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Comparative study of the behaviour of several reinforcement materials in titanium matrix produced by Rapid Sinter Pressing Manufacturing

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ABSTRACT. Regarding titanium matrix composites (TMCs), their properties strongly depend on the reinforcement material employed for their manufacturing; this may lead to a multitude of investigations on TMCs. Considering the diverse typology of the reinforcement, six types of ceramic particles were tested in this investigation: B_4C, SiB_6, TiB_2, TiC, TiN, and BN. In order to compare their behaviour and their own influence on the properties of the TMCs, the same ratio was employed in the starting materials, 30% volume. Among the techniques for developing TMCs, a significant number of authors propose Powder Metallurgy as a favourable route. In this framework, the novel Rapid Sinter Pressing technique was employed to perform the present study, due to its flexibility, repeatability, and reproducibility, as well as short-run cycle times. The processing temperature (930 °C) was set with the intention of evaluating how the reinforcements behave differently depending on their reactivity with the Ti matrix. In this regard, the main objective of the research was to carry out a comparison on the behaviour of seven TMCs fabricated with similar operational parameters via RSP.

KEYWORDS: Microstructure; Rapid sinter pressing; Titanium composites; Tribological behaviour, XRD analysis

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RESUMEN. *Estudio comparativo del comportamiento de diversos materiales de refuerzo en matrices de titanio fabricados mediante compactación por sinterización rápida.* En cuanto a los materiales compuestos de base titanio (TMC), sus propiedades dependen en gran medida del material de refuerzo empleado para su fabricación; dando lugar a una gran diversidad de investigaciones sobre los TMCs. Considerando la diversa tipología del refuerzo, en este estudio se trabajó con seis tipos de partículas cerámicas: B_4C, SiB_6, TiB_2, TiC, TiN y BN. Para poder comparar su comportamiento e influencia sobre las propiedades de los TMCs, se empleó siempre la misma proporción con respecto al material de partida, 30% en volumen. Entre las técnicas que se conocen para desarrollar

TMCs, la pulvimetalurgia ha sido propuesta como una vía favorable por un número significativo de autores. En este marco, para la realización del presente estudio, se utilizó la novedosa técnica *Rapid Sinter Pressing*, debido a su flexibilidad, repetibilidad y reproducibilidad, así como a sus reducidos tiempos de ciclo. La temperatura de procesamiento (930 °C) se estableció con la intención de evaluar cómo los refuerzos afectan de diferente manera, en función de su reactividad con la matriz de Ti. En este sentido, el objetivo principal de esta investigación ha sido realizar una comparativa del comportamiento de siete TMCs fabricados vía de Compactación por Sinterización Rápida (*Rapid Sinter Pressing*) bajo las mismas condiciones de procesado.

KEYWORDS: Análisis de rayos X; Compactación por sinterización rápida; Comportamiento tribológico; Materiales compuestos de base titanio; Microestructura

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1. INTRODUCTION

Studies conducted to investigate the behaviour and manufacturing of Titanium Matrix Composites (TMCs) have been conducted for nearly four decades. From then on, many authors reported the diversity of methods to improve the properties of Ti and its alloys (Smith and Froes, 1984; Ranganath, 1997; Ravi Chandran *et al.*, 2004; Ni *et al.*, 2006; Tjong and Mai, 2008; Tang *et al.*, 2013; Choi *et al.*, 2014; Jiang *et al.*, 2016; Tkachenko *et al.*, 2018; Farías *et al.*, 2019; Pan *et al.*, 2021; Monisha *et al.*, 2022). Insufficient mechanical and tribological properties of Ti and its alloys may detract from their implementation for uses and applications in which these properties were an imperative need. For that reason, various interesting strategies to strengthen Ti and its alloys were investigated, such as solid solution strengthening, grain boundary strengthening, and dispersing secondary reinforcement particles in the Ti matrix (Hayat *et al.*, 2019; Wang *et al.*, 2022).

In the context of dispersing secondary particles, intensive analysis has been carried out to find how reinforcement goodness lied in adequate bonding to the matrix and its uniform distribution inside the matrix (Wang *et al.*, 2019; Fang *et al.*, 2021; Mohanavel and Vijayakumar, 2021). In this regard, with the use of ceramic particles, which could react with titanium, the optimal properties of TMCs can reasonably be expected to be achieved.

Technological advances allowed the development of TMCs via powder metallurgy (PM) (Ammisetti and Kruthiventi, 2020). A novel technique among these diverse processes, Rapid Sinter Pressing (RSP) is considered. This technique allows the fabrication of specimens in a short cycle run through hot consolidation at high pressure (Montealegre-Meléndez *et al.*, 2017). In this study, RSP has been selected to fabricate the TMCs due to their short operational time and flexibility.

In the comparative carried out in the present investigation, various reinforcements have been selected, not only by the good stability and integrity in the matrix (TiC and TiN) (Mishra and Sherbakov, 2016; Huang *et al.*, 2016), but also by their reactivity with Ti to form secondary reinforcement phases (B_4C, TiB_2, SiB_6, and BN) (Ni *et al.*, 2006; Radhakrishna Bhat *et al.*, 2002; Popov *et al.*, 2017; Montealegre-Melendez *et al.*, 2011; Sabahi Namini *et al.*, 2017). In this regard, a different behaviour of the produced TMCs might be expected.

