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Effects of Processing Parameters on Microstructure and Mechanical Properties of Powder-Thixoforged SiC_p/6061 Al Composite

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A novel processing technology for the fabrication of particle reinforced metal matrix composites, powder thixoforming (PTF), was proposed and 6061 Al-based composites reinforced with 10% volume fractions of SiC particles (SiC_p) were fabricated. The effects of processing parameters, such as reheating time, mould temperature and reheating temperature, on its microstructure and mechanical properties were investigated. The results indicated that all the three processing parameters exerted a significant influence on the microstructure and mechanical properties. The behavior of SiC_p changes with the processing parameters. The best comprehensive mechanical properties with an ultimate tensile strength (UTS) of 228 MPa, elongation of 5.3% and a Vickers hardness of 66.4 HV are obtained when the composite is thixoforged under the reheating temperature of 660 ^oC for 90 min and the mould temperature of 250 ^oC.

Keywords: *powder-thixoforging, SiC_p/6061 Al composite, processing parameters, microstructure, mechanical properties*

1. Introduction

Aluminum matrix composites (AMCs), especially those reinforced by ceramic particles such as SiC and Al_2O_3, have wide applications in the fields of aerospace and automobile because of their superior strength, stiffness, wear resistance and high-temperature mechanical properties[1-4]. So far, there are lots of methods to fabricating particle reinforced AMCs to be developed[5-8]. Among them, powder metallurgy (PM) has been widely used due to the uniform dispersion of reinforcements and low processing temperature[9,10]. But numerous voids are inevitably incorporated into the as-obtained composites in spite of the employment of some advanced sintering methods[10]. Moreover, it is not feasible to produce components with large size or complex shape. Thixoforming, a promising metal-forming technology that can significantly diminish voids and be available for producing large-sized and shape-complicated components, is introduced to be integrated with PM, and hence a novel technology named powder thixoforming (PTF) can be developed. A composite ingot is first obtained using the blending and pressing procedures of PM. The ingot is then partially remelted and a non-dendritic semisolid ingot is achieved. Finally, the semisolid ingot is thixoformed and a composite component is prepared. The PTF not only inherits the merits of the PM, but also retains the advantages of thixoforming. So far, the technologies that are most similar to PTF are pseudo-semisolid forming[11,12] and semisolid powder processing[13]. The former has pseudo-semisolid forming temperature at which the matrix (Al or Cu) is in liquid state and the reinforcement (SiC_p or W_p) is in solid state, and its solid fraction can be as high as 60%-70%. The latter has bad thixoformability owing to its high solid fraction (>90%) and the corresponding researches mainly concentrate on the influences of SiC volume fraction and particle size as well as forming pressure on the mechanical properties. Unfortunately, the existing studies about PTF have mainly emphasized on the microstructure evolution during partial remelting and mechanical properties of aluminum matrix alloys[14-16]. Only one report involved the effects of solution treatment on microstructure and mechanical properties of SiC_p/6061 Al matrix composites fabricated by PTF[17].

In attempt to improve the mechanical performance of the AMCs components, it is necessary to first optimize the processing parameters[15]. Early researches on the thixoforged alloys revealed that the three processing parameters, such as reheating time, mould temperature and reheating temperature, exerted a large effect on the microstructure and mechanical properties[18,19]. Hence, the effects of the three parameters on microstructure and mechanical properties of powder-thixoforged 10vol.%SiC_p/6061 Al composite were investigated in this work.

2. Materials and methods

2.1. Composite preparation

The raw materials utilized in this work were atomized 6061 Al powders with an average size of 18.37 μm and pre-oxidized SiC_p with an average size of 6.94 μm. As reported in

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a previous study[15], the solidus and liquidus temperatures of the 6061 matrix alloy were 610.2 and 674.6 ºC, respectively. Firstly, the 6061 Al powders were homogeneously mixed with 10 vol.% of SiC_p using ball milling in an ND7-21 planetary ball-milling machine at a mixing time, rotation speed and ball-to-powder weight ratio of 40 min, 100 rpm and 5:1, respectively. Bulk composite ingots with a diameter of 45 mm and a height of 30 mm as the starting ingots for thixoforging were then prepared by cold pressing of the powder mixture under a pressure of 145 MPa. One ingot was heated in a resistance furnace at a semisolid temperature for a time, and then quickly placed into a forging mold with a cavity of 60 mm×60 mm×30 mm and thixoforged under a pressure of 105 MPa. The detailed parameters utilized in this work are shown in Table 1. Repeating the above processing procedures in accordance with the parameters listed in Table 1, the thixoforged composites under different processing parameters were obtained. To examine the temperature change in the specimen during partial remelting, a thermocouple was placed in the center of a specimen during partial remelting at a semisolid temperature of 660 ºC.

Table 1: Processing parameters utilized in this work

Reheating time/min	Mould temperature/ºC	Reheating temperature/ºC
70, 80, 90, 100	300	660
90	200, 250, 300, 350	660
90	250	650, 655, 660, 665

2.2. Material characterization

Metallographic specimens with diameter of 10 mm and length of 10 mm were machined from the central region of the thixoforged composites, and then ground, finished, polished and etched using an aqueous solution of 10vol.% NaOH. Subsequently, the specimens were observed on a QUANTA FEG 450 scanning electron microscope (SEM) so as to clarify the variation in microstructure. Some typical fracture surfaces and their side views were also observed on the SEM in attempt to verify the detailed fracture mechanisms of the composites.

2.3. Performance testing

Tensile specimens were cut from the central region of each thixoforged composite. The dimensions of the tensile specimen are displayed in Figure 1. The tensile tests were conducted on a WDW-100D universal material testing machine with a cross head speed of 0.5 mm/s. Minimum five tests were conducted for each composite. The hardness was examined on an HBRVU-187.5 Brinell-Rockwell-Vickers optical hardness tester with an applied load of 30 kg and a holding time of 30 s. An average of at least four tests examined in the different positions of each specimen was taken as the hardness of the composite.

