

# Titanium Oxide and their Effects on Structure, Physical Properties and Electrochemical Corrosion Parameters of Alloys

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## Abstract

Effect of adding titanium oxide nanoparticles to bismuth or tin based alloys on microstructure, physical properties and corrosion parameters has been studied. Surface properties of tin or bismuth alloys such as hardness and corrosion parameters improved after adding titanium oxide. Matrix structure of tin or bismuth alloys changed after adding titanium oxide due to form a solid solution with caused a lattice distortion or growth formed phases. A little variation caused in melting temperature for bismuth or tin based after adding different ratio from titanium oxide.

**Keywords:** Alloys, Titanium oxide, Corrosion parameters, Microstructure, Mechanical properties

## Introduction

Materials are so significant in the development of civilization. Almost no metals are used in pure form, but they are always combined with each other to recover one or more properties. An alloy may be defined as a substance that has the metallic properties and is composed of two or more chemical elements of which at least one is a metal. Most alloys are great importance in industry and in the arts than are the pure metals. Several researches reported that, modification structure by adding alloying elements to tin or bismuth-based alloys caused minor/ or major effects on measured physical properties such as elastic modulus, hardness, melting temperature, internal friction, spreading, resistivity and electrochemical corrosion behavior with corrosion parameters [1-17]. Microstructure, mechanical and thermal properties of bismuth or tin based alloys are studied [18-23] studied at different conditions. Matrix structure of these alloys is changed which effects on all measured physical properties.

## Titanium dioxide (TiO<sub>2</sub>)

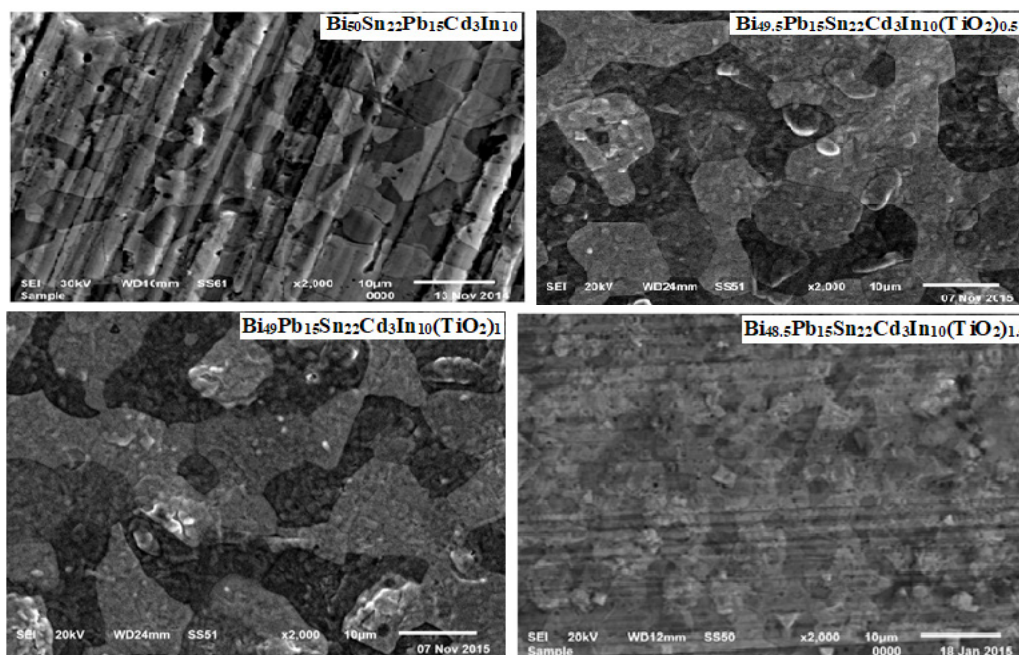
Titanium and some of its alloys are used as biomaterials for dental and orthopedic applications. Titanium is used in condensers and turbine blades in electric power plants. It is also incorporated into the architecture of buildings, roofs, piping and cable. Titanium dioxide has a wide range of applications, from paint to sunscreen to food coloring. It has eight modifications rutile, anatase, brookite,  $\alpha$ -PbO<sub>2</sub>-like, baddeleyite like, cotunnite-like, orthorhombic OI and cubic phases) also exist. Titanium Dioxide has high gloss, good whiteness, good discernibility, good liquidity, extraordinary hiding power and good coloring power, good weather resisting property and chalk resistance performance. It has the highest refractive index. Titanium dioxide melts at 1843 °C and its density is 4.23gm/cm<sup>3</sup>.

## Microstructure

$\text{Sn}_{82-x}\text{Bi}_{15}\text{Zn}_3\text{Ti}_2\text{O}_x$  (x= 0.3, 0.6, 0.9 and 1.2) alloys consist of tetragonal  $\beta$ -Sn phase, hexagonal Bi phase, Zn phase with undetected Ti<sub>2</sub>O or intermetallic compounds and solid solution from dissolved atoms that changed alloy matrix structure. Adding different ratio (0.5 to 1.5 wt. % at the expense of bismuth) from titanium oxide (TiO<sub>2</sub>) to  $\text{Bi}_{50-x}\text{Pb}_{15}\text{Sn}_{22}\text{Cd}_3\text{In}_{10}$  alloy caused a change in matrix structure such as feature formed phases, crystal size, lattice

distortion, lattice parameters, (a and c), and unit volume cell (V) [9] as listed in Table 1. Scanning electron micrographs, SEM, of  $\text{Bi}_{50-x}\text{Pb}_{15}\text{Sn}_{22}\text{In}_{10}\text{Cd}_3(\text{TiO}_2)_x$  ( $x=0$  to 1.5 wt.%) alloys show heterogeneous

structure (different feature for formed phases with different grain size beside a solid solution) as shown in Figure 1 which agreed with x-ray analysis.



**Figure 1:** SEM of  $\text{Bi}_{50-x}\text{Pb}_{15}\text{Sn}_{22}\text{In}_{10}\text{Cd}_3(\text{TiO}_2)_x$  alloys [9].

**Table 1:** Crystal size, lattice parameters and lattice distortion of rhombohedral Bi phase [9].

Alloys	Particle size Å	$a_{\text{rho}}$ Å	Lattice Distortion $\times 10^{-3}$
$\text{Bi}_{50}\text{Sn}_{22}\text{Pb}_{15}\text{Cd}_3\text{In}_{10}$	357.64	4.75	1.44
$\text{Bi}_{49.5}\text{Pb}_{15}\text{Sn}_{22}\text{Cd}_3\text{In}_{10}(\text{TiO}_2)_{0.5}$	283.29	4.68	1.43
$\text{Bi}_{49}\text{Pb}_{15}\text{Sn}_{22}\text{Cd}_3\text{In}_{10}(\text{TiO}_2)_1$	356.94	4.68	1.86
$\text{Bi}_{48.5}\text{Pb}_{15}\text{Sn}_{22}\text{Cd}_3\text{In}_{10}(\text{TiO}_2)_{1.5}$	301.45	4.79	1.74

$\text{Sn}_{82-x}\text{Bi}_{15}\text{Zn}_3\text{Ti}_2\text{O}_x$  ( $x=0.3, 0.6, 0.9$  and  $1.2$ ) alloys consist of tetragonal  $\beta$ -Sn phase, hexagonal Bi phase, Zn phase with undetected  $\text{Ti}_2\text{O}$  or intermetallic compounds and solid solution from dissolved atoms that changed alloy matrix structure. From SEM, Figure 2, adding  $\text{Ti}_2\text{O}$  to  $\text{Sn}_{82}\text{Bi}_{15}\text{Zn}_3$  alloy caused a change in its matrix microstructure (quantity, size and orientation of formed phases) [24]. Lattice microstrain,  $\epsilon$ , determined from draw the relation between full width half maximum, FWHM, and  $4\tan\theta$  using Williamson and Hall equation. Lattice microstrain of  $\text{Sn}_{82}\text{Bi}_{15}\text{Zn}_3$  alloy increased after adding titanium dioxide as listed in Table 2.