With the aim of promoting a benchmarking analysis of the reinforcements on the TMCs behaviour, the same volume content of ceramic particles (30% vol.) has been employed in the manufacturing of the TMCs. Furthermore, identical operational parameters have been set to determine how each one acts and reacts with the matrix. Characterisation of the specimens provided the comparison of the physical and tribological properties of the samples. Through X-ray diffraction (XRD) analysis and microstructural study, interesting conclusions could be drawn from these obtained results.

The novelty of this research lies in the combination of the manufacturing process, RSP, with the diversity of reinforcements employed under the same operating conditions. In this regard, an interesting pursuit of the best Ti matrix-reinforcement system could be driven. Concerning the objectives of this study, TMCs were made from seven powder blends to study the behaviour of the titanium reinforced matrices developed via RSP at similar parameters. The conclusions drawn in this research may turn out to be interesting for obtaining complete information about the goodness of this RSP technique for fabricating TMCs. It was observed how the temperature was a limitation to promote secondary reactions; in this context, the TMCs made from the smaller starting powders presented lower properties related to the possible agglomeration of particles that occurred during the manufacturing process.

2. MATERIALS AND METHODS

Composite matrices were made of titanium powder grade 1 (<45 µm, with spherical particles, supplied by TLS); its oxygen content was less than or equal to 0.18 wt.-% according to the supplier's information. With the intention of providing information about the behaviour of various reinforcements in titanium, the selection of seven ceramic reinforcements was carried out considering their different typologies and morphologies. Table 1 shows the main characteristics of the reinforcements. All the starting powders were analysed with a Mastersizer 2000 (Malvern Instruments, Malvern UK) to determine their particle size. In addition, their morphology was examined by Scanning Electron Microscopy (SEM; FEI Teneo, Hillsboro, OR, USA), as shown in Fig. 1.

As it is seen in Fig. 1, there were significant differences among the morphology of the starting powders. In this respect, the particle characteristics may affect the final properties of the TMCs in different ways. In the case of fine particles, agglomerations were clearly observed in the SEM images, in Fig. 1d), with SiB_6 reinforcement, and Fig. 1f), corresponding to the TiC starting powder. In this context, the possible repercussions of this phenomenon on the final properties of the composites were examined. Therefore, special attention should also be paid to the characterisation results of the specimens reinforced with other fine particles.

After the starting materials characterization was performed, the manufacture of the TMCs was carried out. In Fig. 2 a detailed sketch of the fabrication process is presented. The first stage was the preparation of the seven blends. The composition of the TMC in vol.-% was set to a fixed value of 30 vol.-%, independently of the reinforcement used; in Table 2 there is a list with the compositions and identification of the named TMCs. The powder mixing stage was performed on a Sintris Mixer (Sintris Macchine S.R.L., Piacenza, Italy). This process lasts two hours, employing ceramic balls (3 mm in diameter, Al_2O_3), to obtain dispersed ceramic particles in

Table 1. Sample list with powder sizes, supplier information, and morphology

Id	d_{10}	d_{50}	d_{90}	Supplier	Morphology
B_4C coarse	39.052	63.757	102.028	ABCR	Irregular with sharp edges
B_4C fine	15.439	23.307	34.945	ABCR	Irregular with sharp edges
SiB_6	3.911	11.341	33.421	ABCR	Irregular rounded with agglomerations of finer particles
TiB_2	1.652	4.988	13.297	Treibadner	Irregular
TiC	2.559	7.571	15.393	ABCR	Irregular
TiN	1.660	6.583	16.180	H.C. STARCK	Irregular
cBN	42.102	58.234	80.419	China Abrasives	Irregular with sharp edges