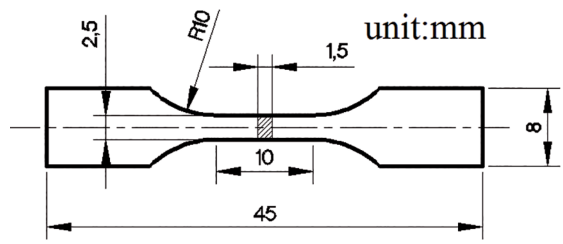

Figure 1: Schematic of the utilized tensile testing sheet

3. Results and discussions

3.1. Semisolid microstructure prior to thixoforging

As is well known, a semisolid microstructure with small and globular primary particles surrounded by liquid phase is vital to semisolid forming[10]. Hence, it is essential to clarify whether the SiC_p/6061 Al composite utilized in this paper can obtain such a semisolid microstructure after being partially remelted. As presented in Figure 2a, the microstructure of the as-cold-pressed composite bulk consists of mechanically bonded Al powders with SiC_p distributed in the intergranular regions. After a bulk composite specimen with a diameter of 22 mm was heated at 660 ºC for 30 min, the size of the primary particles is slightly smaller than that of the initial powder in the as-cold-pressed specimen (Figure 2b). Moreover, owing to the reactions of SiC_p with the liquid phase at semisolid state[20], the size of the SiC_p is also slightly smaller than that in the as-cold-pressed specimen (comparing Figures 2a and b). When the bulk alloy with a diameter of 45 mm was heated at 660 ºC for 90 min, the primary particles become larger and more spherical than those in the as-cold-pressed condition (comparing Figures 2a and c) due to the following reasons. First, the reheating of the larger ingot needs relatively longer time. As shown in Figure 3, the temperature in the central region of the sample didn't reach the setting temperature of 660 ºC until it was reheated for 74 min, while it would only take 20 min for the smaller specimen[14]. It is known that the primary particles would inevitably coarsen during partial remelting, and the longer reheating time leads to the larger primary particle size. Second, the big curvatures of the edges and corners of the primary particles give rise to the low melt point and the melting of these places leads to the near spherical particles[15]. Besides, the SiC_p around the primary particles impede the attached growth of the secondarily solidified structures (SSSs) onto the primary particles, consequently diminishing the generation of irregular particles in the composite. Even so, the irregular primary particle size in the larger ingot is still smaller than 50 μm.

Hence, it is concluded that the semisolid microstructure of the 10vol.%SiC_p/6061 Al composite with a diameter of 45 mm is suitable for thixoforming considering the size and

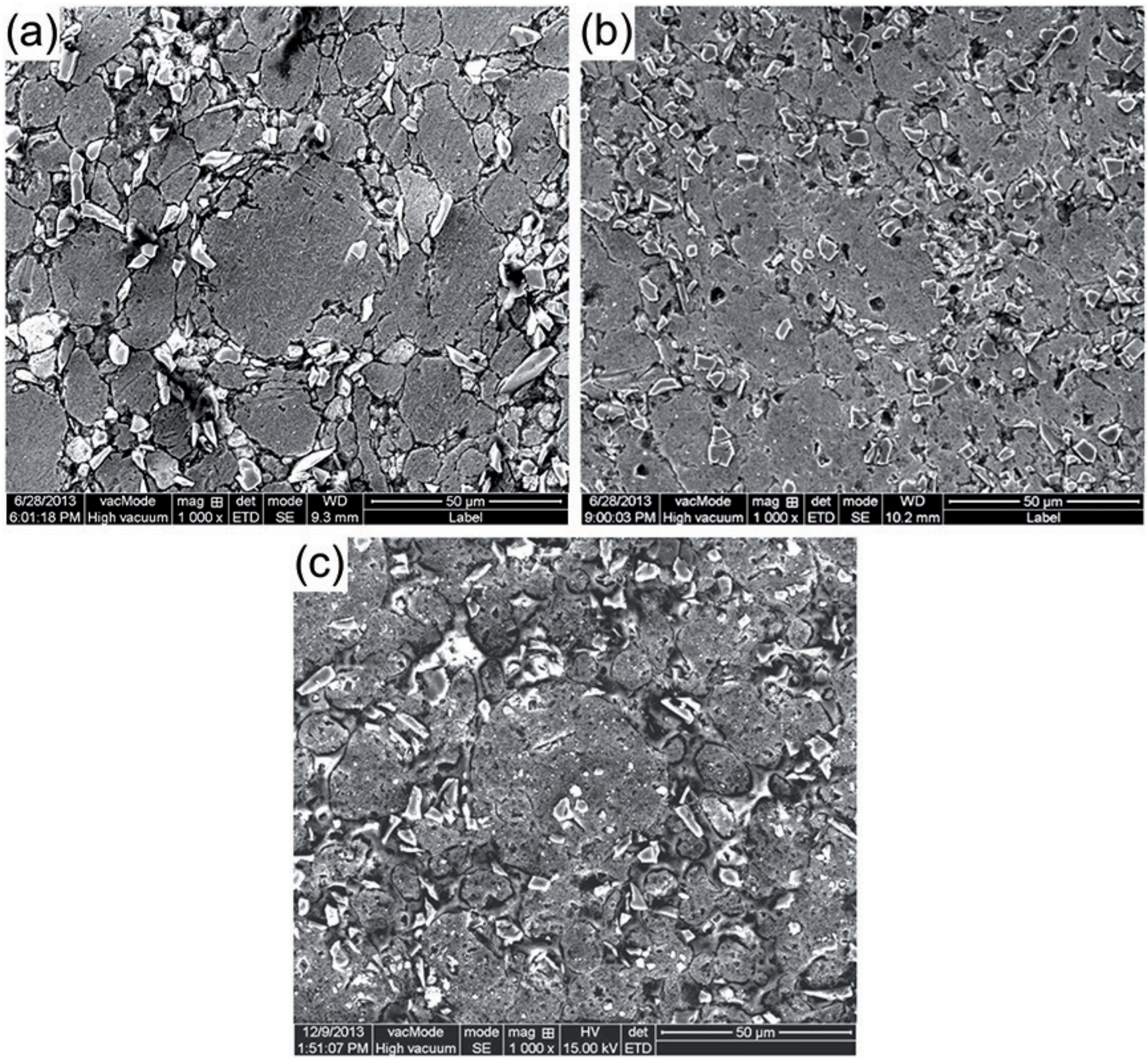

Figure 2: Microstructures of (a) as-cold-pressed, (b) semisolid (heated at 660 ºC for 30 min) ingot with diameter of 22 mm and (c) semisolid (heated at 660 ºC for 90 min) ingot with diameter of 45 mm

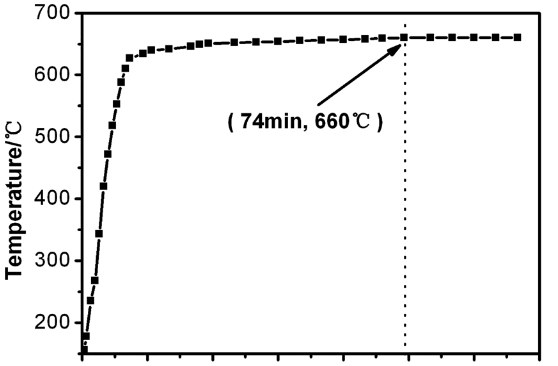

Figure 3: Temperature variation of composite ingot (with diameter of 45 mm) with reheating time at 660 ºC

morphology of the primary particles. It must be noted that the solid primary particles and the liquid phase in the water-quenched microstructures are difficult to be distinguished primarily due to the small amount of eutectic phases and small size of the primary particles. Nevertheless, the following experimental results corroborate that the liquid fraction in this composite is also adequate for thixoforming.

