Al-4V showed a remarkable improvement with the addition of the tungsten fibers. The interface layer between the W fiber and the Ti-6Al-4V matrix was a diffusion layer as shown in Fig.3 (c) and (d). The HIP1 specimen exhibited relatively larger areas of diffusion phase than those of the HIP2 one. The difference may be caused by the difference of heating and cooling rate in each HIP process, where the slower rate in the HIP1 process might result in a larger amount of diffusing of W atoms into the matrix.

The results of hardness test shown in Table 4 also suggested that the average hardness increases proportionally to the area of the diffusion phase in the matrix.

The existence of the diffusion phase improved the local strength of the interfaces between the reinforcing fibers and surrounding matrix materials, resulting in a good reinforcing effect of the W fibers on the overall static strength of the MMC. The observation of a fracture surface of a tensile specimen shown in Fig.6 exhibits the vast majority of broken fibers, where as “pull-out fibers” were hardly found. That suggested a strong interface was achieved in the present MMC.

4.2 Deterioration of fatigue limit:

From a simple empirical relation between fatigue limit σ_W and Vickers hardness number HV, expressed as $\sigma_W \fallingdotseq 1.6HV$, the fatigue limit of the composite was expected to be improved according to the increase of hardness number. However, the fatigue limit of the MMC in this work actually deteriorated: The reasons for this might be attributed to the low ductility of the matrix associated by defects, such as, clustering of fibers, micro-cracks and porosity. Particularly, fiber-clusters seemed to reduce the crack initiation resistance of this MMC.

Fig.7 (a) shows the observation of crack initiation in a HIP1-W/ Ti-6Al-4V specimen started from a cluster of fibers [see Fig.7 (b) for details] and secondary micro-cracks (mostly inter-granular) were frequently observed on the fatigue fracture zone [see Fig. 7 (c)].

The fracture surface of HIP2 showed multi initiation cracks and porosity [view Fig.7 (d) an (e)].

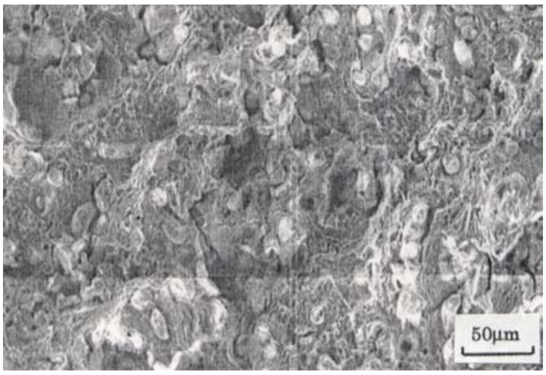


Fig.6 Tensile fracture surface observed with SEM

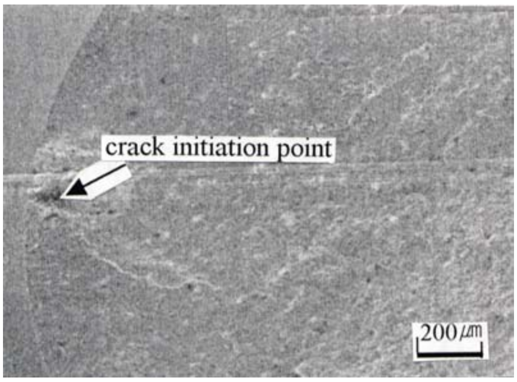
Table 6. The density of porosity

Materials	Porosity density (%)
H2-0	-
H2-6	3.26
H2-9	3.55
H2-12	4.01

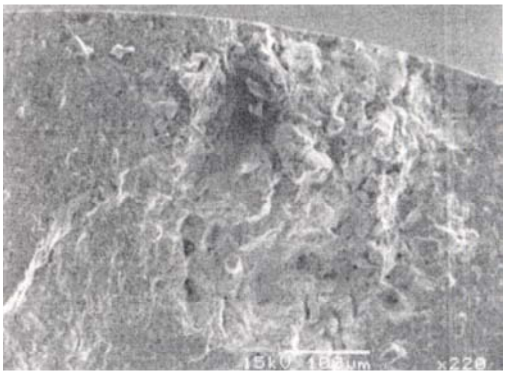
Several cracks initiating from the surface of the fatigue specimen and then coalescing to propagate were observed. The results of quantitative analysis of the density of porosity in the HIP2-specimens, represented by the percentage of area exposed on a specified area are shown in Table 6. The porosity density seems to increase with an increase in the fibers volume fraction.

The fatigue limit of the HIP2-0%W/Ti-6Al-4V specimens without fibers exhibited an excellent result; even better than that of the conventional Ti-6Al-4V specimen. Consequently, the existence of defects caused by the addition of fibers into the Ti-6Al-4V matrix seems to be the major problem in order to improve the fatigue properties of the MMCs. To assess the influence of the effects of the distribution of fibers on the fatigue properties of W/Ti-6Al-4V, much more rigorous studies on this subject are required. Within the limitation of the present work, it was found that rotary swaging (RS) treatment gave a better result to the fatigue limit than the free forging (FF) one. The improvement of fatigue property might be expected when an adequate HIP process associated with a secondary process such as RS is developed to overcome with the problems understood by the present study.