**Table 2:** Lattice microstrain of  $\text{Sn}_{82-x}\text{Bi}_{15}\text{Zn}_3\text{Ti}_2\text{O}_x$  alloys [24].

Alloys	$\epsilon$
$\text{Sn}_{82}\text{Bi}_{15}\text{Zn}_3$	0.011
$\text{Sn}_{81.7}\text{Bi}_{15}\text{Zn}_3(\text{TiO}_2)_{0.3}$	0.041
$\text{Sn}_{81.4}\text{Bi}_{15}\text{Zn}_3(\text{TiO}_2)_{0.6}$	0.054

$\text{Sn}_{81.1}\text{Bi}_{15}\text{Zn}_3(\text{TiO}_2)_{0.9}$	0.021
$\text{Sn}_{80.8}\text{Bi}_{15}\text{Zn}_3(\text{TiO}_2)_{1.2}$	0.066

$\text{Sn}_{60}\text{Bi}_{30-x}\text{Sb}_6\text{Zn}_4\text{Cu}_{0.7}\text{Ti}_2\text{O}_x$  ( $x=0, 0.3, 0.6, 0.9$  and  $1.2$ ) alloys consist of tetragonal  $\beta$ -Sn phase, hexagonal Bi phase, Zn phase, undetected phases such as  $\text{Ti}_2\text{O}$  or Sb or Cu or intermetallic compounds and solid solution from dissolved atoms [25]. Lattice microstrain of  $\text{Sn}_{60}\text{Bi}_{30}\text{Sb}_6\text{Zn}_4\text{Cu}_{0.7}$  alloys varied after adding titanium oxide as listed in Table 3. SEM of  $\text{Sn}_{60}\text{Bi}_{30-x}\text{Sb}_6\text{Zn}_4\text{Cu}_{0.7}\text{Ti}_2\text{O}_x$  alloys show heterogeneous structure from formed phases in matrix structure as shown in Figure 3 which agree with x-ray analysis.

**Table 3:** Lattice microstrain of  $\text{Sn}_{60}\text{Bi}_{30-x}\text{Sb}_6\text{Zn}_4\text{Cu}_{0.7}\text{Ti}_2\text{O}_x$  alloys [25].

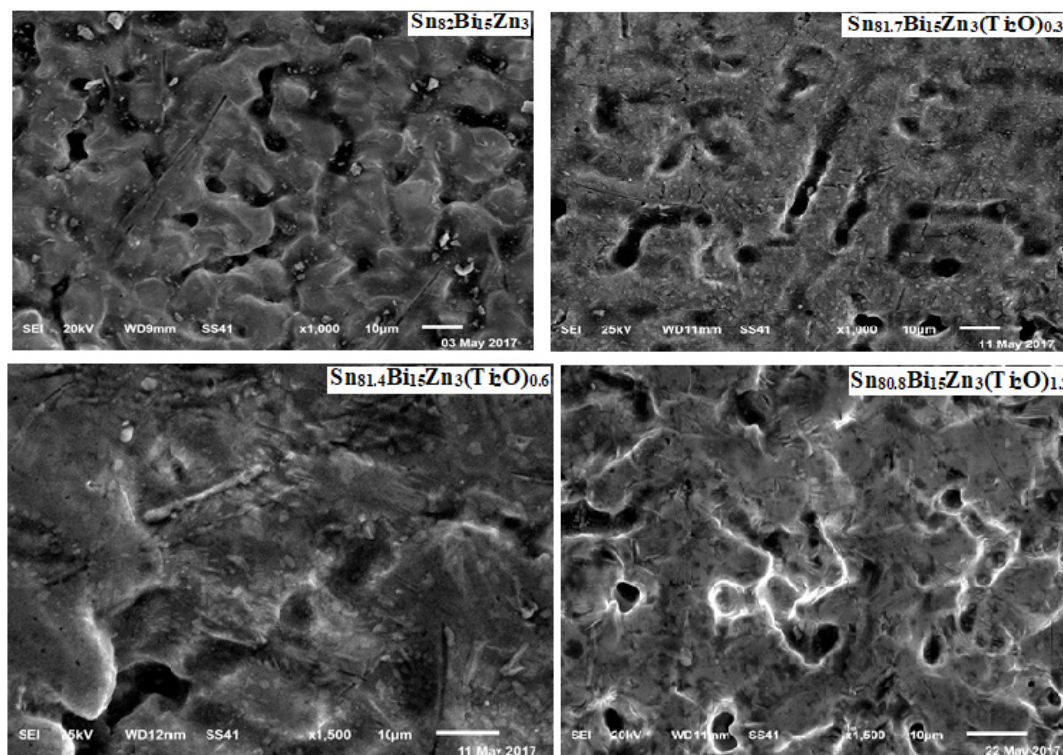
Alloys	$\epsilon$
$\text{Sn}_{82}\text{Bi}_{15}\text{Zn}_3$	0.12
$\text{Sn}_{81.7}\text{Bi}_{15}\text{Zn}_3(\text{TiO}_2)_{0.3}$	0.06
$\text{Sn}_{81.4}\text{Bi}_{15}\text{Zn}_3(\text{TiO}_2)_{0.6}$	0.12
$\text{Sn}_{81.1}\text{Bi}_{15}\text{Zn}_3(\text{TiO}_2)_{0.9}$	0.1
$\text{Sn}_{80.8}\text{Bi}_{15}\text{Zn}_3(\text{TiO}_2)_{1.2}$	0.13

The  $\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{10}\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_x$  ( $x=0.5$  to 1.5 wt.%) alloys consist of tetragonal  $\beta$ -Sn phase and hexagonal Bi phase with formed a solid solution or undetected phases. The crystallinity, crystal size and orientations for formed phases of  $\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{10}\text{Cu}_2\text{Zn}_2$  alloy changed after adding titanium oxide nanoparticles [26]. The estimated crystal size was given through measured diffraction pattern broadening by Scherer formula. Crystal size of  $\beta$ -Sn phase in  $\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{10}\text{Cu}_2\text{Zn}_2$  alloy varied after adding titanium dioxide