3.2. *Effects of reheating time on microstructure and mechanical properties*

Figure 4 displays the typical stress-strain curves of the 10vol.% SiC_p/6061 Al composite under different processing parameters. Table 2 gives the average tensile properties and hardness of the SiC_p/6061 Al composite thixoformed under

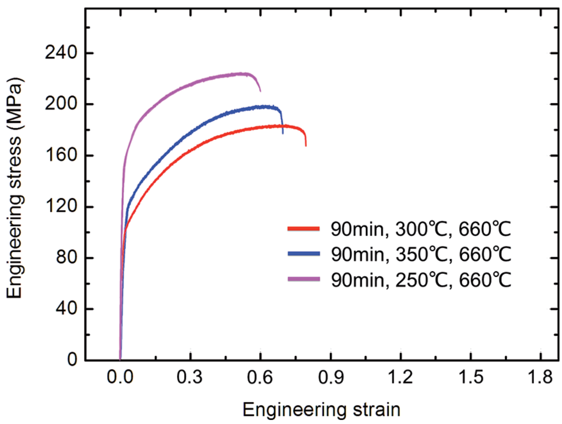

Figure 4: Typical stress-strain curves of 10vol.% SiC_p/6061 Al composite under different processing parameters

different conditions. It is evident that the maximum UTS and hardness of the composite are up to 228 MPa and 66.4 HV, respectively, representing an enhancement of 15.7% and 20.3% than those of the matrix alloy[21]. However, its elongation decreases to 5.3%, a reduction of 51.8% in comparison with the matrix alloy. Since 6061 aluminum alloy can be heat-treated so as to further improve its properties[22], it can be expected that higher performance would be achieved after the 10vol.%SiC_p/6061 Al composite is appropriately heat-treated.

From Table 2, it can be found that as the reheating time varies, the highest values of UTS and elongation are 199 MPa and 6.2%, respectively, at the time of 90 min. Generally, the effect of the reheating time on the tensile properties seems quite small. Taking the UTS and elongation as the criterion for evaluating the mechanical properties of the composite, it is evident that the reheating time of 90 min is the most suitable. Even so, the reheating time has limited influence on the composite's UTS in view of the existing experimental results.

Figure 5 depicts the thixoforged microstructures of SiC_p/6061 Al composite after being reheated at 660 ^{0}C for different durations. Aggregation of SiC_p can be observed to some extent in the secondarily solidified structures (SSSs) between the primary particles. The smaller secondarily primary particles in the SSSs are difficult to be differentiated from each other due to the existence of small-sized SiC_p. Besides, owing to the direct growth of the secondarily primary particles on the primary particles, the grain boundaries of primary particles are also hard to be identified. When the composite is heated for 70 min, the temperature in the central region of the ingot doesn't reach the setting temperature of 660 ^{0}C (Figure 3), revealing that the semisolid system is not up to its final equilibrium solid-liquid state and the liquid fraction is lower than that of the equilibrium value. The reheating duration of 70 min is the shortest in this work, so the liquid fraction is the least. As is well known, the deformation process of a semisolid non-dendritic ingot under pressure involves four regimes, liquid flow (LF), flow of liquid incorporating solid particles (FLS), sliding between solid particles (SS) and plastic deformation of solid particles (PDS)[23,24]. The former two regimes dominate when the solid primary particles are encompassed by liquid phase while the latter ones are dominant when the solid particles become in contact with each other. When the ingot is heated for 70 min, the distance between the neighboring primary particles should be very short, and even they connect with each other due to the low liquid faction. So the deformation during the initial stage of thixoforming is controlled by LF and FLS regimes. Then the deformation mechanisms would rapidly transform into SS and PDS regimes because of the

Table 2: UTS, elongation and hardness of powder-thixoforged SiC_p/6061 Al composite

	Reheating time/min (mould temperature: 300 ^{0}C; reheating temperature: 660 ^{0}C)			
	70	80	90	100
UTS (MPa)	198±2.0	195±2.4	199±1.9	192±3.2
Elongation (%)	5.0±0.4	5.1±0.5	6.2±0.3	5.0±0.6
Hardness (HV)	51.6±2.5	58.8±1.9	63.3±2.1	78.5±1.7
	Mould temperature/^{0}C (reheating time: 90min; reheating temperature: 660 ^{0}C)			
	200	250	300	350
UTS (MPa)	214±3.6	228±3.2	199±1.9	184±3.5
Elongation (%)	4.7±0.5	5.3±0.5	6.2±0.3	6.4±0.6
Hardness (HV)	60.1±3.1	66.4±2.3	63.3±2.1	67.3±2.4
	Reheating temperature/^{0}C (mould temperature: 250^{0}C; reheating time: 90min)			
	650	655	660	665
UTS (MPa)	197±3.3	211±3.5	228±3.2	198±4.2
Elongation (%)	3.3±0.2	4.2±0.2	5.3±0.5	7.7±0.6
Hardness (HV)	79.3±3.3	65.4±2.9	66.4±2.3	72.6±4.3