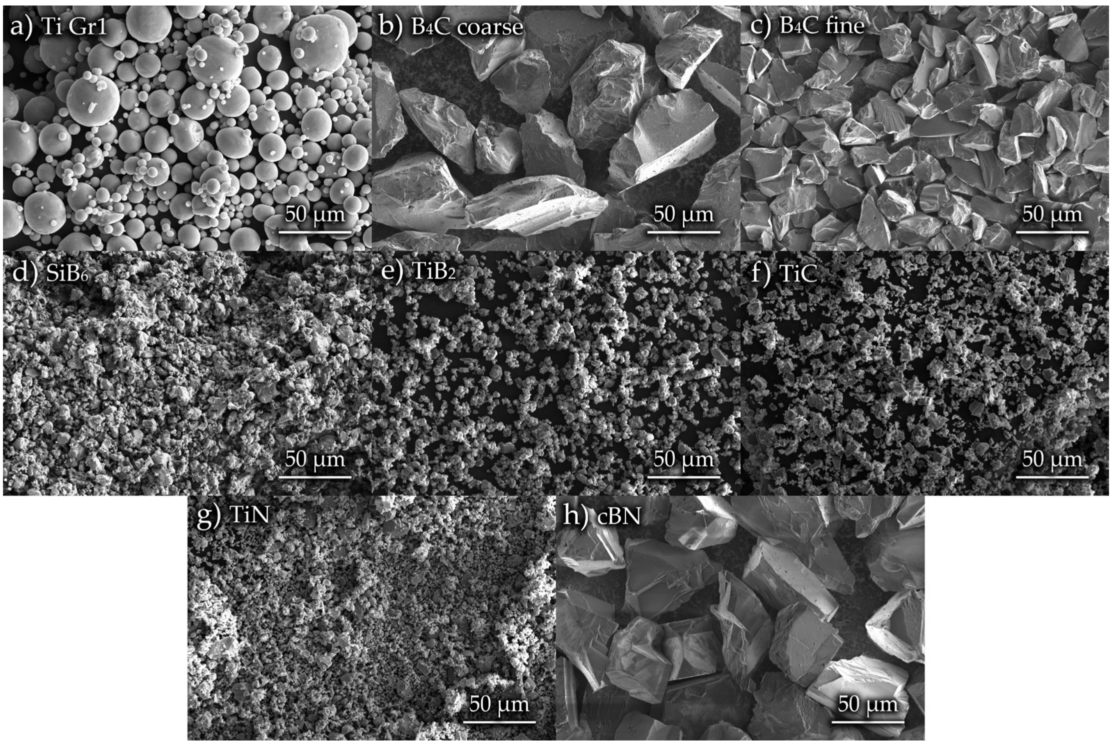

Figure 1. SEM images of the powders: a) Ti Grade 1; b) coarse B_4C; c) fine B_4C; d) SiB_6; e) TiB_2; f) TiC; g) TiN; h) cBN.

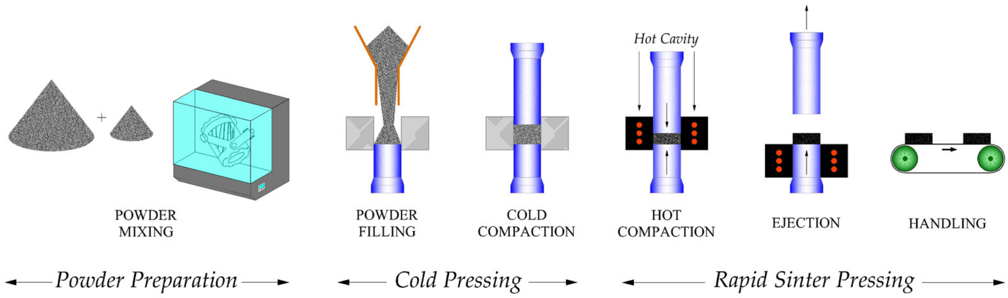

Figure 2. Manufacturing sketch of the composites.

Table 2. Sample list with compositional information and powder sizes

Id	TMCs Composition	Reinforcement powder size
TMC1	Ti + 30 vol% B_4C coarse	B_4C, 45-75 µm
TMC2	Ti + 30 vol% B_4C fine	B_4C, 8-32 µm
TMC3	Ti + 30 vol% SiB_6	SiB_6, < 45 µm
TMC4	Ti + 30 vol% TiB_2	TiB_2, < 10 µm
TMC5	Ti + 30 vol% TiC	TiC, 4,9 µm
TMC6	Ti + 30 vol% TiN	TiN, < 10 µm
TMC7	Ti + 30 vol% cBN	cBN, 325/400 µm sieves

Ti powder. The prepared mixture was placed in the feeding hopper. The die was then filled, and, subsequently, cold compaction was performed. The next step was hot compaction at 930 ºC for 1 minute at 150 MPa. The final step was the ejection of the specimens and their handling.

The characterization of the composites was conducted, and their microstructures and properties were evaluated. The specimens were thoroughly metallographically prepared: the first step was the grinding with SiC abrasive paper, up to 1200 grit; secondly, wet polishing was performed for 25 minutes with a mixture of colloidal silica and hydrogen in a 9/1 ratio in volume; after that, the Kroll etching was made to reveal the microstructure of the samples for microstructural examination. A microstructural study was performed by optical microscopy (OM, Nikon Model Epiphot 200, Tokyo, Japan). Then, X-ray diffraction (XRD) analysis was carried out on a Brunker D8 Advance A25 (Billerica, MA, USA), to identify the phases present in the TMCs. XRD analyses of the specimens were performed with Cu-K_α radiation at a wavelength of 1.5418 Å and a scanning angle (2θ) in the range of 30° to 65°. Physical and mechanical properties were determined; composite density measurement was established using the Archimedean method (ASTM C373-14 (2014)). One density measurement was performed in each of the samples produced. The results obtained were compared with measurements performed with other control techniques, such as geometric density (ASTM B962-13 (2014)), ten measurements per sample). To quantify the hardness of the specimens, a tester model, Struers-Duramin A300 (Ballerup, Denmark) was used to determine Vickers hardness (HV10). Six indentations were made on each specimen to avoid possible ceramic particles. Young's modulus was measured by the ultrasonic method (Olympus 38 DL, Tokyo, Japan) (Davis, 1989).