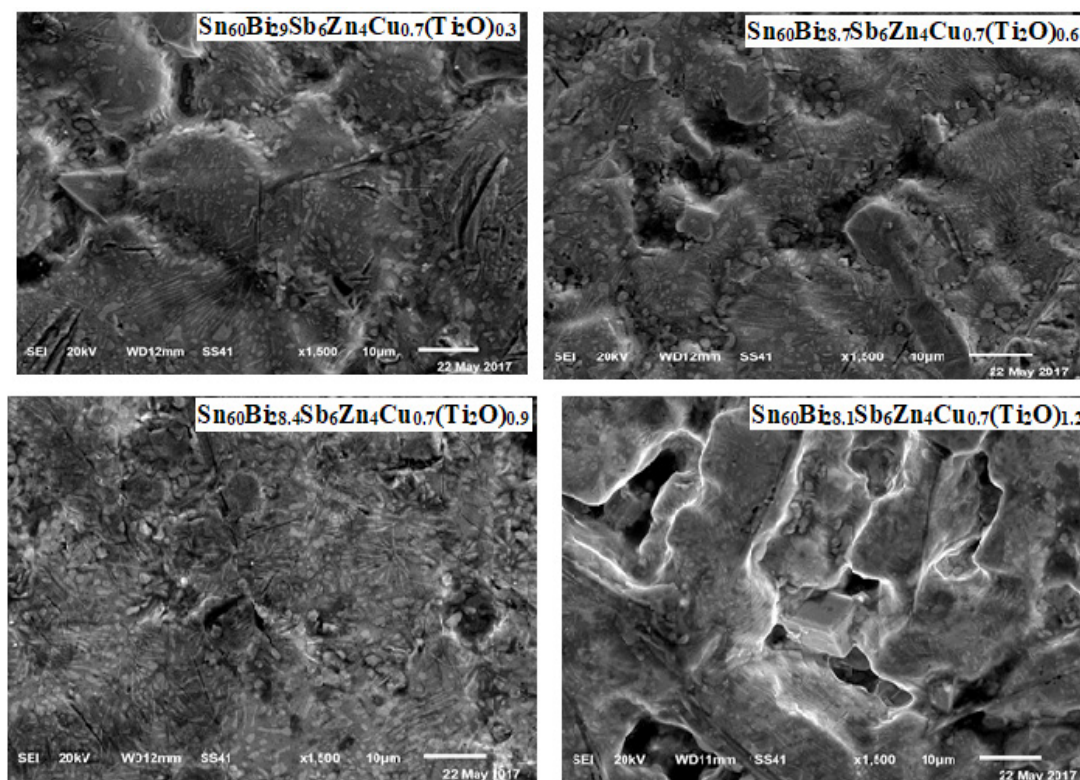


as presented in Table 4. Lattice microstrain of  $\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{10}\text{Cu}_2\text{Zn}_2$  alloy decreased after adding titanium oxide up to 1wt. % and then increased as listed in Table 4. The  $\text{Sn}_{76}\text{Al}_{10}\text{Bi}_9\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_1$  alloy has lower microstrain value. SEM show that adding different ratio from  $\text{TiO}_2$  nanoparticles to  $\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{10}\text{Cu}_2\text{Zn}_2$  alloy changed the shape

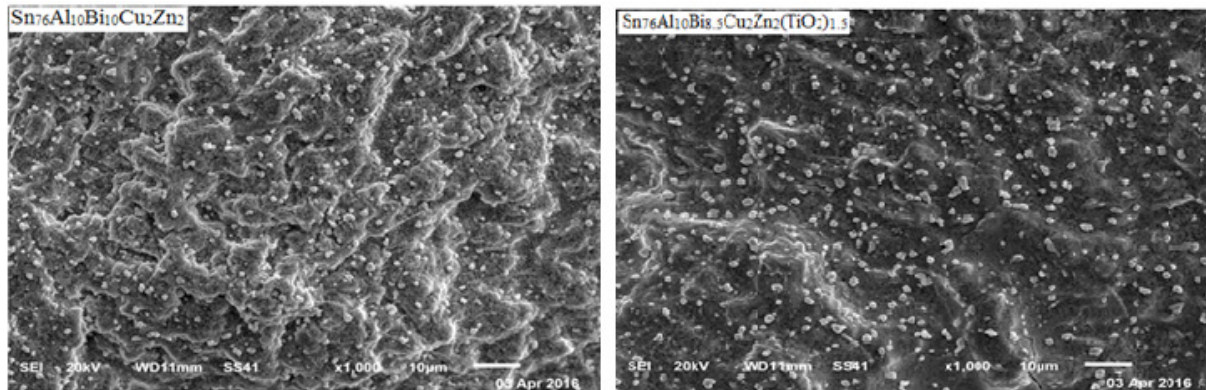
and size of dendrite structure and disturbed dissolved atoms as grains in it as seen in Figure 4. SEM analysis for used alloys shows heterogeneity structure and that is agreed with x-ray analysis [26].



**Figure 2:** SEM of  $\text{Sn}_{82-x}\text{Bi}_{15}\text{Zn}_3\text{TiO}_x$  alloys [24].



**Figure 3:** SEM of  $\text{Sn}_{60}\text{Bi}_{8-30-x}\text{Sb}_6\text{Zn}_4\text{Cu}_{0.7}\text{TiO}_x$  alloys [25].

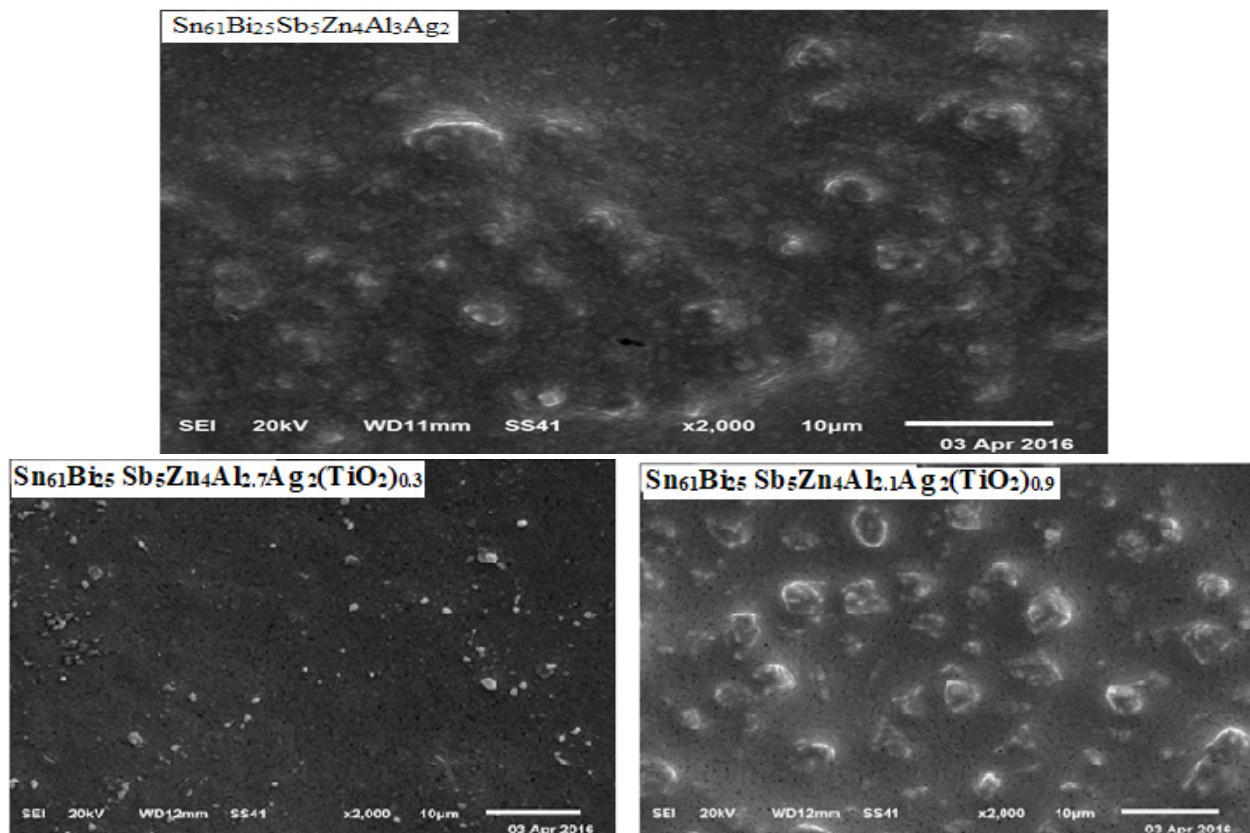


**Figure 4:** SEM of  $\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{10-x}\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_x$  alloys [26].

**Table 4:** Crystal size of  $\beta$ -Sn and lattice microstrain in  $\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{10-x}\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_x$  alloys [26].

Alloys	(Sn) $\tau$ (Å)	$\epsilon \times 10^{-3}$
$\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{10}\text{Cu}_2\text{Zn}_2$	347.647	0.9
$\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{9.5}\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_{0.5}$	387.704	0.7
$\text{Sn}_{76}\text{Al}_{10}\text{Bi}_9\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_1$	383.817	0.4
$\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{8.5}\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_{1.5}$	352.74	1.3

$\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_{3-x}\text{Ag}_2(\text{TiO}_2)_x$  ( $x=0.3$  to 1.2 wt.%) alloys consist of  $\beta$ -Sn phase, hexagonal Bi phase and dissolved Sb, Zn, Al, Ag atoms with  $\text{TiO}_2$  nanoparticles or undetected phases in matrix [27]. Crystal size of  $\beta$ -Sn phase in  $\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_3\text{Ag}_2$  alloy varied after adding  $\text{TiO}_2$  nanoparticles as listed in Table 5.  $\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_{2.4}\text{Ag}_2(\text{TiO}_2)_{0.6}$  alloy has higher lattice microstrain and lower  $\beta$ -Sn phase crystal size. SEM of  $\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_{3-x}\text{Ag}_2(\text{TiO}_2)_x$  alloys [27], Figure 5, show that the matrix structure of  $\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_3\text{Ag}_2$  alloy changed after adding  $\text{TiO}_2$  which agree with x-ray analysis and affected all measured properties.