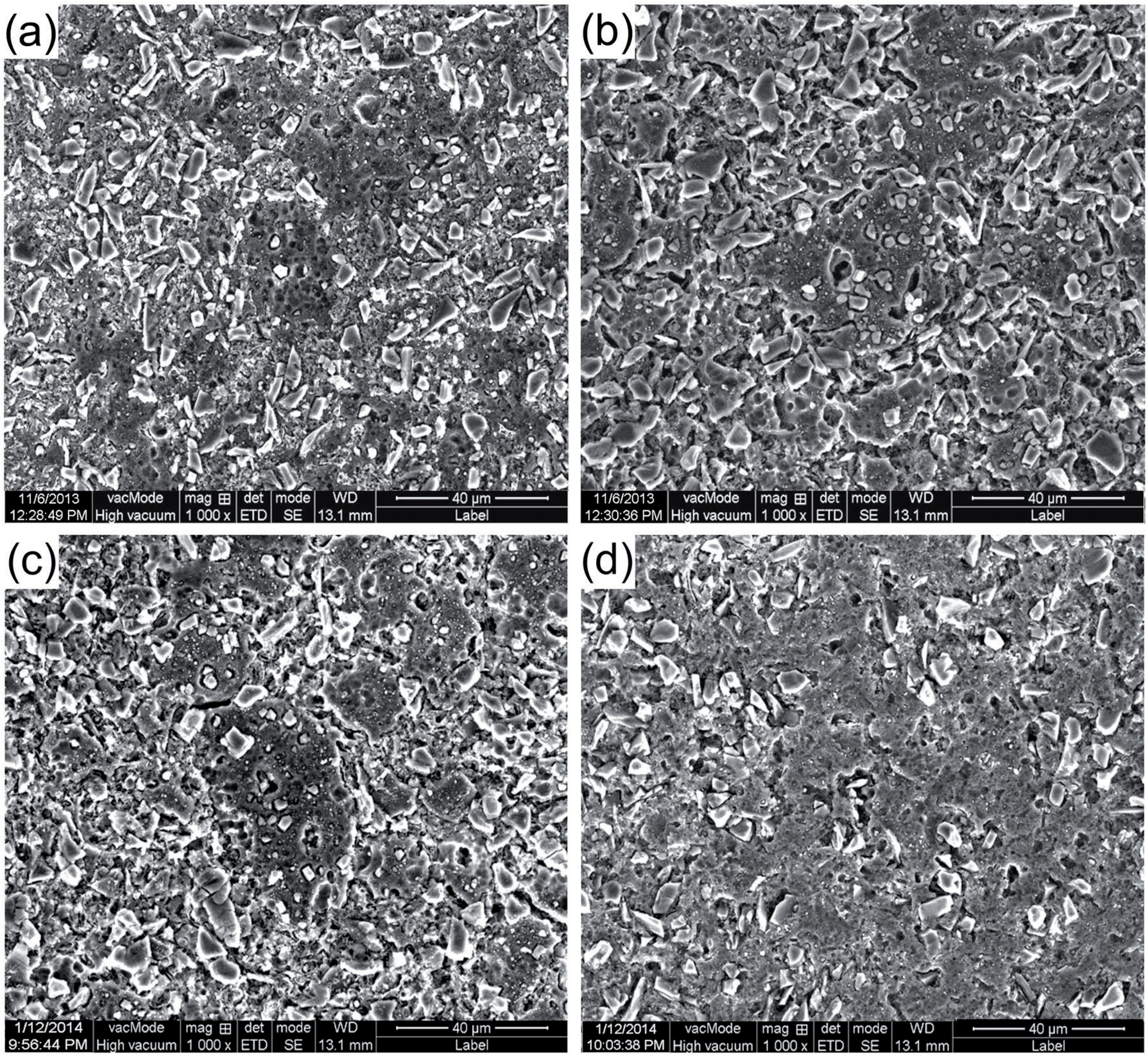

Figure 5: Microstructures of the SiC_p/6061 Al composite thixoforged under reheating at 660 ^oC for (a)70 min, (b)80min, (c)90min and (d)100min

least liquid phase at this stage, accelerating the formation of large-sized interconnected primary particles (Figure 5a). It is just due to the least liquid fraction at the time of 70 min that the mould filling ability and the feeding ability to solidification shrinkage are the worst, resulting in the easy formation of porosities in the SSSs. That is, the SSSs between the primary particles may serve as the weak points of this composite. Hence, cracks preferentially initiated and then propagated along these structures during tensile testing (marked by arrows in Figure 6a). Results from the corresponding fracture surface indicate that fracture across the matrix alloy is dominant (Figure 7a) and the debonding of SiC_p/matrix interfaces is only occasionally observed (marked by arrows in Figure 7a'). It is therefore reasonable to give the composite thixoforged under 70 min relatively lower tensile properties (Table 2).

When the reheating time is extended to 80 min, the temperature in the central region of the sample is up to the setting temperature of 660 ^oC. The liquid fraction should be increased to the maximum value at this temperature, leading to the improvement of the mould filling ability, especially the feeding ability to solidification shrinkage in the process of thixoforging. Consequently, the compactness of the SSSs is enhanced (Figure 7b). Besides, the fragmentation of SiC_p could be observed on the fracture surface (marked by arrows A in Figure 7b'), implying that the bonding of SiC_p/matrix interfaces is relatively strong. However, the rate of the microstructural evolution in the process of partial remelting is always laggard than that of the temperature rise[21]. Especially, the addition of SiC_p would impede the heat transfer, and thus the liquid fraction is still smaller than what the temperature corresponds to. Under this condition, the distribution of SiC_p

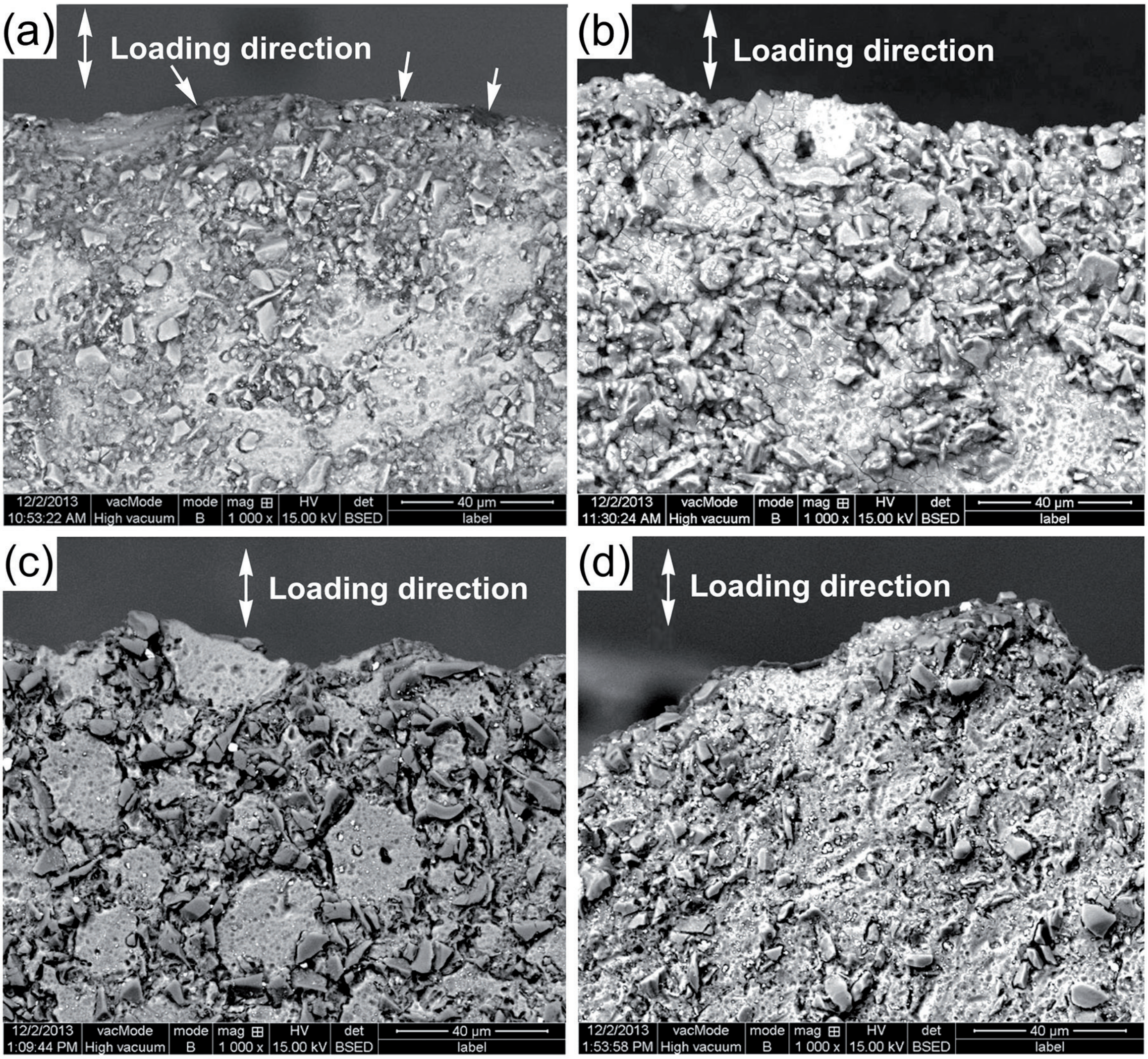

Figure 6: Side views of fracture surfaces of the SiC_p/6061 Al composite thixoforged under reheating times of (a)70 min, (b)80min, (c)90min and (d)100min

is limited within some local liquid regions, i.e., the local SSSs regions (Figure 5b). It can be clearly observed that SiC_p aggregate around the primary particles on the side view of the fracture surface (Figure 6b). A stress concentration can easily generate in these sites owing to the inhomogeneous deformation during thixoforging. Moreover, the pores between the SiC_p are difficult to be fed and the SiC_p/SiC_p interfaces are actually not well-bonded, resulting in the debonding of SiC_p on the fracture surface (marked by arrows B in Figure 7b'). It is just due to the aggregation and debonding of SiC_p that the UTS of the composite is decreased at the reheating time of 80 min (Table 2).