The tribological tests were carried out on a ball-on-disc tribometer (Microtest MT/30/NI, Madrid, Spain) under a load of 3 N on an alumina ball of 6 mm diameter at room temperature, with a sliding speed of 125 mm/s for a distance of 500 m on the surface on a path of 3 mm in radius. The worn surfaces were characterised by optical microscopy with a Leica Zeiss DMV6 microscope (Leica Microsystems, Wetzlar, Germany). One tribological test was performed per sample. This characterization method was performed according to previous authors' work, and was based on existing literature (Cheng *et al.*, 2022; Wang *et al.*, 2022).

3. RESULTS AND DISCUSSION

This section was divided into subheadings to provide a clear description of the results obtained after the TMC production and characterisation, in addition to a concise discussion of them.

a. Microstructural analysis and X-ray diffraction (XRD)

One of the goodness of the RSP method is the high pressure applied during hot consolidation. The resistance of the die allowed pressures up to 150 MPa. Nevertheless, temperature was the limiting factor. As it was previously commented, the samples were consolidated below 150 MPa, and the temperature was set up to 930 °C, according to the device existing stringency of its metallic dies (Pérez-Soriano *et al.*, 2020).

In previous research work, the authors presented the appearance of secondary phases caused by the reaction between the titanium matrix and the reinforcement materials (Arevalo *et al.*, 2016a; Neubauer *et al.*, 2016; Montealegre-Meléndez *et al.*, 2016;

Arevalo *et al.*, 2017; Montealegre-Meléndez *et al.*, 2017). Concerning secondary phase formation, there is a significant influence of the operational parameters and the behaviour of the ceramic reinforcements. A slight increase in the operation temperature could contribute to the appearance of new phases in the matrix (Arevalo *et al.*, 2016b).

In the present investigation, similar parameters were employed to develop TMCs, and various ceramic reinforcements were tested. Therefore, the re-

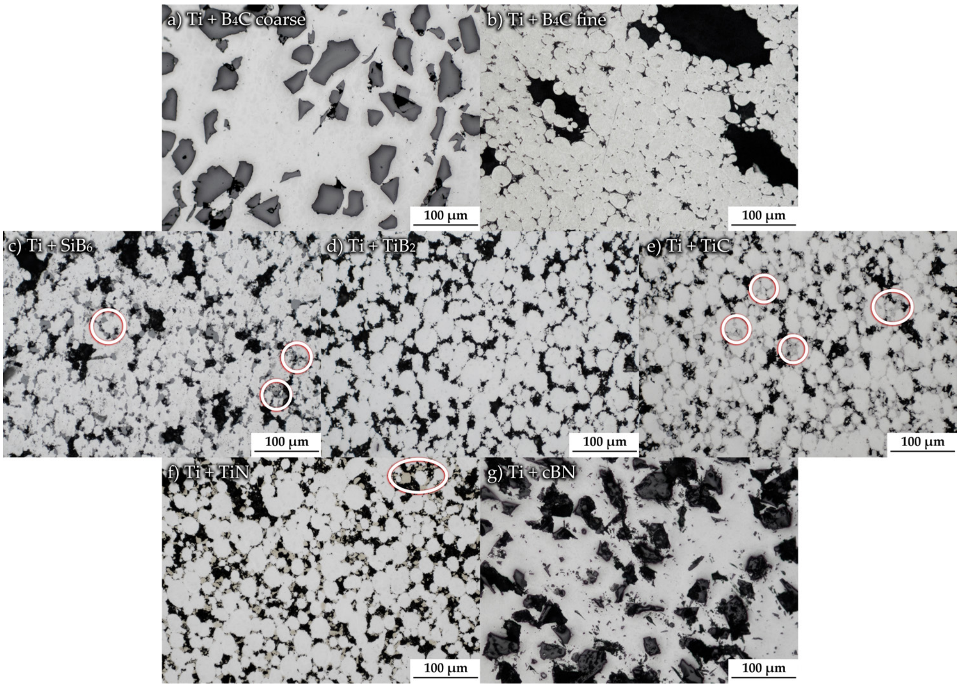

Figure 3. OM 200x images of the different TMCs studied: a) Ti + B_4C coarse; b) Ti + B_4C fine; c) Ti + SiB_6; d) Ti + TiB_2; e) Ti + TiC; f) Ti +TiN; g) Ti + cBN.