**Figure 5:** SEM of  $\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_{3-x}\text{Ag}_2(\text{TiO}_2)_x$  alloys [27].

$\text{Sn}_{80}\text{Sb}_{15}\text{Pb}_5$  alloy consists of  $\beta$ -Sn and SbSn intermetallic phases. After adding different ratio of titanium oxide ( $\text{TiO}_2$ ) nanoparticles to  $\text{Sn}_{80}\text{Sb}_{15}\text{Pb}_5$  alloy, SbSn intermetallic phase disappeared with

changing matrix microstructure [28]. Lattice parameters, ( $a$  and  $c$ ), unit volume cell ( $V$ ) and crystal size ( $\tau$ ) of  $\beta$ -Sn phase in  $\text{Sn}_{80-x}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_x$  ( $x = 0, 0.5, 1$  and 1.5 wt. %) alloys are determined



and then recorded in Table 6. Little variation occurred in lattice parameters and unit volume of  $\beta$ -Sn in  $\text{Sn}_{80-x}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_x$  alloys but a major variation in  $\beta$ -Sn crystal size after adding titanium oxide nanoparticles. Scanning electron micrographs, SEM, of  $\text{Sn}_{80}\text{Sb}_{15}\text{Pb}_5$  and  $\text{Sn}_{78.5}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_{1.5}$  alloys show heterogeneous structure as shown in Figure 6 and that agreed with x-ray analysis. Adding  $\text{TiO}_2$  caused a change in matrix microstructure of  $\text{Sn}_{80}\text{Sb}_{15}\text{Pb}_5$  alloy.

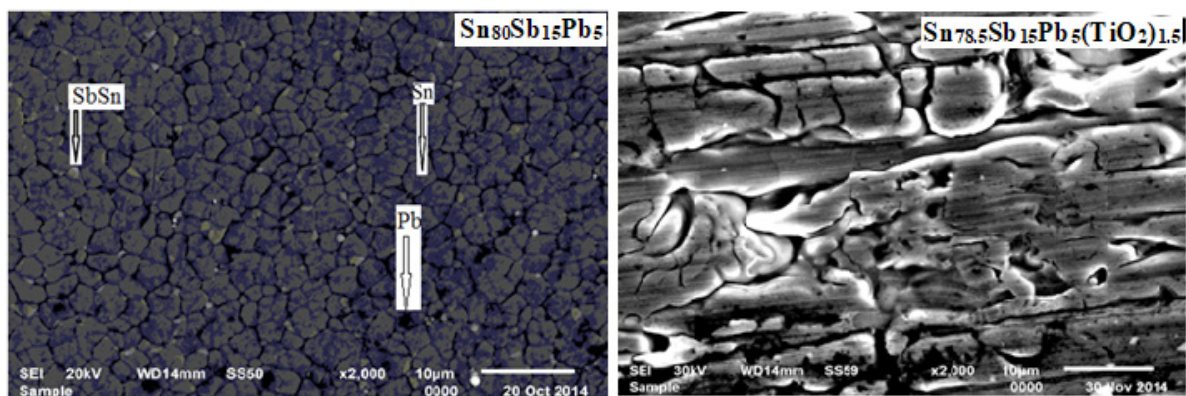
**Table 5:** Crystal size of  $\beta$ -Sn and lattice microstrain in  $\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_{3-x}\text{Ag}_2(\text{TiO}_2)_x$  alloys [27].

Alloys	(Sn) $\tau$ (Å)	$\epsilon \times 10^{-3}$
$\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_3\text{Ag}_2$	465.93	0.4
$\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_{2.7}\text{Ag}_2(\text{TiO}_2)_{0.3}$	522.97	0.4

$\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_{2.4}\text{Ag}_2(\text{TiO}_2)_{0.6}$	300.46	2.3
$\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_{2.1}\text{Ag}_2(\text{TiO}_2)_{0.9}$	611	0.8
$\text{Bi}_{25}\text{Sn}_{61}\text{Sb}_5\text{Zn}_4\text{Al}_{1.8}\text{Ag}_2(\text{TiO}_2)_{1.2}$	692.52	0.5
$\text{Bi}_{25}\text{Sn}_{61}\text{Sb}_5\text{Zn}_4\text{Al}_{1.5}\text{Ag}_2(\text{TiO}_2)_{1.5}$	388.4	1.8

**Table 6:** Matrix parameters (a, b, c, V and  $\tau$ ) of  $\text{Sn}_{80-x}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_x$  alloys [28].

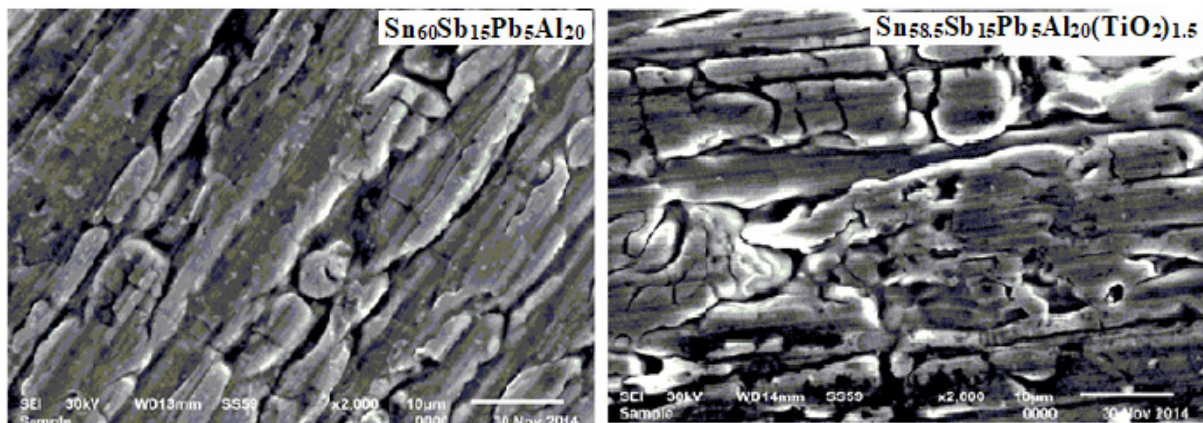
Alloys	a Å	b Å	c Å	V Å <sup>3</sup>	$\tau$ (Å)
$\text{Sn}_{80}\text{Sb}_{15}\text{Pb}_5$	5.854	3.184	0.543	109.144	317.25
$\text{Sn}_{79.5}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_{0.5}$	5.84	3.188	0.545	108.88	395.12
$\text{Sn}_{79}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_1$	5.84	3.180	0.544	108.77	448.06
$\text{Sn}_{78.5}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_{1.5}$	5.84	3.188	0.545	108.65	415.38



**Figure 6:** SEM of  $\text{Sn}_{80-x}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_x$  alloys [28].

$\text{Sn}_{60-x}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_x$  ( $x = 0.5, 1$  and  $1.5$  wt.%) alloys consist of  $\beta$ -Sn, Pb and SbSn intermetallic phases [28]. The determined lattice parameters, unit volume cell and crystal size of  $\beta$ -Sn phase in  $\text{Sn}_{60-x}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_x$  recorded in Table 7. A little variation happened in lattice parameters and unit volume of  $\beta$ -Sn in  $\text{Sn}_{80-x}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_x$  alloys after adding titanium oxide nanoparticles but a major variation occurred in  $\beta$ -Sn crystal size. That is because

$\text{TiO}_2$  nanoparticles dissolved in matrix alloy formed a solid solution and resultant in disappeared or appeared phases with changed the shape of rest phases. Dissimilar structure for  $\text{Sn}_{60}\text{Sb}_{15}\text{Pb}_5\text{Al}_{20}$  and  $\text{Sn}_{58.5}\text{Sb}_{15}\text{Pb}_5\text{Al}_{20}(\text{TiO}_2)_{1.5}$  alloys are shown in scanning electron micrographs, Figure 7, which agreed with x-ray analysis. That is meant adding  $\text{TiO}_2$  caused a change in matrix microstructure [28].