As the time is prolonged to 90 min, the semisolid system reaches its final equilibrium solid-liquid state. The liquid fraction is up to the maximum value at this temperature and the distribution of the SiC_p that are located in liquid phase becomes uniform (Figure 5c). It can be expected that the deformation in the process of thixoforging should also become homogeneous. Simultaneously, the flowability and feeding ability to solidification shrinkage get further improved, giving rise to the enhanced microstructure compactness of the composite. The cracks propagate across the primary particles as well as the SSSs (Figure 6c). The corresponding fracture surface is characterized by fractured SiC_p and small dimples (Figures 7c-c'). Due to the improvement in the microstructure compactness and SiC_p uniformity, the mechanical properties of the composite are improved to some degree (Table 2).

When the time is prolonged to 100 min, the primary particles coarsen into larger ones and the neighboring particles agglomerate and contact each other (Figure 5d). Owing to the coarsening of the primary particles, the liquid phase also segregates. Thus, the SiC_p enwrapped by the liquid phase also agglomerates to a certain extent, leading to the generation of stress concentration and pores in these sites

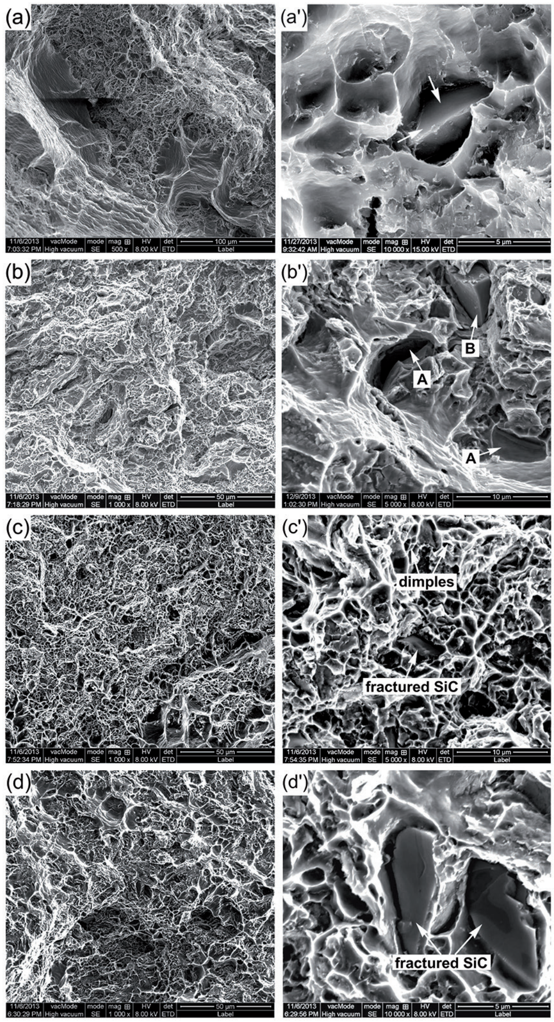

Figure 7: Fracture surfaces of the SiC_p/6061 Al composite thixoforged under reheating times of (a-a')70 min, (b-b')80min, (c-c')90min and (d-d')100min

during thixoforging. The cracks thereby developed along the SSSs (Figure 6d) and some aggregated SiC_p fractured (Figures 7d-d'). It can therefore be concluded that the increased pores as well as the stress concentration account for the decrease in the tensile properties of the composite (Table 2).

From the discussion above, it can be concluded that the employed reheating time has a large effect on the microstructure, but a slight effect on the mechanical properties of the SiC_p/6061 Al composite. Before the semisolid system is up to its final equilibrium solid-liquid state, as the reheating time increases, so does the liquid fraction. Consequently, the flowability and feeding ability to solidification shrinkage get improved and the microstructure becomes compact, leading to the change of crack propagation from the SSSs to both the SSSs and primary particles. Thus, the elongation and hardness become higher and higher, and the peak values can't be reached until the semisolid system attains its final equilibrium solid-liquid state. Nevertheless, once the reheating time is further prolonged, the microstructure becomes incompact and the stress concentration appears due to the liquid segregation as well as the corresponding segregation of SiC_p resulted from the coarsening of the primary particles. As a result, the tensile properties of the composite are decreased. The path for crack propagation then transforms along the SSSs again.

3.3. Effects of mould temperature on microstructure and mechanical properties

The UTS first increases when the mould temperature rises from 200 to 250 ^{0}C and then decreases (Table 2). The composite formed at the mould temperature of 250 ^{0}C possesses the best comprehensive mechanical properties with an UTS of 228 MPa, elongation of 5.3% and a Vickers hardness of 66.4 HV.

Results from a previous study[21] revealed that the mould temperature primarily influenced the liquid solidification rate, which in turn affected the deformation process during thixoforging as well as the resulting primary particle size. When the mould is at a low temperature of 200 ^{0}C, the liquid solidification is rapid. The time is too short to fully operate the LF and FLS regimes. As a result, the solid/liquid segregation generated by LF regime is avoided, and a uniform distribution of the primary particles and the SiC_p in the SSSs can be obtained (Figure 8a). With the rise of the temperature, the time for the operation of LF and FLS regimes gradually becomes longer, thus the liquid fraction in the central region as well as the SiC_p amount and distribution uniformity gets reduced (Figure 8b). As the temperature is further elevated to 350 ^{0}C, due to the improved FLS regime, only a relatively small amount of SiC_p distribute in the central region (Figure 8c). In addition, the primary particles coarsen into larger ones and connect with each other in the thixoformed composites.

