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REINFORCEMENT AND HOT WORKABILITY OF ALUMINIUM ALLOY 7075 PARTICULATE COMPOSITES: A REVIEW

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Abstract

A proper selection of matrix and reinforcement result in the best combinations of physical and mechanical properties in the resulting a metal matrix composite (MMC). Al 7075 and Silicon Carbide (SiC) are commonly used as matrix and reinforcement, respectively, in the aviation and space ventures, which is mostly attributed to its low weight-to-strength ratio, high wear, and excellent creep resistance. This work reviews the properties of aluminium matrix composites that are reinforced with different particles. The first objective is to analyse the influence of volume fraction (or wet fraction) and grain size induced by different reinforcement particles on the mechanical properties of Al 7075 composites, while the second objective is to study the hot workability of Al 7075/SiCp composites in the context of its forming temperature, strain rate, volume fraction, and grain size. It has been found that the presence of hard and brittle ceramic reinforcement in aluminum matrix composites (AMCs) lead to reduce the elongation and fracture toughness of the resulting composite. Moreover, large grain size and high volume fractions (42 µm, 21%, and 32%, respectively) of reinforced particles result in the loss of ductility in the majority of MMCs. On the other hand, with a high percentage of reinforcements, metal matrix composites experiences poor hot working. In addition, the maximum deformation efficiency that can be obtained by Al 7075 reinforced with silicon carbide particles is 44%, at a volume fraction of 15%, grain size of 20 µm, temperature of 400°C, and a strain rate of 0.1 s^{-1}.

Keywords: Aluminum particulate metal matrix composite, Al 7075 composites, Hot working, Mechanical properties.

Nomenclatures

f_1	A fundamental measure of the ductility of the workpiece.
f_2	*A function of the material, friction and the process.*
T	*Temperature, ^oC*

Greek Symbols

σ_{max}	Maximum tensile strength, MPa
σ_y	Yield stress, MPa

Abbreviations

Al_4C_3	Aluminum Carbide
Al_1O_3	Aluminum Oxide
Al_2O_3	Alumina
AMC_s	Aluminum Matrix Composites
B_4C	Boron Carbide
BN	Boron Nitride
DRX	Dynamic Recrystallization
ESA	European Space Agency
HBS	Hot Bird Satellite
MgO	Magnesium oxide
TiB	Titanium Boride
TiB_2	Titanium Diboride
TiC	Titanium Carbide
TiO_2	Titanium Dioxide
ZrB_2	Zirconium Diboride

1. Introduction

Materials science applications have seen many facets of research, encompassing the development of lightweight materials with improved properties such as specific strength, wear resistance fatigue, stiffness, and creep, especially at high working temperatures where these properties are absent from base alloys [1-5]. Recently, aluminum, magnesium, and titanium alloys are becoming especially crucial in many applications due to their lightweights, stable dimensionally, good machinability, and low power consumption/energy efficiency. However, these alloys exhibit decreased in mechanical properties at temperatures lower than 200°C, which is detrimental to their potential applications as critical components in the aerospace and automotive industry [6]. The best way to realize this goal is to fabricate composites from light metals and alloys [7, 8]. Based on the mechanical properties of composite materials compared with metals such as specific strength, higher specific stiffness, corrosion and fatigue resistance, they can be used to produce high-performance construction materials [9-11]. The main applications of metal matrix composite are for aerostructural components and parts in aeropropulsion systems and aeronautical subsystems [12-15]. MMCs are used in both commercial aeronautical and military industries. Figure 1 shows the application of MMCs in an F-16 aircraft [16].

Fig. 1. Application of metal matrix composites in F16 aircraft [16].

Composite materials are also increasingly utilized in aircraft base structure such as B787, Airbus A380, F35, and Typhoon. Figure 2 shows the increased usage of composites in several types of Boeing aircraft [9].

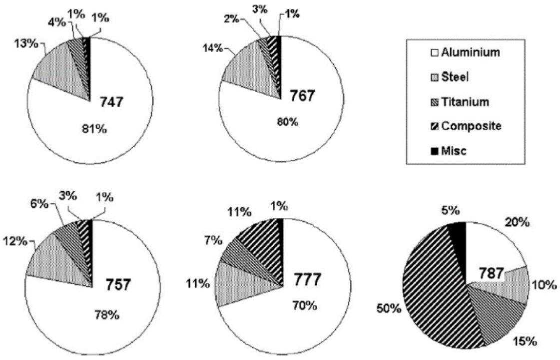

Fig. 2. Materials used in Boeing airplanes [9].

The European Space Agency (ESA) utilized Beryllium aluminum composite on a mechanism for its Hot Bird Satellite (HBS) [17]. Currently, Metal Matrix Composites (MMCs) are being used in a package of applications pertaining to aircrafts, the car industry, cutting tools, and sporting products. Aluminum matrix composites are preferred due to its low weight and extraordinary strength-to-weight ratio [18-20].

Aluminum as a matrix alloy and particles as reinforcement, have seen wide applications in MMCs for structural applications in the marine industry, aircraft and automobile [14, 15, 21, 22]. The automobile applications are piston rings, diesel engine pistons, cylinder liners, brake discs, drive shafts, connecting rods, due to its excellent properties and high specific strength [21, 23]. Metal-matrix composites made up of ductile aluminum alloys and stronger second-phase reinforcements such as ceramic oxides, nitrides, carbides, and graphite exhibit greatly improved the resulting mechanical properties, which are reliant upon particle sizes and volume fractions of the reinforcement particles [21, 24]. Das et al. [25] agreed with this supposition, and pointed out that the strength of composites is determined by the fabrication process, grain size, microstructure, and composition.