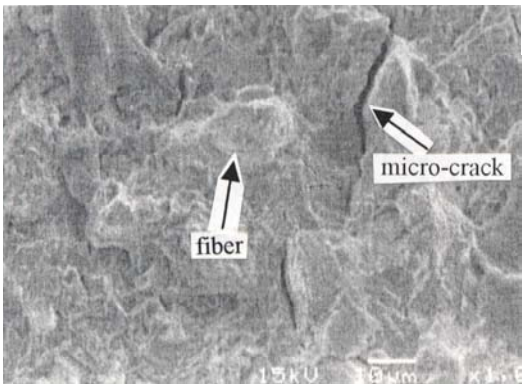
In addition, the polishing process of the fatigue specimen may also have an affect on the fatigue limit of the MMCs specimen. As shown in Fig. 7 (f), the electro-polished specimens' surface exhibits W-fiber-extrusion (resulted from the fact that W-fibers were relatively cathodic with respect to the Ti-6Al-4V matrix in electro-polishing process) and the difference of stress concentration at



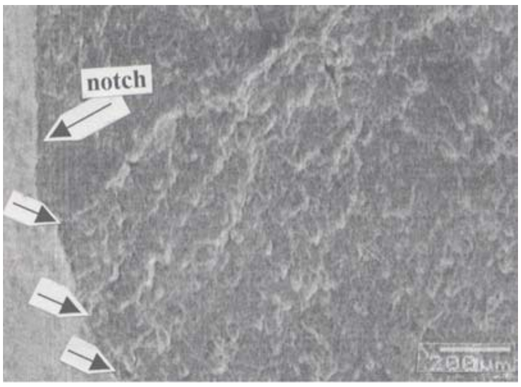
(a) Crack initiation point HIP1-9



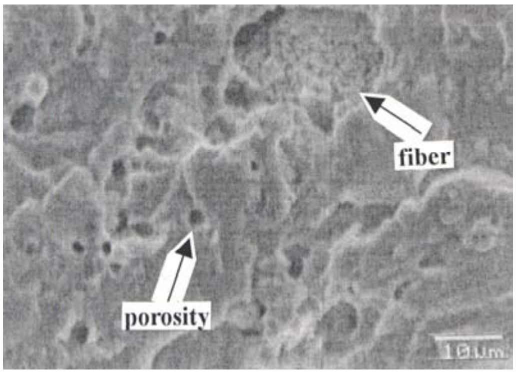
(b) Magnificent crack initiation point



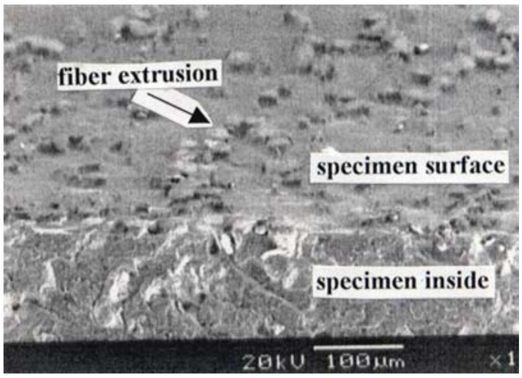
(c) Micro-cracks in the matrix HIP1-9



(d) Multi cracks initiation points HIP2-9



(e) Porosity in the matrix HIP2-9



(f) Fiber extrusion HIP2-9

Fig.7 Fatigue fracture surface observed with SEM

the interphaces of W-fibers/matrix may be attributed to the reason why the fatigue limit of the electro-polished specimens was lower than that of the mechanically polished ones.

5. RESULTS

The testing results on HIP fabricated W/Ti-6Al-4V MMCs have been reported and discussed. The main conclusions are follows;

1. W-fibers reinforced Ti-6Al-4V matrix composite could be produced by the HIP process used in this work.
2. The hardness number and the tensile strength of MMCs produced by the above process showed higher values in comparison with those of conventional Ti-6Al-4V by about 20-30% and 15% respectively. Both hardness and tensile strength with tended to increase the increase of in volume fraction of tungsten fibers.
3. However, fatigue limit of the MMCs unexpectedly deteriorated. The defects such as clustering of fiber, micro-cracks and porosity, etc. were considered to be the major reson.
4. Within the present work, the employment of high heating and cooling rates in the HIP process led to the better property of the composite. HIP2 process is found to be comparatively better than HIP1 for producing W/Ti-6Al-4V MMCs.

REFERENCES

(1) T.Hayashi , The composite material engineering, (1980), p1173-1181
(2) R.O.Ritchie, R.H.Dauskardt and B.N.Cox., Fatigue of Advanced Materials, MEPE Ltd, (1991), 315.9
(3) H,Ochiai et al.: Journal of the Japan Society for Composite Materials, 21-2, (1995), p37-46.
(4) W.F.Smith., Structure and Properties of Engineering Alloys, McGraw-Hill Book Co., (1994)
(5) M.J.Donachie,Jr., Titanium a technical guide, ASM international, (1988)
(6) T.Kimura et al.: Journal of the Japan Society of Mechanical Engineers, 28-11, (1998), p897-901.
(7) Titanium material researchers, Present aspect of Titanium materials research in Japan, (1989), p81