When the mould temperature is 200 ^{0}C, the feeding ability to solidification shrinkage is the worst as a result of the rapidest solidification rate. Thus, porosities can easily generate in the SSSs and these sites act as the weak points of the composite. Results from the side view of fracture surface indicate that cracks preferentially propagate along the SSSs during tensile testing (marked by arrows in Figure 9a). The corresponding fracture surface is characterized by small dimples and a small amount of fractured SiC_p (Figures 10a-a'). Despite the relatively uniform microstructure at this temperature, the mechanical properties of the composite, especially the elongation and the hardness, are actually not so high due to the incompactness of the microstructure. As the temperature rises to 250 ^{0}C, the solidification rate becomes slower and the feeding ability to the shrinkage porosities gets improved. Although the SSSs in the composite still serve as the weak points at this temperature (Figure 9b), the compactness of microstructure is enhanced to a certain degree. Furthermore, the bonding strength of SiC_p/matrix interfaces is also improved due to the enhanced

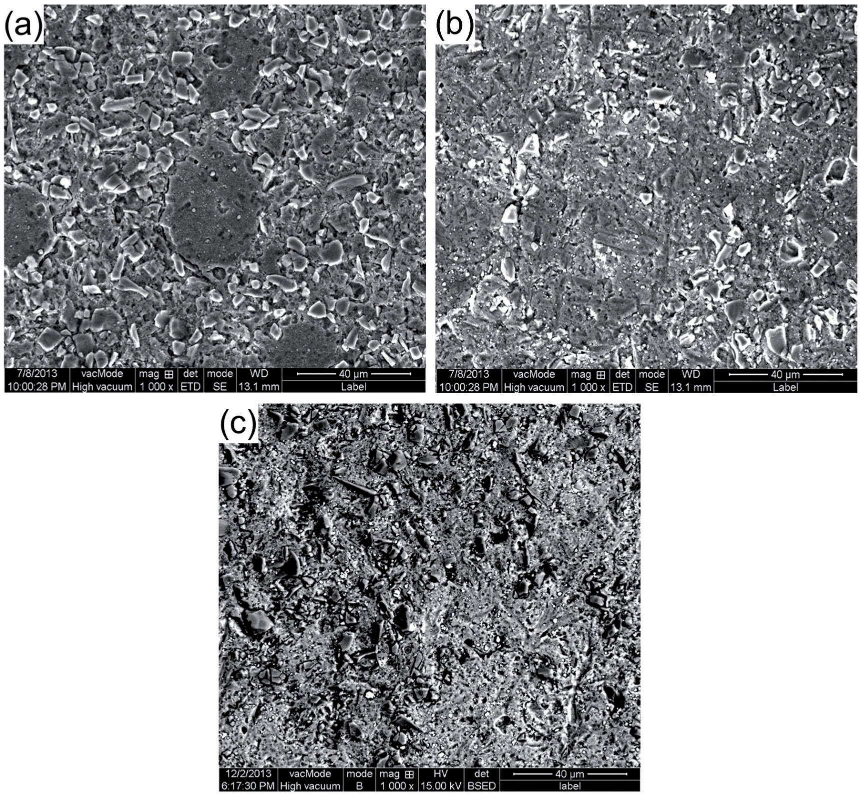

Figure 8: Microstructures of the SiC_p/6061 Al composite thixoforged at mould temperatures of (a)200 ºC, (b)250 ºC and (c)350ºC.

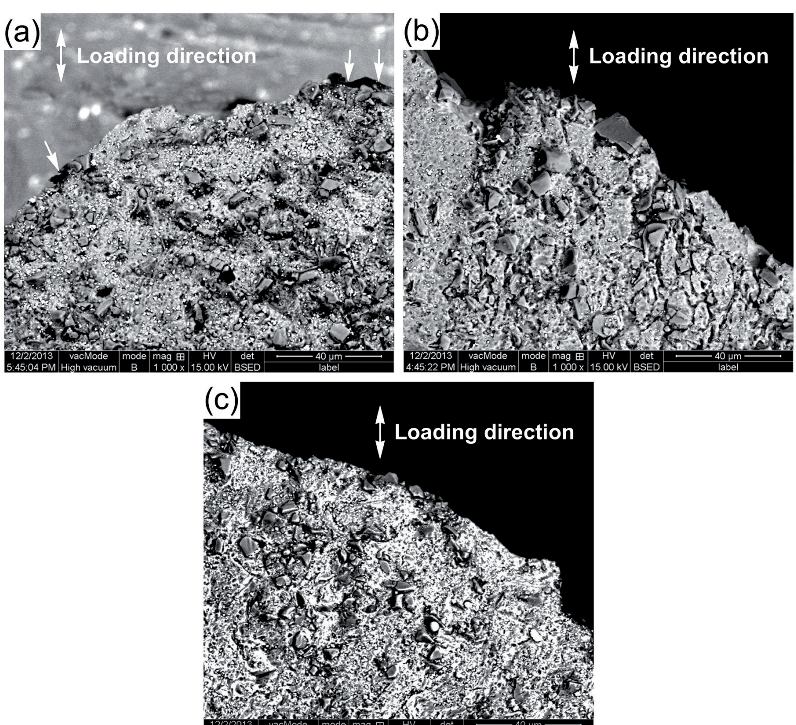

Figure 9: Side views of fracture surfaces of the SiC_p/6061 Al composite thixoforged at mould temperatures of (a)200 ºC, (b)250 ºC and (c)350 ºC

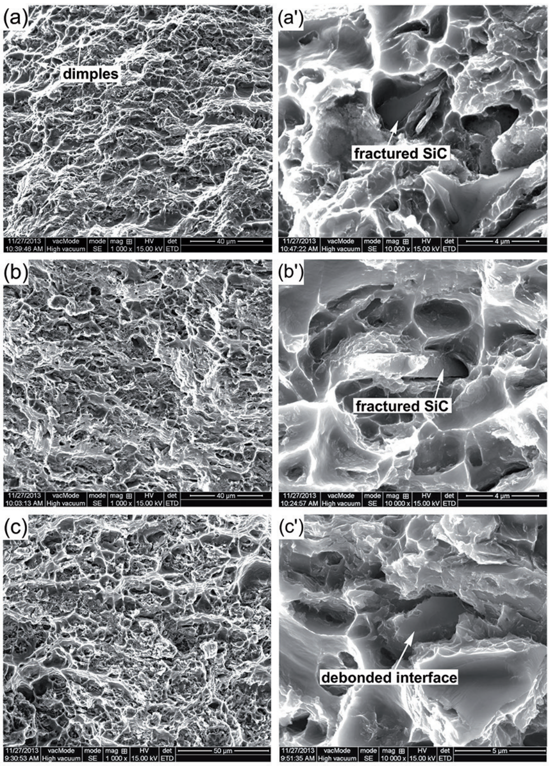

Figure 10: Fracture surfaces of the SiC_p/6061 Al composite thixoforged at mould temperatures of: (a-a')200 ^{0}C, (b-b')250 ^{0}C and (c-c')350 ^{0}C

microstructure compactness, giving rise to the fragmentation of SiC_p accompanied with the large plastic deformation in the surrounding matrix during tensile testing (Figures 10b-b'). The mechanical properties are correspondingly improved. However, the time for the operation of LF regime becomes longer owing to the slower solidification rate, leading to the solid/liquid segregation. Besides, the distribution of the SiC_p becomes relatively heterogeneous. Therefore, the increase range of the mechanical properties is not very large. When the temperature is elevated to 350 ^{0}C, SiC_p agglomerate in some local regions around the primary particles and the primary particles coarsen into larger ones and connect with each other (Figure 8c). As a result, the deformation during thixoforging becomes more heterogeneous and the stress concentration gets higher accompanied with the relatively weaker bonding strength of the SiC_p/matrix interfaces. Although the crack propagation is still along the SSSs (Figure 9c), the behavior of SiC_p changes from fragmentation to the debonding (Figures 10c-c'). Under such conditions, the UTS is decreased (Table 2).