The 7000 series of Al alloys is a lot stronger compared to other groups of aluminum alloys, and are preferred in the manufacture of stringers, upper wing skins, and vertical / horizontal stabilizers in aircrafts [9, 26]. Al 7000 series alloys are reported to have tensile strengths of 572 MPa [27]. High strength aluminum alloys such as Al 7075-T6 are used as structural aircraft materials due to its high strength to weight ratio, relatively low cost, and machinability [28-31]. However, it should also be pointed out that aluminum alloys of both the 7000 and 2000 series are unsuitable for supersonic aircraft because their strength ebbs at temperatures beyond 100°C [32]. Based on the reported properties of the Al 7000 series, the presence of a second reinforcement phase such as nitride, ceramic oxide, and carbide particulates render them particularly attractive [33]. In this context, aluminum particulate metal matrix composites are widely used due to their low density and excellent mechanical properties [34].

Composites that use high strength alloy as its matrix are susceptible to damages by silicon carbide particles at low strains, especially when the reinforcement particles are of large grain sizes. Moreover, the usual decreasing strain-to-failure that is omnipresent in composites (compare with the base alloy) proved that damages pertaining to more particles would occur gradually as the stress gets closer and closer to the ultimate tensile strength via necking. The progression of voids via the aluminum matrix is assumed to be enhanced due to the initial damages to the silicon carbide particles [35]. Despite these advantages, these materials are of low ductility at room temperature and reported poor toughness, mostly owing to the presence of large amounts of reinforcement whisker or particles. The elongation-to-failure of these composites at room temperature are commonly at under 10% [36].

Recently, research being conducted on improving the mechanical properties and workability of Al 7075 matrix via elucidating the optimal working conditions such as forming temperature, strain and strain rate for both matrix and reinforcement materials [37-41].

Zhang et al. [36] reported that the total extension-to-fracture is directly proportional to temperature and inversely proportional to strain rates .A maximum elongation of 70.3% is reported at a temperature of 450°C and at an initial strain rate of 0.001 s^{-1}. Rajamuthamil selvan and Ramanathan [42] pointed out that excellent workability is assumed to be at vol.15% (volume fraction) and 20 μm (grain size) for SiC.

Primary or secondary plastic deformation processes such as rolling, extrusion, forging, friction processing, or superplastic forming are applicable for the improvements to strength, ductility, microstructure and close shape forming in MMCs. The optimization of processing parameters (e.g., deformation rate, deformation, and temperature) is crucial towards tuning the microstructure and mechanical properties of the resulting composites [43]. Subsequently, metal matrix composites are more complex to form compared to their monolithic alloy counterparts. Therefore, it is important to the study the hot working and reinforcement of particulate aluminum matrix composites within a range of temperatures, different strain rates, various grain size and volume fraction (or weight fraction).

2. Metal Matrix Composites

The term composite in materials science is defined as to when two or more materials are combined in order to mitigate certain weaknesses of a particularly useful component [44]. Generally, MMC is a material where the toughness and ductility of a metal matrix is combined with the strength and hardness of ceramic particles [45, 46]. The main factor precipitating the resurgence of MMCs is the development of reinforcement materials, which results in either decreased cost or enhanced properties. Reinforcement materials are classified into three major categories; fibers, whiskers, and particles, all of which are commonly ceramics of the nitrides, oxides and carbides groups that are utilized due to their respective stiffness and specific strengths at room and elevated temperatures [47].

Ceramic materials perform well, especially at high temperatures, however they tend to suffer from low toughness, rendering their usage in service parts almost impossible. Specific properties pertaining to these materials can be exploited to produce metal matrix composites by way of using them as reinforcement particles in metals [48].

Aluminum reinforced with silicon carbides (SiCs) is regarded as a particulate composite system. However, it should also be pointed out that within this system, several microstructural variables are present, all of which are influential upon the mechanical properties of the resulting composites. Some of these variables include aging condition, matrix alloy, volume fraction, and the grain size of reinforcement particles. Usage of an alloy with a stronger matrix results in a stronger composite, although the presence of reinforcement particles will somewhat mitigate this strength increase when using higher strength alloy. Furthermore, in the case of highest strength alloys, reinforcement particles decreased the overall strength of the resulting composites. Generally, it was determined that the volume fraction of the reinforcement is directly proportional to the yield stresses and tensile strengths, and is inversely proportional to the toughness and ductility of the resulting composites. It should also be pointed out that at a certain volume fraction of reinforcements, tensile properties such as tensile stress, yield stress, and ductility are directly proportional to the particle size [49].

MMCs can be fabricated via the accumulation of the reinforcement material into the matrix. These processes include co-deposition and spray atomization, plasma spraying, powder metallurgy, squeeze casting and, stir casting. In materials science, MMCs can be produced using low cost methods such as casting [50].

2.1. Reinforcement of Al 7075 by SiC particles

Al 7075 is tougher and of very high tensile strength, making it the preferred material in the automobile and aerospace industries. Table 1 shows its chemical composition.