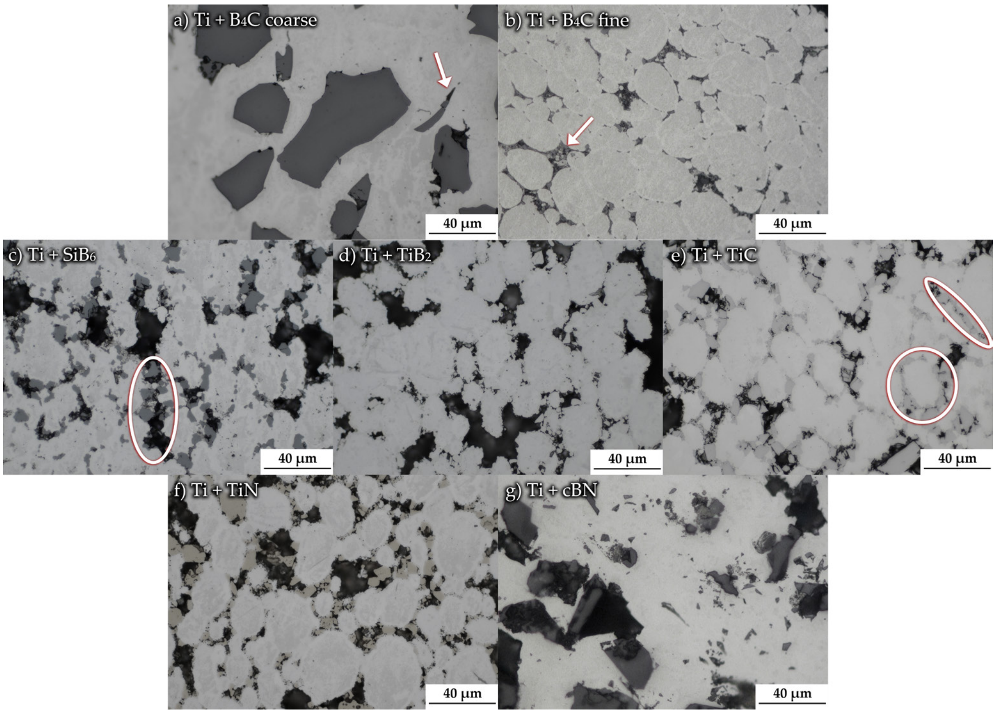

Figure 4. OM 500x images of the different TMCs studied: a) Ti + B_4C coarse; b) Ti + B_4C fine; c) Ti + SiB_6; d) Ti + TiB_2; e) Ti + TiC; f) Ti +TiN; g) Ti + cBN.