Based on the above discussion, it can be summarized that the mould temperature has a large effect on both microstructure and mechanical properties of the SiC_p/6061 Al composite. When the composite is thixoforged at a lower temperature, the microstructure and the stress distribution during thixoforging are relatively uniform. But the solidification rate is the rapidest and porosities can easily form in SSSs, the mechanical properties are therefore not so high. With the rise of the temperature, the solidification rate of the liquid phase slows down and the microstructure becomes more compact, the mechanical properties are accordingly improved. Correspondingly, the interfacial debonding of SiC_p/matrix changes into the facture of SiC_p. However, further elevating temperature makes the microstructure, especially the distribution of the SiC_p, more nonuniform, resulting in the easy formation of stress concentration in these sites. In addition, the primary particles coarsen into larger ones and connect with each other in the thixoformed ingots. Therefore, a decrease in the tensile properties of the composite inevitably appears. Simultaneously, the behavior of SiC_p transforms from fragmentation to interface debonding.

3.4 Effects of reheating temperature on microstructure and mechanical properties

The UTS continuously increases as the reheating temperature rises from 650 to 660 ^{0}C, and then decreases when the temperature further rises to 665 ^{0}C. In view of the best comprehensive mechanical properties, reheating at 660 ^{0}C is the most appropriate.

Figure 11 depicts the microstructures of the SiC_p/6061 Al composite thixoforged at different reheating temperatures. A previous research revealed that the amount of liquid phase in this composite was relatively small and the neighboring primary particles had a high tendency to coarsen into larger ones when the reheating temperatures are 650 and 655 ^{0}C [21]. As shown in Figures 11a and b, some of the primary particles connect together and the SiC_p tend to distribute in the boundaries of the interconnected primary particles. As the temperature rises to 665 ^{0}C, large amounts of liquid phase are formed and severe agglomeration of phase constituents including SiC_p occurs due to the enough operation of LF regime during thixoforging (Figure 11c).

When the reheating temperature is 650 ^{0}C, the amount of liquid phase is relatively small. As stated in the section of 3.2, porosities generated in the SSSs would serve as the weak points of this composite. As displayed in Figure 12a, cracks preferentially propagate along the SSSs during tensile testing (marked by arrows). Simultaneously, the boundaries of the interconnected primary particles should also become the weak points due to the large deformation stress generated in the process of thixoforging. But SiC_p that distribute in the boundaries would inhibit the crack propagation along these sites. The composite at this temperature is therefore strengthened. Nevertheless, the imposed stress concentration would easily lead the SiC_p to fracture (Figures 13a-a'). As the temperature rises to 655 ^{0}C, the amount of liquid phase increases, and consequently the microstructure compactness gets improved. Therefore, the UTS of the composite is enhanced. The crack propagation is mainly along the SSSs as

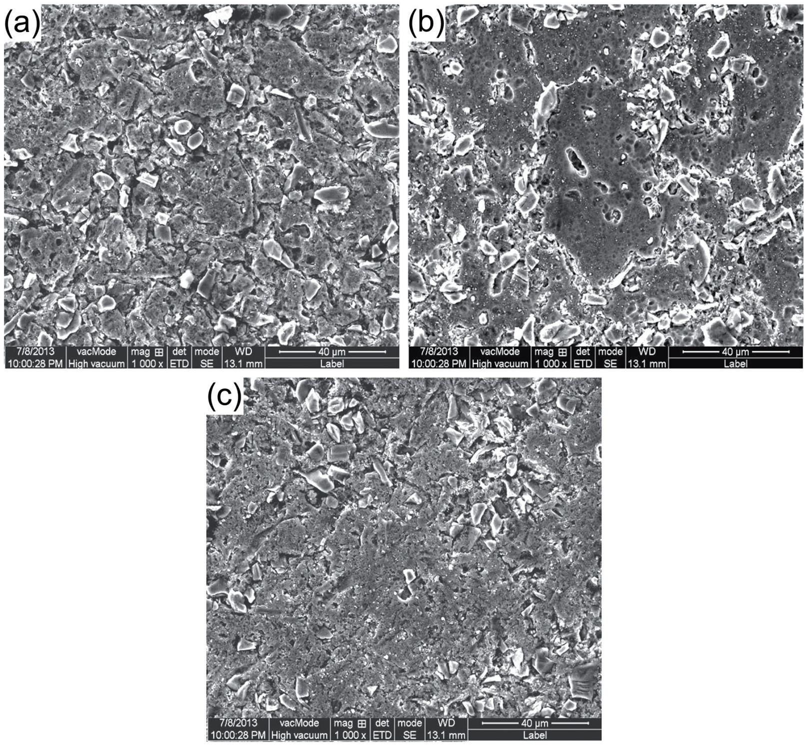

Figure 11: Microstructures of the 10vol.%SiC_p/6061 Al composite thixoforged at reheating temperatures of: (a)650 ºC, (b)655 ºC and (c)665 ºC

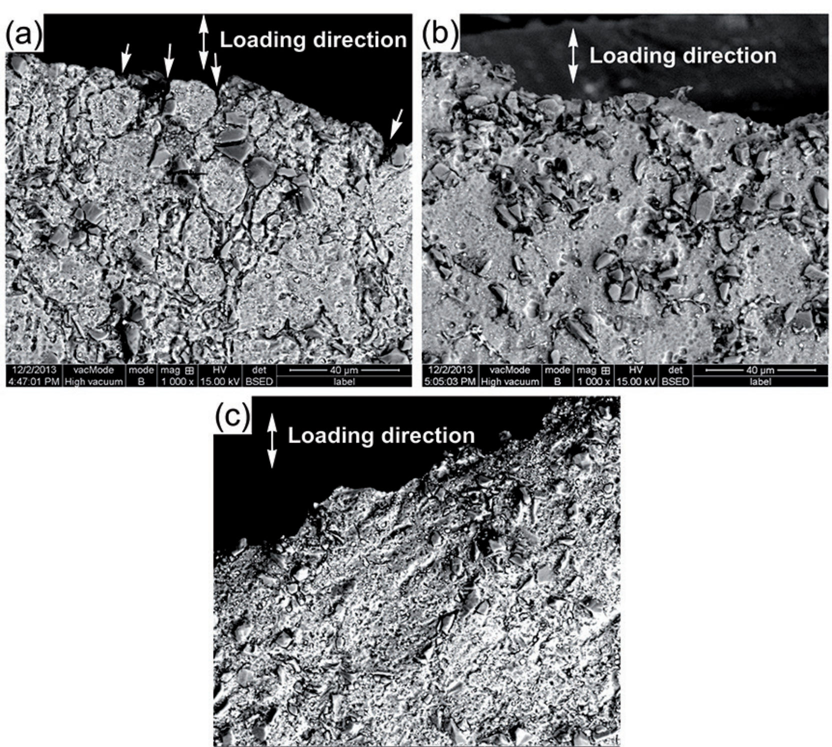

Figure 12: Side views of fracture surfaces of the 10vol.%SiCp/6061 Al composite thixoforged at reheating temperatures of: (a)650 ºC, (b)655 ºC and (c)665ºC