Table 1. The chemical composition of Al 7075 alloy [51].

Weight	Cu	Mg	Mn	Si	Fe	Cr	Zn	Ti	Others	
									Each	Total
Min.	1.2	2.1	-	-	-	0.18	5.1	-	-	-
Max.	2.0	2.9	0.30	0.40	0.50	0.28	6.1	0.20	0.05	0.15

Reinforcement materials that are common in commercial applications include silicon carbide (SiC), boron carbide (B_4C), alumina (Al_2O_3), titanium carbide

(TiC) and titanium diboride (TiB). (SiC) is by far the most ubiquitous, followed by Al_2O_3 and (TiC) [52]. In fact, it is characterized by high wear resistant and excellent mechanical properties, such as modulus of elasticity of ~400 - 450 GPa, compressive strength of 3,900 MPa, fracture toughness within 4.1 - 4.3 $MPa.m^{1/2}$, and hardness of ~2300 - 2850 Hv. It is also highly resistant to thermal shock and high temperature damages. Its high strength remains unperturbed up to temperatures of ~1400°C. Moreover, these carbides are highly resistant to chemical attacks compared to other ceramics and remains inert when used with aluminum up to temperatures of ~500°C [34].

Nearly, all commercial MMCs rely on discontinuous reinforcement, although MMCs with continuous graphite, SiC, and Al_2O_3 fibers, for example, are not common. The discontinuous mode of SiC reinforcement is used primarily due to its cost saving factor [44, 47], ease to fabricate via both powder metallurgy (PM) and ingot metallurgy (IM) techniques, and the resulting near-isotropic behaviour of the subsequent produced parts [44, 48].

Aluminum matrix composites (AMCs) has been particularly important due to their excellent mechanical properties in the context of conventional monolithic aluminum without losing the corrosion resistance inherent in aluminum [53] . The enhanced properties of (AMCs) are correlated to the properties of the matrix and the reinforcement and their corresponding interface. B_2C, SiC, and Al_2O_3 are regarded as excellent reinforcements for (AMCs) due to their reported high hardness values and thermal and chemical stability [54].

Qi [55] outlined that 7xxx alloys are high strength Al alloys, where its main strengthening precipitate is $MgZn_2$ (a metastable form of this phase is of quite high strength). Experiments with SiC reinforced with this series, resulted in strength of the composite that is less than the matrix post identical T6 treatment, as per Table 2. Other researchers like [32, 47, 51] supported this supposition.

Table 2. Room temperature properties of extrusions based on 7xxx alloys(T6 Condition) [55].

Material	0.2% Proof Stress (MPa)	U.T.S (MPa)	Elongation %
7075	565	650	9.4
7075+10%SiC	420	516	3.0
7091	520	590	10.2
7091+20%SiC	400	470	1.9

Both grain size and volume fraction reinforcement are crucial towards the resulting microstructures and properties of MMCs. These two parameters can be elucidated randomly or experimentally, and are not governed by any particular set of rules.

Generally, increasing the strength and ductility of the composite are caused by fine grain size and a relatively large volume fraction of the reinforcement. However, taking full advantage of the strength and ductility is a complex affair because they are rather inhomogeneous distributed. Good distribution of reinforcements helps to upgrade mechanical and physical properties of the composites, while the opposite (poor distribution) will cancel the desired benefits of reinforcement addition. The particulate size of both the matrix and reinforcements is directly influential upon the distribution of the particles in power metallurgy of MMCs. To further flesh out this relationship, Tan and Zhang [56] proposed a model where uniform distribution is predictable only if the critical value does not exceed the reinforcement particle sizes. This critical value is a function of factors such as volume fraction, the size of matrix powder, and reduction ratio of secondary processing.

Pilot trials were conducted on Al 7075 as a matrix, and silicon carbide (SiCp) as its reinforcement at 20, 25, and 30 wt%. The distribution of silicon particles is not uniform in Al 7075 when the percentage of the particles exceeds 25 %. Moreover, the surface finish is poor and tool wear high. On the other hand, composite at 5wt% or less of reinforcement failed to resist tool machining. For a uniform distribution, minimized tool wear and excellent surface finish, the percentage of silicon carbide should be between 10-15 wt.% [57]. Also, It was proven that at 10 wt.% of SiC particles, the tensile strength is maximized while the hardness increase by 10.48 percentage with (5-15) wt.% of similar particles [58].

Generally, at a constant volume fraction, yield stress, ultimate tensile stress, and ductility are inversely related to particle sizes. This is due to bigger particle sizes being more likely to fail at a certain stresses, leading to low applied stress resulting in internal damage compared to its smaller counterparts [49].

Silicon carbide particles (SiCp) resulted in lower improvement in strength and stiffness, but they are a lot cheaper to produce. Its diameter is within (3-200 μm), and its particles measures (~ 10 μm) in diameter, thus reducing its tendency to fracture, which is common in coarse particles. Moreover, it results in more directional properties compared to that of continuous fibers and whiskers. The combination of aluminum alloys and SiC results in tremendous improvements to its strength-to-weight ratio [55].