**Figure 7:** SEM of  $\text{Sn}_{60-x}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_x$  alloys [28].

$\text{Sn}_{64.5-x}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_x$  ( $x = 0.5, 1$  and  $1.5$  wt. %) alloys consist of  $\beta$ -Sn,  $\text{Ag}_3\text{Sn}$  and hexagonal Bi phases [29]. That is meant that in atoms and  $\text{TiO}_2$  nanoparticles dissolved in alloy matrix

forming a solid solution with changing microstructure. Lattice parameters, unit volume cell and crystal size of  $\beta$ -Sn in  $\text{Sn}_{64.5-x}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_x$  alloys are determined and then presented in

Table 8. Unit cell volume of  $\beta$ -Sn in  $\text{Sn}_{64.5-x}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_x$  alloys decreased but lattice parameter,  $a$ , and crystal size varied after adding  $\text{TiO}_2$  nanoparticles. The internal lattice microstrain of  $\text{Sn}_{64.5-x}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_x$  alloys also was determined then show in Table 8. Lattice strain of  $\text{Sn}_{64.5-x}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_x$  increased with increasing  $\text{TiO}_2$  nanoparticles ratio.

**Table 7:** Matrix parameters ( $a$ ,  $b$ ,  $c$ ,  $V$  and  $\tau$ ) of  $\text{Sn}_{60-x}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_x$  alloys [28].

Alloys	$a \text{ \AA}$	$c \text{ \AA}$	$V \text{ \AA}^3$	$\tau \text{ (\AA)}$
$\text{Sn}_{60}\text{Sb}_{15}\text{Pb}_5\text{Al}_{20}$	5.85	3.189	0.545	109.29
$\text{Sn}_{59.5}\text{Sb}_{15}\text{Pb}_5\text{Al}_{20}(\text{TiO}_2)_{0.5}$	5.85	3.187	0.544	108.97
$\text{Sn}_{59}\text{Sb}_{15}\text{Pb}_5\text{Al}_{20}(\text{TiO}_2)_1$	5.85	3.186	0.544	108.96
$\text{Sn}_{58.5}\text{Sb}_{15}\text{Pb}_5\text{Al}_{20}(\text{TiO}_2)_{1.5}$	5.85	3.188	0.544	109.15

**Table 8:** Matrix parameters ( $a$ ,  $c$ ,  $V$ ,  $\tau$  and  $\epsilon$ ) of  $\text{Sn}_{64.5-x}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_x$  alloys [29].

Alloys	$a \text{ \AA}$	$c \text{ \AA}$	$V \text{ \AA}^3$	$\tau \text{ (\AA)}$	$\epsilon \times 10^{-4}$
$\text{Sn}_{64.5}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2$	5.851	3.29	112.622	300.19	2
$\text{Sn}_{64}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_{0.5}$	5.856	3.196	109.599	261.516	7
$\text{Sn}_{63.5}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_1$	5.851	3.1927	109.288	293.482	5
$\text{Sn}_{63}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_{1.5}$	5.857	3.1911	109.468	311.438	6

$\text{Sn}_{87-x}\text{Sb}_{10}\text{Pb}_3(\text{TiO}_2)_x$  ( $x=0.5, 1$  and  $1.5$  wt. %) alloys consist of  $\beta$ -Sn, Pb/or Sb and SbSn intermetallic phases [30]. Adding  $\text{TiO}_2$  to  $\text{Sn}_{87}\text{Sb}_{10}\text{Pb}_3$  alloy caused a change in Sn matrix structure such as lattice parameters and formed crystal structure (crystallinity, crystal size and the orientation) as seen in Table 9. That is because  $\text{TiO}_2$  nanoparticles dissolved in Sn matrix formed a solid solution and other accumulated particles formed a trace of phases. Also  $\text{Sn}_{80-x}\text{Al}_{20}(\text{TiO}_2)_x$  ( $x=0.5, 1$  and  $1.5$  wt.%) alloys consist of  $\beta$ -Sn and Al phases [31]. Adding  $\text{TiO}_2$  to  $\text{Sn}_{80}\text{Al}_{20}$  alloy caused a change in Sn matrix such as lattice parameters and formed crystal structure (crystallinity and crystal size) as seen in Table 10.

**Table 9:** Matrix parameters ( $a$ ,  $c$ ,  $V$  and  $\tau$ ) of  $\text{Sn}_{64.5-x}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_x$  alloys [30].

Alloys	$a \text{ \AA}$	$c \text{ \AA}$	$V \text{ \AA}^3$	$\tau \text{ (\AA)}$
$\text{Sn}_{87}\text{Sb}_{10}\text{Pb}_3$	5.857	3.17	108.88	355.44
$\text{Sn}_{86.5}\text{Sb}_{10}\text{Pb}_3(\text{TiO}_2)_{0.5}$	5.841	3.18	108.62	514.28
$\text{Sn}_{86}\text{Sb}_{10}\text{Pb}_3(\text{TiO}_2)_1$	5.841	3.2	109.15	508.04
$\text{Sn}_{85.5}\text{Sb}_{10}\text{Pb}_3(\text{TiO}_2)_{1.5}$	5.843	3.19	108.83	529.68

**Table 10:** Matrix parameters ( $a$ ,  $c$ ,  $V$  and  $\tau$ ) of  $\text{Sn}_{80-x}\text{Al}_{20}(\text{TiO}_2)_x$  alloys [30].

Alloys	$a \text{ \AA}$	$c \text{ \AA}$	$V \text{ \AA}^3$	$\tau \text{ (\AA)}$
$\text{Sn}_{80}\text{Al}_{20}$	5.84	3.19	108.65	461.64
$\text{Sn}_{79.5}\text{Al}_{20}(\text{TiO}_2)_{0.5}$	5.88	3.10	106.42	390.49
$\text{Sn}_{79}\text{Al}_{20}(\text{TiO}_2)_1$	5.84	3.16	107.69	689.28
$\text{Sn}_{78.5}\text{Al}_{20}(\text{TiO}_2)_{1.5}$	5.84	3.17	108.08	

## Thermal properties

Measurement of thermal parameters is very inertial for their applications, particularly in the construction of devices. The melting temperature value of  $\text{Bi}_{50-x}\text{Pb}_{15}\text{Sn}_{22}\text{In}_{10}\text{Cd}_3(\text{TiO}_2)_x$  alloys increased after adding  $\text{TiO}_2$  nanoparticles which dependent on alloy compositions or alloy structure as presented in Table 11. The melting temperature value of  $\text{Sn}_{82}\text{Bi}_{15}\text{Zn}_3$  alloy is decreased after adding different ratio from titanium oxide as listed in Table 12. The melting temperature value of  $\text{Sn}_{60}\text{Bi}_{29}\text{Sb}_6\text{Zn}_4\text{Cu}_{0.7}$  alloy is varied after adding different ratio from titanium oxide as shown in Table 13. But no significant effect on melting temperature value of  $\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{10}\text{Cu}_2\text{Zn}_2$  alloy after adding titanium dioxide nanoparticles as presented in Table 14.

**Table 11:** Melting temperature of  $\text{Bi}_{50-x}\text{Pb}_{15}\text{Sn}_{22}\text{In}_{10}\text{Cd}_3(\text{TiO}_2)_x$  alloys [9].