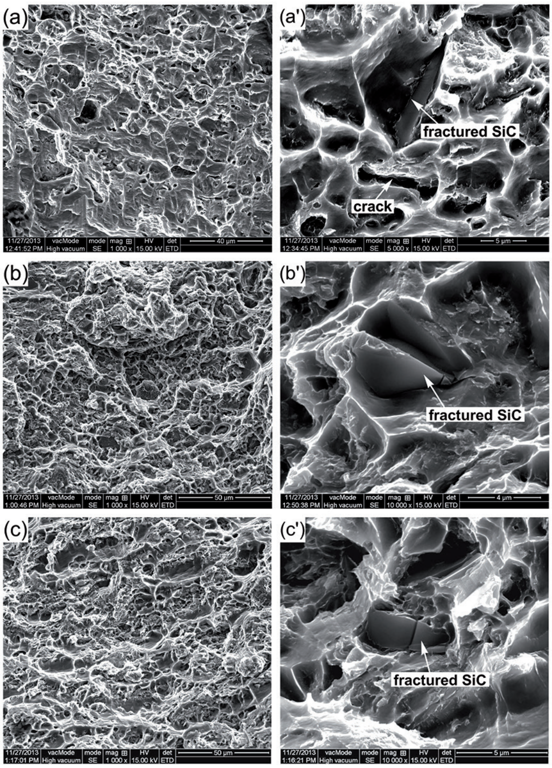

Figure 13: Fracture surfaces of the 10vol.%SiC_p/6061 Al composite thixoforged at reheating temperatures of: (a-a')650 ^{0}C, (b-b')655 ^{0}C and (c-c')665^{0}C

well as the primary particles (Figure 12b), and the behavior of SiC_p belongs to the failure induced by the fractured SiC_p (Figures 13b-b'). When the temperature is further elevated to 665 ^{0}C, large amounts of liquid phase form. In spite of the SiC_p agglomeration, the bonding strength of the SiC_p/matrix interfaces is relatively high because the liquid phase is enough for enwrapping SiC_p and possible interface reactions. The cracks still develop along the SSSs (Figure 12c). Besides, the stress concentration should be easily formed in the regions of the aggregated SiC_p, giving rise to the fragmentation of SiC_p when it exceeds certain value (Figures 13c-c'). It is evident that the incompact microstructure as well as stress concentration accounts for the decrease in the UTS of the composite.

In summary, the reheating temperature also has an obvious effect on both microstructure and mechanical properties of the SiC_p/6061 Al composite. As the temperature rises, so does the liquid fraction. The feeding ability to solidification shrinkage gets improved and consequently the microstructure becomes more compact, resulting in the gradually enhanced tensile properties. The best comprehensive mechanical properties with an UTS of 228 MPa, elongation of 5.3% and a Vickers hardness of 66.4 HV are obtained at the reheating temperature of 660 ^{0}C. Nevertheless, once the reheating temperature is further elevated, too much liquid phase is formed and the microstructure becomes incompact due to segregation of phase constituents. Simultaneously, the stress concentration appears especially due to the segregation of SiC_p. As a result, the UTS of the composite is decreased. However, the behavior of SiC_p remains its fragmentation irrespective of the reheating temperature.

The aforementioned experimental results demonstrate that all the three processing parameters have a large effect on the microstructure of the thixoforged 10vol.%SiC_p/6061 Al composite. But the influence of mould temperature and reheating temperature on the mechanical properties is larger than that of reheating time. The cracks always propagate along the SSSs regardless of the processing parameters. As the reheating time increases, the behavior of SiC_p transforms from the interface debonding to the fragmentation of SiC_p, while this transformation is opposite when the mould temperature varies. Because of the imposed stress concentration on the SiC_p, its behavior is always the fragmentation of SiC_p as the reheating temperature changes. The best comprehensive mechanical properties with an UTS of 228 MPa, elongation of 5.3% and a Vickers hardness of 66.4 HV can be obtained when the composite is thixoforged at the reheating temperature of 660 ^{0}C for 90 min and mould temperature of 250 ^{0}C, which represent increases of 16.3% and 10.7% for the UTS and hardness as compared to the powder-thixoforged 6061 matrix alloy[15]. In comparison with those previously reported 10vol.%SiC_p/6061 Al composites fabricated by conventional methods, such as semisolid stirring[25], the proposed composite in this paper not only shows a much higher ductility while maintaining a considerable tensile strength, but also is feasible to produce components with large size or complex shape. Besides, it can be expected that higher tensile properties of this composite can be further achieved after being properly heat-treated due to the characteristics of its matrix alloy. It is therefore concluded that powder-thixoforged composites with high mechanical properties can be achieved by adjusting the processing parameters of reheating time, reheating temperature and mould temperature to obtain a compact microstructure with a uniform distribution of SiC_p.

4. Conclusions

In this paper, the effects of processing parameters on microstructure and mechanical properties of powder-thixoforged SiC_p/6061 Al composite have been investigated. The obtained results will play a crucial part in understanding the mechanical behaviors of the powder-thixoforged SiC_p/6061 Al composite and thus lay the foundation for further investigation on its heat treatment behaviors. The following conclusions can be drawn:

1. The reheating time, mould temperature and reheating temperature exert large effects on microstructure and mechanical properties of the 10vol.%SiC_p/6061 Al composite. Both the microstructure variations with reheating time or reheating temperature primarily result from the changes of the liquid

amount in the process of thixoforging. But the microstructure evolution with mould temperature is mainly attributed to the changes in the solidification rate. The mechanical properties depend primarily on the shrinkage porosities, stress concentration, microstructure and SiC_p uniformity.

2. Cracks always propagate along the SSSs regardless of the processing parameters. As the reheating time increases, the behavior of SiC_p transforms from the interface debonding to the fragmentation of SiC_p, while this transformation is opposite when the mould temperature varies. Because of the imposed stress concentration on the SiC_p, its behavior remains the fragmentation as the reheating temperature changes.
3. The effect of the reheating temperature and mould temperature on the mechanical properties of the composite is larger than that of the reheating time.
4. The best comprehensive mechanical properties with an UTS of 228 MPa, elongation of 5.3% and a Vickers hardness of 66.4 HV can be obtained when the composite is thixoforged at the reheating temperature of 660 ^{0}C for 90 min and mould temperature of 250 ^{0}C.
5. Powder-thixoforged composites with high mechanical properties can be achieved by adjusting the processing parameters of reheating time, reheating temperature and mould temperature to obtain a compact microstructure with a uniform distribution of SiC_p.

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