2.2. Reinforcement of Al 7075 by B_4C particles

Although, SiC, Al_2O_3, TiC, B_4C, TiO_2, , TiB_2 , MgO and BN can be used to reinforce Aluminum matrix composites (AMCs), Al_2O_3 and SiC are particularly widespread in literature [50]. Moreover, B_4C, Al_2O_3, and SiC are characterized by its high hardness, thermal and chemical stabilities, rendering them as excellent reinforcement materials for AMCs [54]. Boron carbide (B_4C) possess a high hardness value, low specific gravity, good chemical stability, and high elastic modulus, making it an excellent as a reinforcing phase for AMCs in many structural applications. Reports have shown that AMCs reinforced with B_4C have superior mechanical properties compared to that of unreinforced alloys [32]. In fact, the presence of B_4C results in good properties such as very high wear resistance and hardness, and low densities. B_4C is also capable of enhancing the mechanical properties of Al 7000-alloys. It was shown in some studies that the fabrication of AL-7075/B_4C via the casting process resulted in remarkable flexibility and compressive and tensile strengths (497 MPa) , (300 MPa), and (350 MPa), respectively [59].

In general, increasing the content of B_4C resulted in increased hardness, compressive yield strength, and the bending strength of the composite [12]. However, the addition of too much B_4C will result in decreased hardness and bending strengths due to the formation of B_4C agglomerates, as shown in Fig. 3. The addition of optimal amounts of B_4C particles will result in significant improvements to the mechanical properties of the resulting composites. Figure 4 shows these improvements after the addition of (7.5 wt.%) B_4C.

Figure 4 shows the fracture strengths of all sintered samples are quite high, while the yield stresses of the composites are significantly greater than that of the unreinforced alloy. The yield stress and fracture stress of the Al 7075/7.5 wt.% B_4C composite are 895 MPa and 600 MPa, respectively.

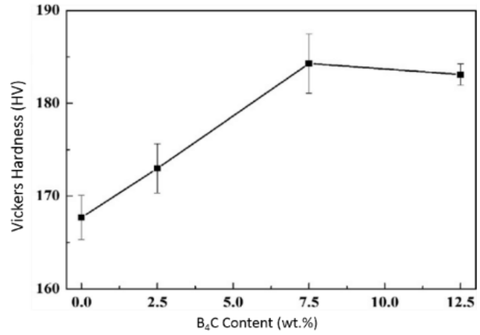

Fig. 3. Hardness of Al-7075/B_4C composites with various B_4C weight fractions [12].

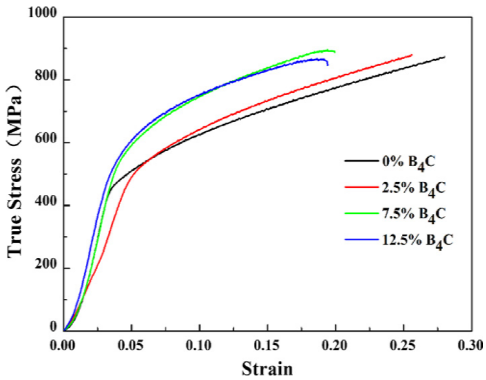

Fig. 4. Compressive stress-strain curve of Al 7075/B_4C composites with the different B_4C weight fractions [12].

Pedersen et al. [28] reported that most mechanical properties are directly proportional to volume fraction of B_4C particles. Figure 5 shows the gradual increase in the tensile, compression, and flexural strengths, while Fig. 6 explains the significant influence of the particles on the hardness due to increasing the ceramic phase in the metallic matrix. In other words, the presence of the B_4C reinforcement particles act as obstacles to the movement of dislocations, increasing the overall hardness of the composite to levels exceeding that of the original alloys.

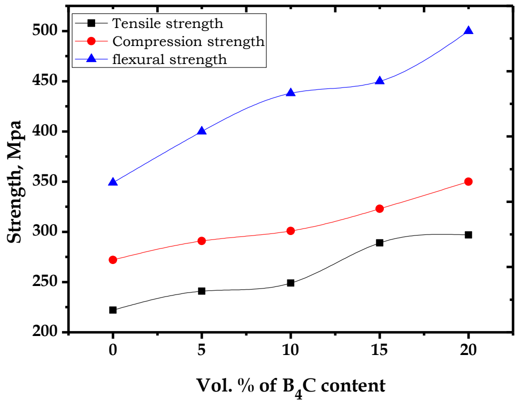

Fig. 5. Variation of tensile, compression and flexural strengths with varying content of the B_4C.

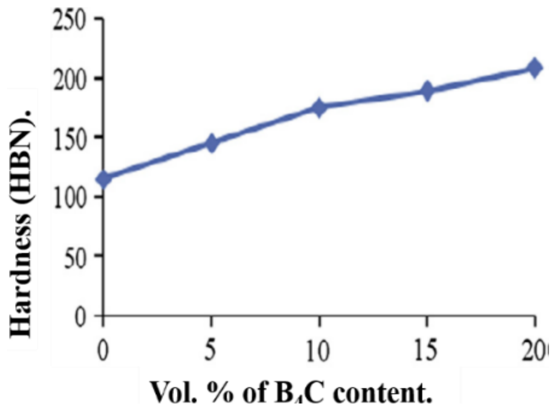

Fig. 6. Variation of hardness with varying content of the B_4C [28].

The flexural strength of composite with a 10% volume fraction of B_4C exceeded that of its base alloy. This means, the composite exhibited sufficient ductility to achieve higher strength of 20% volume fraction B_4C in the composites, corresponding to an increase in strength to 497 MPa. The fine particle of B_4C eschews the fast expansion of cracks through the composite and corrals the deformation of the composite, both actions that enhance the flexural strength of the composite.