Alloys	Melting Temperature $^{\circ}\text{C}$
$\text{Bi}_{50}\text{Sn}_{22}\text{Pb}_{15}\text{Cd}_3\text{In}_{10}$	58.22
$\text{Bi}_{49.5}\text{Pb}_{15}\text{Sn}_{22}\text{Cd}_3\text{In}_{10}(\text{TiO}_2)_{0.5}$	68.84
$\text{Bi}_{49}\text{Pb}_{15}\text{Sn}_{22}\text{Cd}_3\text{In}_{10}(\text{TiO}_2)_1$	91.37
$\text{Bi}_{48.5}\text{Pb}_{15}\text{Sn}_{22}\text{Cd}_3\text{In}_{10}(\text{TiO}_2)_{1.5}$	109.63

**Table 12:** Melting temperature of  $\text{Sn}_{82-x}\text{Bi}_{15}\text{Zn}_3\text{Ti}_2\text{O}_x$  alloys [24].

Alloys	Melting Temperature $^{\circ}\text{C}$
$\text{Sn}_{82}\text{Bi}_{15}\text{Zn}_3$	216.42
$\text{Sn}_{81.7}\text{Bi}_{15}\text{Zn}_3(\text{Ti}_2\text{O})_{0.3}$	212
$\text{Sn}_{81.4}\text{Bi}_{15}\text{Zn}_3(\text{Ti}_2\text{O})_{0.6}$	210.7
$\text{Sn}_{81.1}\text{Bi}_{15}\text{Zn}_3(\text{Ti}_2\text{O})_{0.9}$	187.11
$\text{Sn}_{80.8}\text{Bi}_{15}\text{Zn}_3(\text{Ti}_2\text{O})_{1.2}$	187.3

**Table 13:** Melting temperature of  $\text{Sn}_{60}\text{Bi}_{30-x}\text{Sb}_6\text{Zn}_4\text{Cu}_{0.7}(\text{Ti}_2\text{O})_x$  alloys [25].

Alloys	Melting Temperature $^{\circ}\text{C}$
$\text{Sn}_{60}\text{Bi}_{29}\text{Sb}_6\text{Zn}_4\text{Cu}_{0.7}(\text{Ti}_2\text{O})_{0.3}$	187.3
$\text{Sn}_{60}\text{Bi}_{28.7}\text{Sb}_6\text{Zn}_4\text{Cu}_{0.7}(\text{Ti}_2\text{O})_{0.6}$	180.85
$\text{Sn}_{60}\text{Bi}_{28.4}\text{Sb}_6\text{Zn}_4\text{Cu}_{0.7}(\text{Ti}_2\text{O})_{0.9}$	183.26
$\text{Sn}_{60}\text{Bi}_{28.1}\text{Sb}_6\text{Zn}_4\text{Cu}_{0.7}(\text{Ti}_2\text{O})_{1.2}$	175.21

**Table 14:** Melting temperature of  $\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{10}\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_x$  alloys [26].

Alloys	Melting Temperature $^{\circ}\text{C}$
$\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{10}\text{Cu}_2\text{Zn}_2$	212
$\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{9.5}\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_{0.5}$	210.1
$\text{Sn}_{76}\text{Al}_{10}\text{Bi}_9\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_1$	212.3
$\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{8.5}\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_{1.5}$	213.8

Melting temperature of  $\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_3\text{Ag}_2$  alloy varied after adding  $\text{TiO}_2$  nanoparticles as listed in Table 15. It is increased up to 0.9 wt. %  $\text{TiO}_2$  nanoparticles and then it's decreased. Melting temperature of  $\text{Sn}_{80}\text{Sb}_{10}\text{Pb}_5$  alloy decreased after adding  $\text{TiO}_2$  nanoparticles as presented in Table 16. Melting temperature of  $\text{Sn}_{60}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5$  alloy varied after adding  $\text{TiO}_2$  nanoparticles as

presented in Table 17. That is because  $\text{TiO}_2$  nanoparticles due a change in matrix microstructure of  $\text{Sn}_{60}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5$  alloy. But melting temperature of  $\text{Sn}_{64.5-x}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_x$  ( $x=0.5, 1$  and  $1.5$  wt. %) alloys varied after adding  $\text{TiO}_2$  nanoparticles as listed in Table 18.

**Table 15:** Melting temperature of  $\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_3\text{Ag}_2(\text{TiO}_2)_x$  alloys [27].

Alloys	Melting Temperature °C
$\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_3\text{Ag}_2$	167.7
$\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_{2.7}\text{Ag}_2(\text{TiO}_2)_{0.3}$	174.1
$\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_{2.4}\text{Ag}_2(\text{TiO}_2)_{0.6}$	187.5
$\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_{2.1}\text{Ag}_2(\text{TiO}_2)_{0.9}$	189.1
$\text{Bi}_{25}\text{Sn}_{61}\text{Sb}_5\text{Zn}_4\text{Al}_{1.8}\text{Ag}_2(\text{TiO}_2)_{1.2}$	173.5
$\text{Bi}_{25}\text{Sn}_{61}\text{Sb}_5\text{Zn}_4\text{Al}_{1.5}\text{Ag}_2(\text{TiO}_2)_{1.5}$	170.1

**Table 16:** Melting temperature of  $\text{Sn}_{80-x}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_x$  alloys [28].

Alloys	Melting Temperature °C
$\text{Sn}_{80}\text{Sb}_{15}\text{Pb}_5$	231.23
$\text{Sn}_{79.5}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_{0.5}$	228.03
$\text{Sn}_{79}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_1$	225.61
$\text{Sn}_{78.5}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_{1.5}$	227.45

**Table 17:** Melting temperature of  $\text{Sn}_{60-x}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_x$  alloys [28].

Alloys	Melting Temperature °C
$\text{Sn}_{60}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5$	229
$\text{Sn}_{59.5}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_{0.5}$	231.27
$\text{Sn}_{59}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_1$	224.16
$\text{Sn}_{58.5}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_{1.5}$	230.94

**Table 18:** Melting temperature of  $\text{Sn}_{64.5-x}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_x$  alloys [29].

Alloys	Melting Temperature °C
$\text{Sn}_{64.5}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2$	174.12
$\text{Sn}_{64}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_{0.5}$	169.67
$\text{Sn}_{63.5}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_1$	175.94
$\text{Sn}_{63}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_{1.5}$	174.2

Melting temperature of  $\text{Sn}_{87}\text{Sb}_{10}\text{Pb}_3$  alloy decreased after adding  $\text{TiO}_2$  nanoparticles as shown in Table 19. The melting temperature of  $\text{Sn}_{80-x}\text{Al}_{20}(\text{TiO}_2)_x$  ( $x= 0.5$  to  $1.5$  wt.%) alloys are listed in Table 20. Little increased in melting temperature of  $\text{Sn}_{80}\text{Al}_{20}$  alloy after adding  $\text{TiO}_2$  nanoparticles.

**Table 19:** Melting temperature of  $\text{Sn}_{64.5-x}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_x$  alloys [31].

Alloys	Melting Temperature °C
$\text{Sn}_{87}\text{Sb}_{10}\text{Pb}_3$	236.87
$\text{Sn}_{86.5}\text{Sb}_{10}\text{Pb}_3(\text{TiO}_2)_{0.5}$	223.38
$\text{Sn}_{86}\text{Sb}_{10}\text{Pb}_3(\text{TiO}_2)_1$	229.52
$\text{Sn}_{85.5}\text{Sb}_{10}\text{Pb}_3(\text{TiO}_2)_{1.5}$	229.33

**Table 20:** Melting temperature of  $\text{Sn}_{80-x}\text{Al}_{20}(\text{TiO}_2)_x$  alloys [30].

Alloys	Melting Temperature °C
$\text{Sn}_{80}\text{Al}_{20}$	227.03
$\text{Sn}_{79.5}\text{Al}_{20}(\text{TiO}_2)_{0.5}$	228.22
$\text{Sn}_{79}\text{Al}_{20}(\text{TiO}_2)_1$	228.92
$\text{Sn}_{78.5}\text{Al}_{20}(\text{TiO}_2)_{1.5}$	

## Mechanical properties

A significant change in elastic modulus of  $\text{Bi}_{50-x}\text{Pb}_{15}\text{Sn}_{22}\text{Cd}_3\text{In}_{10}(\text{TiO}_2)_x$  ( $x=0.5$  to  $1.5$  wt.%) alloys with adding different ratio from  $\text{TiO}_2$  nanoparticles. Vickers hardness and calculated maximum shear stress of  $\text{Bi}_{50}\text{Pb}_{15}\text{Sn}_{22}\text{Cd}_3\text{In}_{10}$  alloy increased after adding  $(\text{TiO}_2)$  as listed in Table 21.