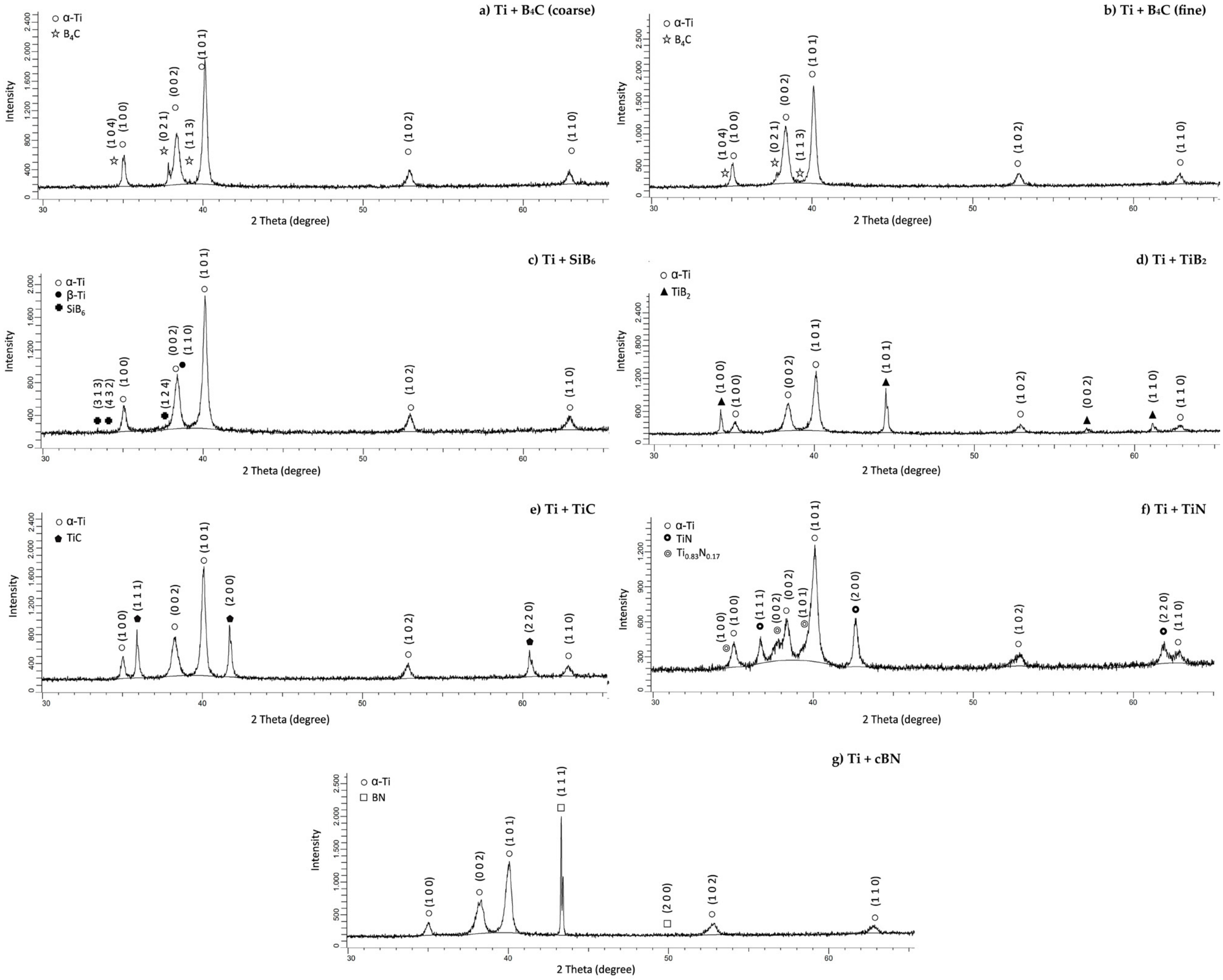

Figure 5. XRD patterns of the TMCs: a) Ti + B_4C coarse; b) Ti + B_4C fine; c) Ti + SiB_6; d) Ti + TiB_2; e) Ti + TiC; f) Ti +TiN; g) Ti + cBN.

activity of the titanium could be analysed when the reinforcement materials were varied. In this regard, the seven TMCs were made from starting powders, which were described above in Table 1 and Table 2.

The TMCs were observed by OM to ascertain the microstructure, and on the basis of the results obtained, a global comparison was carried out. Furthermore, the XRD analysis of each TMC was intended to find the formation of secondary phases or phase variations that occurred during the RSP manufacturing process, where reinforcement and matrix were involved.

In the framework of the reinforcement employed, descriptions of the main characteristics of the fabricated TMCs are reported; the microstructures of the TMCs are shown and commented on (Fig. 3 and Fig. 4), in addition to the XRD results (Fig. 5).

Considering how the B_4C particles behaved towards the Ti matrices, the main parameter to evaluate was the temperature. The processing temperature of 930 ºC and the holding time of 1 minute were insufficient to promote reactions between the Ti and the B and C of the ceramic particles, regardless of the size of the particles (coarse or fine), as it is seen in Fig. 4a and Fig. 4b). Furthermore, the microstructure study revealed that there was no reaction layer surrounding the B_4C particles in TMC1 and TMC2. This was confirmed with the XRD patterns of TMC1 and TMC2, shown in Fig. 5a and Fig. 5b). Predictably, as the temperature and time increases, reactivity may be encouraged between the matrix and the compositional elements of the ceramic particles, as it was studied in a previous research (Arevalo *et al.*, 2019).

The distribution of the B_4C particles differed in these two TMCs (TMC1 and TMC2); if fine particles were employed, the appearance of some agglomerations of ceramic particles can be detected in the titanium matrix (seen in Fig. 3b) and Fig. 4b)). Furthermore, porosity related to these agglomerations was observed more clearly in TMC2; as it can be seen in Fig. 3b), this B_4C fine powder was agglomerated and partially detached, causing large pores.

One significant difference between the microstructure of TMC1 and TMC2 is the distribution of the matrix grain and the reinforcement particles: on one side, the B_4C course particles were surrounded by the Ti matrix grains; on the other side, the B_4C fine particles circumscribed the Ti grains. In this sense, the final properties of these composites are expected to differ slightly. Nevertheless, the XRD results showed that there was no apparition of secondary phases in both cases. It is clearly observed in Fig. 5a-b. The peak of the ceramic particles remains in the diffractogram.

In the study of the microstructure of the TMC3, some agglomerations were observed in Fig. 3c) and Fig. 4c). This phenomenon of fine ceramic particles was also presented in the microstructure of TMC2 as it was commented above. Large agglomeration areas appeared in the Ti matrix. Comparing the microstructure of TMC3 and TMC2, despite the fact that both composites were made from fine ceramic particles as reinforcement, the SiB_6 particles were distributed in some areas as small clusters and in other ones surrounding the Ti grains. This differs from TMC2, in which the B_4C particles were excessively agglomerated into the matrix and, thereafter, torn out during the metallographic preparation.

In TMC3, in which SiB_6 particles were used as reinforcement, the Ti beta phase was detected by XRD analysis, as it was expected, since Si is an element that contributes to stabilizing/promoting the Ti beta phase. Consequently, the final properties of this composite may differ from those of the other specimens. The formation of TiB was not detected by XRD analysis. It suggested that temperature and time were insufficient to allow secondary reactions between the matrix and the B of SiB_6, since this ceramic material was stable at a temperature of 930 ºC.

As it was previously observed in composites whose starting powder was made from fine reinforcement particles, some TiB_2 agglomerations were formed in TMC4 (Fig. 3d and Fig. 4d). Using this reinforcement material, TiB formation can be expected; however, the XRD analysis did not show TiB phase peaks (Fig. 5d)). In this case, time was the limiting factor for the origin of the TiB phase. In this sense, the effect of temperature (930 ºC) was inappreciable, since TiB_2 is a very stable compound.