2.3. Reinforcement of Al 7075 by graphite particles

The addition of graphite to aluminum alloy is known to decrease the resulting tensile strength, flexural strength, compression strength, and hardness. This is mitigated by the addition of (Al_2O_3) particulates in hybrid composites, resulting in a composite that did not exhibit any of the aforementioned problems [60]. The experimental results showed that the mechanical reaction (hardness and strength) of composite is directly proportional to the amount of graphite in the composite and its milling time, as tabulated in Table 3. The main hardening mechanisms associated with the processing route could be an increment in the dislocation density, the formation of (Al_4C_3 phase, and grain size refinement.

Table 3. Mechanical properties of extruded composite [23].

Sample	Milling Time (h)	σ_y (MPa)	Variation (%)	σ_{max} (MP)	Variation (%)	Vickers (μHV)	Variation (%)	Grain size (μm)
Al7075_5Zn0GP-M	0	256.5	-	349.5	-	90.0	-	4
Al7075_5Zn0.0GP	5	280.0	9.2	368.5	5.4	83.0	_78	1.6
Al7075_5Zn0.5GP		265.5	3.5	330.0	_5.6	92.0	2.2	-
Al7075_5Zn1.0GP		295.5	15.2	366.0	4.7	97.0	7.8	1.5
Al7075_5Zn1.5GP		376.0	46.6	413.0	18.2	113.0	25.6	1.3
Al7075_5Zn0.0GP	10	365.0	42.3	437.0	25.0	127.0	41.1	1
Al7075_5Zn0.5GP		305.0	18.9	400.0	14.4	100.0	11.1	-
Al7075_5Zn1.0GP		382.0	48.9	452.0	29.3	120.0	33.3	1
Al7075_5Zn1.5GP		446.0	73.9	520.0	48.8	141.0	56.7	0.9
Al7075-O	0	96.5	_62.4	221.0	_36.8	-	-	
Al7075-T6		503.0	96.1	572.0	63.7	175.0	94.4	
Al7075-T7		435.0	69.6	505.0	44.5	155.0	72.2	

Based on these evidences, the addition of graphite, followed by solid state processing is regarded as an adequate route to prepare aluminium composites that are mechanically resilient due to the highly refined microstructure and the homogeneous distribution of reinforcement particles. Consequently, higher yield strength and dislocation density is observed due to smaller particle sizes [23, 61-63], as per Fig. 7.

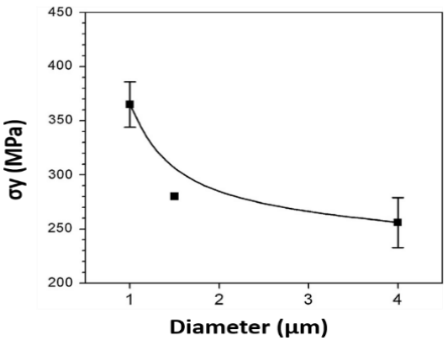

Fig. 7. Variation of yield strength with grain size of graphite [23].

Baradeswaran and Perumal [64] reported that hardness and graphitic content are inversely related at 5wt. % graphite. The flexural strength and graphitic content are also inversely related at similar percentage, as shown in Fig. 8. The wear rate is inversely proportional to the graphitic content, and was lowest at 5wt. %, exhibiting superior wear properties compared to that of other reported compositions.

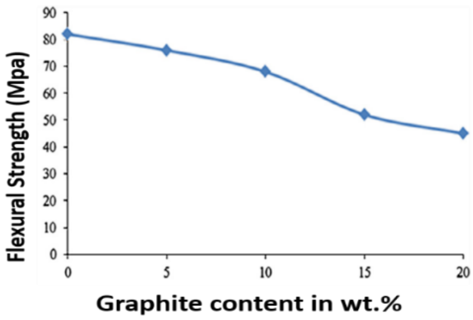

Fig. 8. Variation of flexural strength with graphite content [64].

2.4. Reinforcement of Al 7075 by TiC particles

Commonly referred to TiC particles, which can be used as reinforcement with Al 7075 [38]. TiC, on top of Al_4C_3, SiC, Al_1O_3, B_4C, TiB_2 and ZrB_2, are used as reinforcement particles due to its high elastic modulus and hardness, low chemical reactivity, and density. Moreover, its wetting with molten aluminum is excellent, and it is thermodynamically stable with no observed resulting gases. These aforementioned factors prompted many researchers to consider TiC as a reinforcement particle, especially at elevated aging temperatures, where composites samples might exhibit minimum hardness values during aging treatment, although the unreinforced samples hardness values are lower than its as cast counterparts [64, 65].

2.5. Reinforcement of Al 7075 by Al_2O_3 particles

Ceramic reinforcements that are considered for making aluminum matrix composites include SiC and Al_2O_3, as both possess excellent compatibility with the aluminum matrix [1]. Varma and Vasquez [66] pointed out that the corrosive wear resistance of the composite of Al 7075 reinforced with 10 vol.% of alumina particles exhibited improvements compared to its base alloy. Wu et al. [59] suggested that alumina (Al_2O_3) is most commonly used to fabricate technical ceramics due to its excellent corrosion and wear resistance, high hardness, low electrical conductivity, and low cost. The mechanical properties of (Al_2O_3) reinforced alumina are superior to those of the unreinforced advanced alloys, and stronger and more wear resistance. The enhanced properties of the composites allow for the use of components with lower sectional thickness, and therefore less weight. Unfortunately, these advantages are somewhat nullified by low ductility and fracture toughness.