**Table 21:** Elastic modulus, hardness and maximum shear stress of  $\text{Bi}_{50-x}\text{Pb}_{15}\text{Sn}_{22}\text{In}_{10}\text{Cd}_3(\text{TiO}_2)_x$  alloys [9].

Alloys	E GPa	$H_v$ Kg/mm <sup>2</sup>	$\mu_n$ Kg/mm <sup>2</sup>
$\text{Bi}_{50}\text{Sn}_{22}\text{Pb}_{15}\text{Cd}_3\text{In}_{10}$	29.3	9.72	3.21
$\text{Bi}_{49.5}\text{Pb}_{15}\text{Sn}_{22}\text{Cd}_3\text{In}_{10}(\text{TiO}_2)_{0.5}$	32.03	14.5	4.79
$\text{Bi}_{49}\text{Pb}_{15}\text{Sn}_{22}\text{Cd}_3\text{In}_{10}(\text{TiO}_2)_1$	36.16	19.05	6.27
$\text{Bi}_{48.5}\text{Pb}_{15}\text{Sn}_{22}\text{Cd}_3\text{In}_{10}(\text{TiO}_2)_{1.5}$	23.77	16.6	5.48

Vickers hardness and calculated maximum shear stress of  $\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{10-x}\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_x$  alloys at 10 gram force and indentation time 5 sec are presented in Table 22. Vickers hardness value of  $\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{10}\text{Cu}_2\text{Zn}_2$  alloy varied after adding titanium oxide nanoparticles.

**Table 22:** Vickers hardness and maximum shear stress of  $\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{10-x}\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_x$  alloys [26].

Alloys	$H_v$ Kg/mm <sup>2</sup>	$\mu_n$ Kg/mm <sup>2</sup>
$\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{10}\text{Cu}_2\text{Zn}_2$	46.6	15.38
$\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{9.5}\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_{0.5}$	24.4	8.05
$\text{Sn}_{76}\text{Al}_{10}\text{Bi}_9\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_1$	39.43	13.013
$\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{8.5}\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_{1.5}$	42.2	13.93

**Table 23:** Elastic modulus of  $\text{Sn}_{80-x}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_x$  alloys [28].

Alloys	E GPa
$\text{Sn}_{80}\text{Sb}_{15}\text{Pb}_5$	24.28
$\text{Sn}_{79.5}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_{0.5}$	32.96
$\text{Sn}_{79}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_1$	38.25
$\text{Sn}_{78.5}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_{1.5}$	42.67

Elastic modulus value of  $\text{Sn}_{80-x}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_x$  ( $x= 0, 0.5, 1$  and  $1.5$  wt. %) alloys is listed in Table 23. Elastic modulus of  $\text{Sn}_{80}\text{Sb}_{15}\text{Pb}_5$  alloy increased after adding  $\text{TiO}_2$  nanoparticles because it's dissolved in alloy matrix. The stress exponent values of  $\text{Sn}_{80-x}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_x$  alloys which calculated using Mulheam-Tabor method are given in Table 24. These exponent values are in the range of 2.16 to 3.07 depending on the composition of alloy and that agreed with the pervious results [31,32]. The change in stress exponent values are



attributable to microstructural features (such as change in lattice parameters, solid solution, size and distribution of strengthening phases, intermetallic phases) and that is agree with the pervious results [33].

**Table 24:** Stress exponent (n) of  $\text{Sn}_{80-x}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_x$  alloys [28].

Alloys	Stress Exponent (n)
$\text{Sn}_{80}\text{Sb}_{15}\text{Pb}_5$	3.077
$\text{Sn}_{78.5}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_{1.5}$	2.16

Elastic modulus of  $\text{Sn}_{60-x}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_x$  ( $x= 0.5, 1$  and  $1.5$  wt.%) alloys are registered in Table 25. Elastic modulus of  $\text{Sn}_{60}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5$  alloy varied after adding  $\text{TiO}_2$  nanoparticles. The stress exponent  $\text{Sn}_{60}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5$  alloy decreased after adding  $\text{TiO}_2$  nanoparticles as shown in Table 26. These exponent values are in the range of 2.44 to 5.75 depending on the composition of used alloy. Elastic modulus and Vickers hardness values of  $\text{Sn}_{64.5}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2$  alloy decreased after adding  $\text{TiO}_2$  nanoparticles as shown in Table 27.

**Table 25:** Elastic modulus of  $\text{Sn}_{60-x}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_x$  alloys [28].

Alloys	E GPa
$\text{Sn}_{60}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5$	38.95
$\text{Sn}_{59.5}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_{0.5}$	36.99
$\text{Sn}_{59}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_1$	42.22
$\text{Sn}_{58.5}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_{1.5}$	37.55

**Table 26:** Stress exponent (n) of  $\text{Sn}_{60-x}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_x$  alloys [29].

Alloys	Stress Exponent (n)
$\text{Sn}_{60}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5$	5.749
$\text{Sn}_{58.5}\text{Al}_{20}\text{Sb}_{15}\text{Pb}_5(\text{TiO}_2)_{1.5}$	2.44

**Table 27:** Elastic modulus and Vickers hardness of  $\text{Sn}_{64.5-x}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_x$  alloys [29].

Alloys	E GPa	$H_v$ (Kg/mm <sup>2</sup> )
$\text{Sn}_{64.5}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2$	34.5	23.13
$\text{Sn}_{64}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_{0.5}$	29	17.82
$\text{Sn}_{63.5}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_1$	32.83	17.62
$\text{Sn}_{63}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_{1.5}$	28.25	17.02

The elastic constants are directly related to atomic bonding and structure. Elastic modulus and Vickers hardness values of  $\text{Sn}_{87-x}\text{Sb}_{10}\text{Pb}_3(\text{TiO}_2)_x$  alloys are listed in Table 28. Elastic modulus and Vickers of  $\text{Sn}_{87}\text{Sb}_{10}\text{Pb}_3$  alloy increased after adding different ratio from  $\text{TiO}_2$  nanoparticles. Elastic modulus and Vickers hardness values of  $\text{Sn}_{80-x}\text{Al}_{20}(\text{TiO}_2)_x$  ( $x= 0.5$  to  $1.5$  wt. %) alloys are listed in Table 29. Elastic modulus of  $\text{Sn}_{80}\text{Al}_{20}$  alloy increased after adding different ratio from  $\text{TiO}_2$  nanoparticles. Also, little variation occurred in Vickers hardness at 10-gram force and indentation time 5 sec of  $\text{Sn}_{80}\text{Al}_{20}$  alloy after adding  $\text{TiO}_2$  nanoparticles.

**Table 28:** Elastic modulus and Vickers hardness of  $\text{Sn}_{84.5-x}\text{Ag}_{3.5}\text{Bi}_{30}\text{In}_2(\text{TiO}_2)_x$  alloys [30].