As it was expected in TMC5, as the TiC is a fine powder, there was a presence of fine agglomerations distributed in the titanium matrix (Fig. 3e) and Fig. 4e). It could be appreciated in Fig. 4e) how the fine TiC particles were surrounding the Ti grains. TiC is considered a stable reinforcement that does not react with titanium at 930 ºC; therefore, only TiC peaks were observed in addition to the Ti peaks in Fig. 5e).

The microstructure analysis of TMC6 revealed a microstructure of the reinforcement phases in the matrix similar to those of the other TMCs (Fig. 3f) and Fig. 4f). The grains of the Ti matrix were surrounded by the fine TiN particles, as it is marked in Fig. 3f). For this reinforcement material, it may be noted that the temperature was a slight influence factor on the formation of secondary phases. The integrity of the TiN compound was negligibly affected during the fabrication process. In Fig. 5f), the TMC6 pattern (TiN) showed peaks of the TiN phase and the non-stoichiometric $Ti_{0.83}N_{0.17}$. It suggested that the processing parameters allowed for the diffusion of N.

In TMC7, the morphology and size of the cBN particles could be clearly recognized in the Ti matrix, as it is seen in Fig. 3g) and Fig. 4g). Nevertheless, it could be observed that there were some ceramic particles that could be removed from the matrix. Due to the size of the reinforcement, the appearance of large agglomerations was minor compared to TMC2. It could be said that the finer the size of the reinforcement, the greater the tendency to form agglomerations. Temperature and time were insufficient to promote the reaction between the matrix and this ceramic compound; the BN phase remained unchanged after manufacturing. The peaks of the cubic BN (cBN) phase were detected by XRD analysis, confirmed in Fig. 5g).

Table 3. Young's modulus, hardness, and relative density of the TMCs

Id	Reinforcement	Arch. Rel. density	Geom. Rel. density	Young's modulus (GPa)	Hardness (HV10)
TMC1	B_4C (c)	0.966	0.973	139	390.3 ± 47.8
TMC2	B_4C (f)	0.854	0.856	-	117.4 ± 26.7
TMC3	SiB_6	0.932	0.872	111	215.7 ± 8.3
TMC4	TiB_2	0.898	0.875	126	289.8 ± 23.4
TMC5	TiC	0.958	0.908	135	356.7 ± 16.2
TMC6	TiN	0.933	0.905	121	306.5 ± 5.3
TMC7	cBN	0.981	0.967	173	337.0 ± 35.3

By global comparison, the behaviour of the seven systems formed by the Ti matrix and the ceramic particles: i) despite of the composition of the ceramic particle, the size of the powders could promote the apparition of large agglomerations in the matrix; ii) the processing parameters, temperature and time, were insufficient to promote reactions between the matrix and the reinforcement.

b. Physical and mechanical properties

As it was expected, differences in the TMCs appeared when the starting materials were varied. The resulting properties of the TMCs manufactured from the seven starting blends of titanium-based powder with different ceramic reinforcements are shown in Table 3. It is appreciated how, by employing the largest reinforcement material, the density value increased. This case is clearly observed in TMC1. On the contrary, in TMC2 the lowest density result was obtained. It was caused by the removal of some ceramic agglomerations during the preparation of the samples. Then, the greater the reinforcement particle size, the greater the measured density values.

Regarding the manufacturing parameters, the temperature, as well as the compaction time, were not sufficient to achieve optimal densification in some TMCs. The diffusion phenomenon did not occur due to the short time and the temperature of 930 ºC, not enough to promote it. These values might be improved by slightly increasing the temperature and/or the consolidation time.

The measured hardness values can be observed in Table 3. The presence of reinforcement particles on the surface and agglomerations could alter these results. Significant differences were appreciated between the hardness of the composites in which the reinforcement size was varied, such as TMC1 and TMC2. Both composites presented similar compositions, but the size of the B_4C particles was different; in this case, the hardness decreased from 390.3 for TMC1 to 117.4 for TMC2. In TMC4, in which the particles presented the finest size, the densification was also very low. TMC5 presented slightly higher density than TMC4 and TMC3, nevertheless its starting powder was made from fine particles. In the microstructural study, the size of the TiC particles agglomerations was smaller than the size of the clusters in TMC3, TMC4, and TMC5, as it was observed in Fig. 4c), Fig. 4d), and Fig. 4e).

Two phenomena could affect these different values: i) the removal of particles originating superficial porosity, such as in TMC 2, and ii) coarse ceramic particles, such as in TMC7.

Regarding the Young's modulus, the resulting values are also presented in Table 3. This property was measured using the ultrasonic method; therefore, if there was porosity, the values of the Young's modulus would have been reduced. As it was previously commented, the preparation of the TMC2 involved the removal of some B_4C particles. Due to this porosity found on the surface of the TMC2, the Young's Modulus of this specimen was unable to be measured correctly. Therefore, its value is not presented in Table 3.