The effect of the addition of (Al_2O_3) and graphite on the hardness of the hybrid composites was analysed by [60, 61]. It was shown that the properties were improved with increasing (Al_2O_3) ceramic particulate content. The hardness of hybrid composites is directly proportional with the content of (Al_2O_3) exceeding that of the base alloy in all of the compositions, as it appeared in Fig. 9. The addition of (Al_2O_3) particle increases the tensile strength, as shown in Fig. 10, and the flexural and compression strength of the hybrid composites is greater than that of the base alloy.

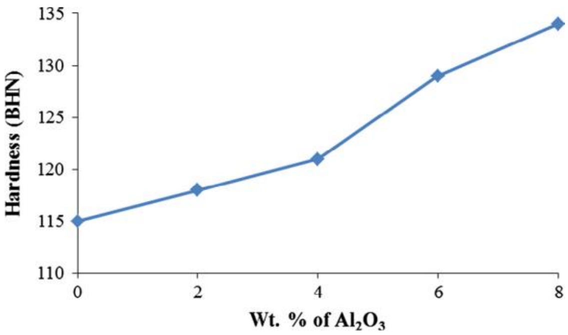

Fig. 9. Brinell hardness of Al 7075/Al_2O_3, 5 wt.% graphite hybrid composites. [60].

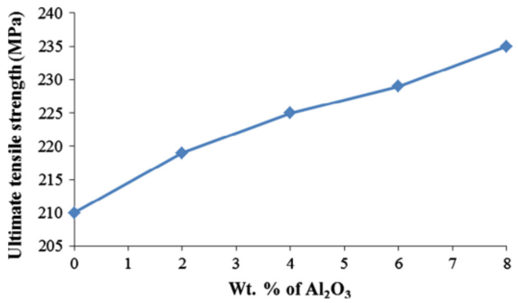

Fig. 10. Variation of tensile strength with varying content of Al_2O_3 and 5 wt.% graphite[60].

3. Hot Working

This section includes two parts, which are definition of the workability and the hot working of the AI 7075 composite.

3.1. Definition of the hot working

Many metalworking processes are conducted at high temperatures, where it would result in large-strains in one or multiple steps. Elevated temperatures would also result in significant changes to the microstructure of the materials, which is one part of the workability termed intrinsic workability, which is a property that is reliant upon the initial conditions and parameters of the process [42].

Workability is defined as a term that deals with the degree at which a certain material can be deformed in a particular metalworking process without undergoing fracture [2], or the degree at which a material can be deformed without failing. Generally, it is reliant upon the process parameters and ductility of the materials. In metalworking, the general mode of failure is ductile fracture. Thus, workability is not regarded as a unique material property, since it is influenced by both process and material variables. Some factors influencing workability include the local state of stress, strain rate, strain, and temperature, while the main process variables include the geometries of the workpiece, punch and die, as well as friction [2, 67]. Higher grain size and product rates are possible in the course of a reasonable hot working process [2].

Material workability is a function of the material, as well as the process, Eq. (1) [68]:

$$workability = f_1\,(material) \times\ f_2\,(Process) \tag{1}$$

where f_1 - A fundamental measure of the ductility of the workpiece and f_2- A function of the material, friction and the process.

Hot working is regarded as deformation at a temperature above 0.5 T_m (melting temperature, in K), strain rate (10^{-3} to 10^3) s^{-1}, and strain range of ~ (0.1 to 50). At the aforementioned temperatures, most metals and alloys have high ductility and low flow stress. Both static and dynamic softening mechanisms occur during the hot working process, which includes preheating, deformation, and subsequent cooling. Hot working is used because alloys and metals can be subjected to large and rapid changes in shape without cracking [55].

3.2. Hot working of the Al 7075/SiCp composites

There are three distinct temperature ranges in Al composites as shown in Table 4. It can be noted that a good range of deformation temperatures for hot working of Al composites are within ~ (300 - 500°C). Working parameters like, temperature, strain rate, grain size, and volume fraction have been analysed by [37, 65, 66, 68] to evaluate the effects of these parameters on the hot workability of a Al 7075/SiCp composite.

Table 4. Temperature range for hot working aluminum metal matrix composite [55].

Deformation Temperature (°C)	Properties
$200 < T < 300$	High flow stress, High work hardening and Low ductility
$300 \le T \le 500$	Low work hardening rate and improved ductility
$T > 500$	Low ductility, fracture related to grain boundary cracking and sliding

Su et al.[69] compared the hot working of two materials; spray-formed MMCs and conventional continuous-cast Al 7075. They reported that for all initial strain rates, the yield strength of the aluminium composite material exceeds that of the continuously cast Al 7075. Moreover, lubricant significantly influence the workability, where cracks are initiated when the true strain exceeded 0.8 for the specimens without lubricant, while the specimens with boron nitride lubrication did not exhibit any cracks whatsoever within the testing range from ~0 - 1.20 of true strain, as shown in Fig. 11.