Alloys	E GPa	$H_v$ (Kg/mm <sup>2</sup> )
$\text{Sn}_{87}\text{Sb}_{10}\text{Pb}_3$	33.02	28.52
$\text{Sn}_{86.5}\text{Sb}_{10}\text{Pb}_3(\text{TiO}_2)_{0.5}$	38.3	31.68
$\text{Sn}_{86}\text{Sb}_{10}\text{Pb}_3(\text{TiO}_2)_1$	39.1	36.53
$\text{Sn}_{85.5}\text{Sb}_{10}\text{Pb}_3(\text{TiO}_2)_{1.5}$	47.2	38.83

**Table 29:** Elastic modulus and Vickers hardness of  $\text{Sn}_{80-x}\text{Al}_{20}(\text{TiO}_2)_x$  alloys [30].

Alloys	E GPa	$H_v$ (Kg/mm <sup>2</sup> )
$\text{Sn}_{80}\text{Al}_{20}$	31.85	34.63
$\text{Sn}_{79.5}\text{Al}_{20}(\text{TiO}_2)_{0.5}$	37.6	35.77
$\text{Sn}_{79}\text{Al}_{20}(\text{TiO}_2)_1$	38.9	37.88
$\text{Sn}_{78.5}\text{Al}_{20}(\text{TiO}_2)_{1.5}$	40.8	

### Corrosion parameters

The corrosion potential ( $E_{\text{corr}}$ ), corrosion current ( $I_{\text{corr}}$ ) and corrosion rate ( $\text{Corr}_{\text{Rate}}$ ) of  $\text{Sn}_{82-x}\text{Bi}_{15}\text{Zn}_3\text{TiO}_x$  ( $x=0.3$  to  $1.2$  wt. %) alloys are presented in Table 30. Corrosion rate and corrosion current of  $\text{Sn}_{82}\text{Bi}_{15}\text{Zn}_3$  alloy decreased after adding ( $\text{Ti}_2\text{O}$ ). The corrosion potential, corrosion current and corrosion rate of  $\text{Sn}_{60}\text{Bi}_{30-x}\text{Sb}_6\text{Zn}_4\text{Cu}_{0.7}(\text{Ti}_2\text{O})_x$  ( $x= 0.3$  to  $1.2$  wt.%) alloys are listed in Table 31. Corrosion rate and corrosion current of  $\text{Sn}_{60}\text{Bi}_{30}\text{Sb}_6\text{Zn}_4\text{Cu}_{0.7}$  alloy varied after adding different ratio from ( $\text{Ti}_2\text{O}$ ).  $\text{Sn}_{60}\text{Bi}_{28.4}\text{Sb}_6\text{Zn}_4\text{Cu}_{0.7}(\text{Ti}_2\text{O})_{0.9}$  alloy has better corrosion resistance.

**Table 30:** Corrosion parameters of  $\text{Sn}_{82-x}\text{Bi}_{15}\text{Zn}_3\text{TiO}_x$  alloys [24].

Alloys	$E_{\text{corr}}$ mV	$I_{\text{corr}}$ uA	$\text{Corr}_{\text{Rate}}$ mpy
$\text{Sn}_{82}\text{Bi}_{15}\text{Zn}_3$	-862	841	348.3
$\text{Sn}_{81.7}\text{Bi}_{15}\text{Zn}_3(\text{Ti}_2\text{O})$	-554	515	235.4
$\text{Sn}_{81.4}\text{Bi}_{15}\text{Zn}_3(\text{Ti}_2\text{O})_{0.6}$	-970	249	113.8
$\text{Sn}_{81.1}\text{Bi}_{15}\text{Zn}_3(\text{Ti}_2\text{O})_{0.9}$	-919	336	153.5
$\text{Sn}_{80.8}\text{Bi}_{15}\text{Zn}_3(\text{Ti}_2\text{O})_{1.2}$	-563	352	164.67

**Table 31:** Corrosion parameters of  $\text{Sn}_{60}\text{Bi}_{30-x}\text{Sb}_6\text{Zn}_4\text{Cu}_{0.7}(\text{Ti}_2\text{O})_x$  alloys [25].

Alloys	$E_{\text{corr}}$ mV	$I_{\text{corr}}$ uA	$\text{Corr}_{\text{Rate}}$ mpy
$\text{Sn}_{60}\text{Bi}_{30}\text{Sb}_6\text{Zn}_4$	-913	719	328.5
$\text{Sn}_{60}\text{Bi}_{29}\text{Sb}_6\text{Zn}_4\text{Cu}_{0.7}(\text{Ti}_2\text{O})_{0.3}$	-771	190	186.83
$\text{Sn}_{60}\text{Bi}_{28.7}\text{Sb}_6\text{Zn}_4\text{Cu}_{0.7}(\text{Ti}_2\text{O})_{0.6}$	-770	283	229.3
$\text{Sn}_{60}\text{Bi}_{28.4}\text{Sb}_6\text{Zn}_4\text{Cu}_{0.7}(\text{Ti}_2\text{O})_{0.9}$	-746	186	176.77
$\text{Sn}_{60}\text{Bi}_{28.1}\text{Sb}_6\text{Zn}_4\text{Cu}_{0.7}(\text{Ti}_2\text{O})_{1.2}$	-809	604	276

The corrosion current, corrosion potential and corrosion rate of  $\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{10-x}\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_x$  ( $x=0.5$  to  $1.5$  wt.%) alloys in 0.25M HCl are presented in Table 32. Corrosion rate and corrosion current of  $\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{10}\text{Cu}_2\text{Zn}_2$  alloy decreased after adding 0.5 and 1.5wt. % titanium oxide nanoparticles but increased after adding 1wt. %.



**Table 32:** Corrosion parameters of  $\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{10-x}\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_x$  alloys [26].

Alloys	$E_{\text{corr}}$ mV	$I_{\text{corr}}$ uA	$\text{Corr}_{\text{Rate}}$ mpy
$\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{10}\text{Cu}_2\text{Zn}_2$	-943	3.69	3.861e3
$\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{9.5}\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_{0.5}$	-873.0	3.27	3.424e3
$\text{Sn}_{76}\text{Al}_{10}\text{Bi}_9\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_1$	-704.0	9.05	9.475e3
$\text{Sn}_{76}\text{Al}_{10}\text{Bi}_{8.5}\text{Cu}_2\text{Zn}_2(\text{TiO}_2)_{1.5}$	-875.0	2.92	3.085e3

Table 33 presents the corrosion potential, corrosion current, and corrosion rate of  $\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_{3-x}\text{Ag}_2(\text{TiO}_2)_x$  ( $x=0.3$  to  $1.2$  wt.%) alloys. Corrosion rate of  $\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_3\text{Ag}_2$  alloy varied decreased up to 0.9wt. % titanium dioxide nanoparticle and then increased with increasing the ratio of titanium dioxide nanoparticle. That is because adding titanium dioxide nanoparticle caused heterogeneous microstructure with affected on microsegregation and reactivity of atoms with HCl solution. The  $\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_{1.5}\text{Ag}_2(\text{TiO}_2)_{1.5}$  alloy has high corrosion resistance.

**Table 33:** Corrosion parameters of  $\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_{3-x}\text{Ag}_2(\text{TiO}_2)_x$  alloys [27].

Alloys	$E_{\text{corr}}$ mV	uA	$\text{Corr}_{\text{Rate}}$ mpy
$\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_3\text{Ag}_2$	-857.0	1.56	1.73e3
$\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_{2.7}\text{Ag}_2(\text{TiO}_2)_{0.3}$	-776.0	3.79	3.97e3
$\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_{2.4}\text{Ag}_2(\text{TiO}_2)_{0.6}$	-825.0	8.19	8.58e3
$\text{Sn}_{61}\text{Bi}_{25}\text{Sb}_5\text{Zn}_4\text{Al}_{2.1}\text{Ag}_2(\text{TiO}_2)_{0.9}$	-539.0	152	159.1
$\text{Bi}_{25}\text{Sn}_{61}\text{Sb}_5\text{Zn}_4\text{Al}_{1.8}\text{Ag}_2(\text{TiO}_2)_{1.2}$	-797.0	3.6	3.77e3
$\text{Bi}_{25}\text{Sn}_{61}\text{Sb}_5\text{Zn}_4\text{Al}_{1.5}\text{Ag}_2(\text{TiO}_2)_{1.5}$	-587	63.4	66.35

## Conclusion

Adding titanium oxide which has low density, high refractive index with higher melting temperature to tin or bismuth-based alloys improved their properties due changed its matrix structure for make it used in different industrial applications.

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