There was a correlation between hardness and the Young's modulus (Table 3); the trend of the values was similar in both properties. When the size of the reinforcement particles was less than 30 µm, the hardness and Young's modulus values were lower than in the TMCs reinforced with coarser particles. A possible answer would be related to the apparition of ceramic particle agglomerations. The fine powders were agglomerated and located at the grain boundaries, affecting the bonding and densification behaviour. According to density values, the larger the powder size in the initial reinforcement material, the more preferred stiffness properties. The agglomerations of the ceramic particles and porosity caused a decrease in the mechanical properties, compared to the specimens where the reinforcement materials were more homogeneously distributed. It is clearly observed in Table 3. At similar composition, the mechanical and physical properties differed substantially in TMC1 and TMC2.

c. Tribological behaviour

By evaluating the tribological behaviour of the TMCs, significant results were obtained. In Fig. 6, the wear resistance of the composites made from the seven starting blends is shown.

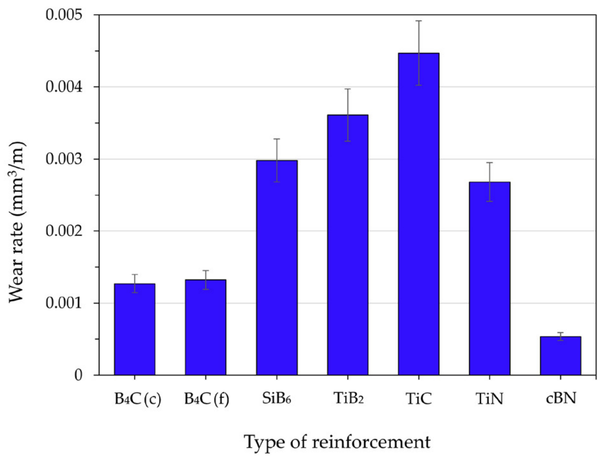

Figure 6. Wear rate vs. type of reinforcement in the specimens.

It is observed that the composites made from TiC showed the highest wear rate (XX). This could be due to the properties of this ceramic material itself.

Using B_4C, TMC1 showed better wear resistance than TMC2. It was an expected result. In this way, if the ceramic particles formed agglomerations and persist at the grain boundaries, the behaviour of the

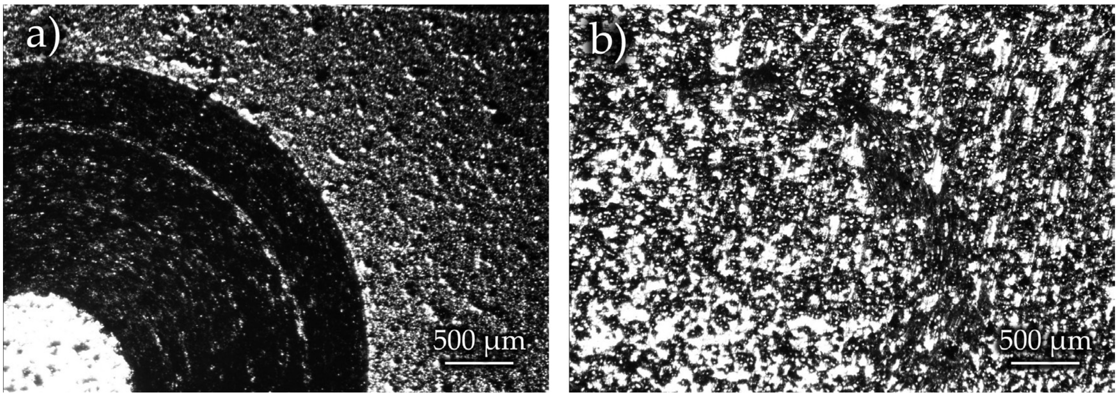

FIGURE 7. Worn surfaces: a) TMC3 (SiB_6) and b) TMC7 (cBN).

soft Ti matrix was measured without taking into account the wear resistance of the ceramic particles. In contrast, in TMC1, wear resistance increased because the coarse B_4C were located in the Ti matrix without agglomeration. Additionally, the wear measured in TMC2 was low due to the high porosity on its surface.

In Fig. 7, the most representative worn surfaces are shown. Comparing the extent of the groove, in TMC3, the grooving on the worn surface indicated the soft Ti matrix in which the Ti beta phase was present. TMC7 exhibited better wear behaviour compared to the other TMCs. This could be attributed to the behaviour of the BN particles itself and how these particles were distributed.

4. CONCLUSIONS

The following conclusions can be drawn:

- The characteristics of the reinforcing particles have a significant influence on the properties such as the density, hardness, and wear behaviour of the TMCs: the smaller the size of the ceramic particles, the greater the number of agglomerations formed. These phenomena minored the properties of the TMCs in general.
- The composition of the starting materials affected the final properties and microstructure of the TMCs. In TMCs whose reinforcement could enhance the formation of the Ti beta phase, there was a slight decrease in the specific stiffness of the TMCs.
- Manufacturing parameters have been adequate for carrying out the comparative study; nevertheless, if better final properties were desired, an increase in temperature and time could contribute to greater diffusion and better densification of the TMCs in addition to the appearance of secondary phases.
- In further research, the optimisation of the mixing procedure has to be evaluated in order to achieve a better distribution of the ceramic particles into the matrix. In this regard, less agglomeration of the powders could contribute to determining the desired properties of the TMCs.

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