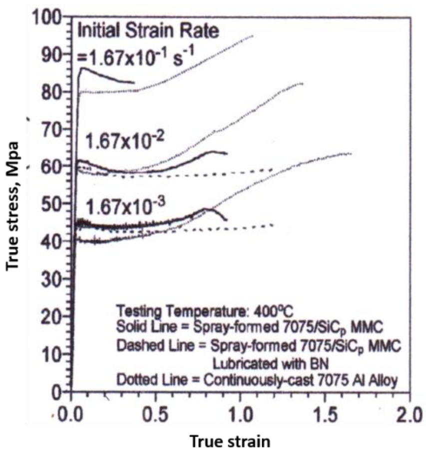

Fig. 11. True stress vs. true strain of spray-formed 7075/SiCp and continuously cast Al 7075 alloys deformed at 400°C for various initial strain rates [69].

The tensile test has been used to investigate the influence of temperature and volume fraction of silicon carbide particles on the mechanical properties Al 7075/SiCp composites [62, 63]. Kulkami et al. [70] show that at room temperature, for Al 7075 reinforced with SiCp with average grain size of (42 μm), yield strength for each composite was higher than this for the unreinforced alloy while the ultimate tensile strength was less. At various elevated temperatures, ultimate tensile and yield strength were decreased because of increasing temperature value and good strength was at 250°C with 13 vol% SiCp composites. Plastic strain to failure (ductility) increases with decreasing volume fraction and increasing temperature for all composites and the superior values were at 350°C and 250°C for 13 vol % SiCp composites as shown in Fig. 12.

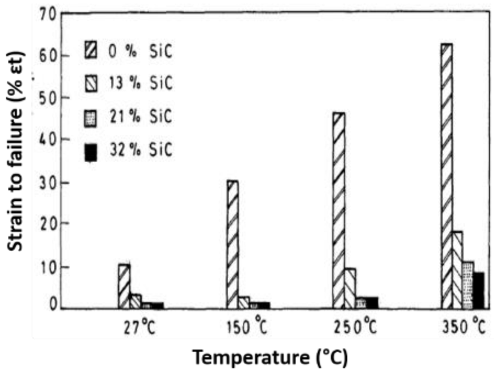

Fig. 12. Variation of strain to failure (ductility) for AA7075/SiCp composites with respect to volume fraction and temperature [70].

Razaghian et al. [71] analysed the influence of temperature on the tensile properties and fracture behaviour of 7075 aluminium alloy reinforced with 15 vol.% of SiC particles, with an average particle size of (14 μm). They reported that at room temperature, the particle fracture were visible for larger particles and within regions of clusters of particles, while at high-temperatures, void nucleation was evident within the matrix between the adjacent particles. Figure 13 elucidates the relationships between engineering stress-strain curve, where it is evident that the maximum strain is at a temperature of 350°C. Moreover, yield and ultimate tensile strength are inversely proportional to the forming temperature. The composite exhibited a much lower elongation compared to the base alloy in the temperature range of 25-400°C, while at 350°C, its elongation is at its maximum at ~50%, as shown in Fig. 14.

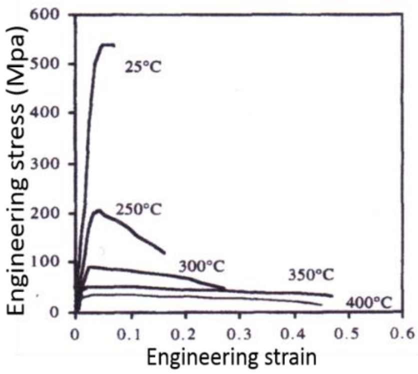

Fig. 13. The engineering stress/strain curves of the composite in the T6 condition at different temperatures[71].

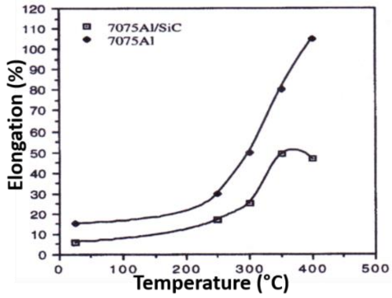

Fig. 14. The effect of temperature on tensile ductility for the7075Al/SiC composite and monolithic alloy[71].

Working parameters like, temperature, strain rate, grain size, and volume fraction have been analysed by [37, 61, 62, 64] to evaluate the effects of these parameters on the hot workability of a Al 7075/SiCp composite.

Rajamuthamil selvan and Ramanathan [72] analysed the flow stress of Al 7075 and Al 7075 with vol. 10%, 15%, and 20% of silicon carbide particles (SiCp) during their respective hot working. They reported that the flow stress is reliant upon several factors, such as microstructure, deformation mode, alloying composition, and temperature. Moreover, it is influenced by other factors that are irrelevant to the hot working process, like grain size, prior strain history, phases, deformation, metallurgical structure, chemical composition. The other factors that are explicitly linked to the deformation process, like strain rate or deformation rate, strain or deformation degree, and deformation temperature. Figures (15 - 18) show the flow curves for both materials at different strain rates and at 350°C for the base alloy and at 400°C for the composites. It is clear that in Fig. 15 strain hardening rate is comparatively high while the flow stress is considerably low at lower strain rate. Subsequently, the flow stress decreases with decreasing strain. In addition, the deformation is adiabatic at high strain rates but is isothermal at lower strain rates. The dispersive hardening effect of silicon carbide particle is suggested as the reason for increasing the strength of the composites.

Increasing temperature led to decreasing strain hardening rates. In addition, the flow stress is directly proportional to volume fraction due to the localized lattice rotation, but its influence is not significant at low volume fractions. Increased reinforcement particle content is insignificant vis-à-vis the stress. Lower percent SiCp composites exhibited lower compressive strength against high percentage of SiCp.

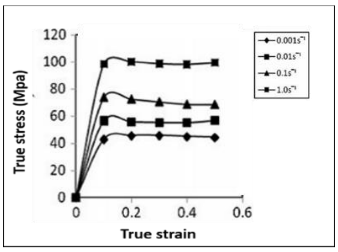

Fig. 15. The flow curves of Al 7075 for different strain rates at constant temperature of 350°C [72].

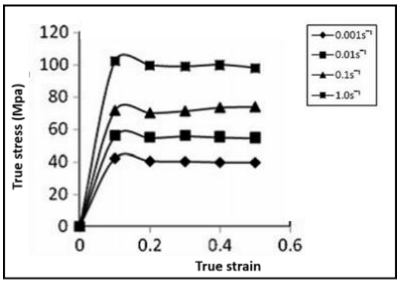

Fig. 16. The flow curves of Al 7075/10 % SiC_p for different strain rates at constant temperature of 400 °C [72].

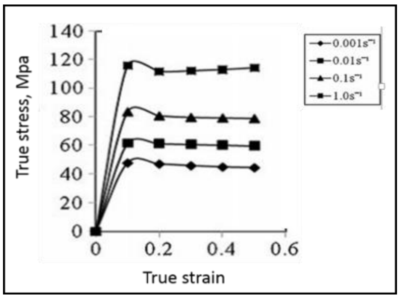

Fig. 17. The flow curves of Al 7075/15 % SiCp for different strain rates at constant temperature of 400°C [72].

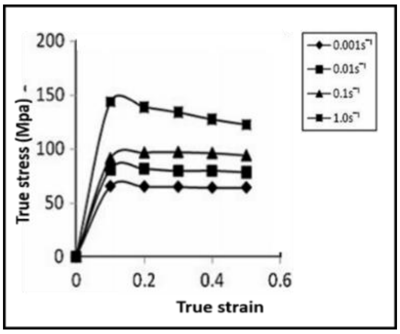

Fig. 18. The flow curves of 7075Al/20 % SiCp for different strain rates at constant temperature 400°C [72].

It is observed that particle debonding in the composites with vol.10 % of reinforcement and void formation occurs in vol.20%SiCp composite at a greater strain rate of 1 s^{-1} and minimum temperatures of (300-350°C). These effects are more significant at higher amounts of reinforcements. The particle cracking is noted in composites having higher volume fraction (15% and 20% SiCp). The debonding factor is relatively higher in composites with low amounts of reinforcement. The hot workability of a composite with 15% SiCp has been duly enhanced. The maximum power dissipation efficiency was 44% in the dynamic recrystallization (DRX) domain of 15% SiCp composite, exceeding that of other Al 7075/SiCp composites and Al 7075 due to the decreased porosity, hardening of the material, strengthening and grain refinement. Subsequently, the composite with high deformation efficiency at vol. 15%SiCp is known to possess excellent workability in the hot working process.

Classical true stress-strain curves at different strain rate and constant temperature, and different temperatures and certain strain rates are shown in Figs. 19 and 20, respectively, representing stir cast Al 7075 with vol.20% SiC particles with a grain size of 63 μm [1]. The flow stress curve in Fig. 19 shows the occurrence of dynamic recrystallization. In general, (DRX) is useful in hot working as it provides excellent workability and stable flow to the material by concurrently softening it and reconstituting its microstructure. It can be noted that flow stress is directly correlated with the strain rate and inversely correlated with temperature. Strain rate deformation is directly proportional to work hardening rates, while at lower strain rates, strain hardening in mitigated by softening due to the higher temperature. This results in a near steady state flow curve. On the other hand, the true stress vs. true strain plot at 450°C exhibits strain hardening, as shown in Fig. 20, while at higher temperatures, flow softening is seen post-critical strain. The effect of work hardening is obvious at lower temperatures. Overall, it was discovered that the optimal working parameters for hot compression of the composite, which is done by mapping the strain rates of 0.018 s^{-1} - 0.16 s^{-1} at temperature range of 445 - 485°C. Moreover, the instability zones occurred at higher strain rate and it expanded with increasing strain.

Rajamuthamil selvan et al. [73] analysed the hot working behaviour of Al 7075 reinforced with vol.10% of SiCp using microstructural observations and ‘‘processing maps’’. It was discovered that the optimal working parameters are within (390-440°C) and a strain rate of (0.1-0.9 s^{-1}), with deformation efficiencies of 26-30%.

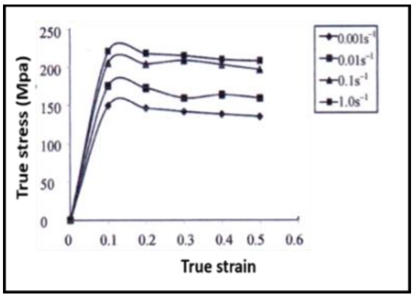

Fig. 19. The flow curves of Al 7075 Vol. 20%SiCp (63 μm) for different strain rates at constant temperature of 450°C [1].

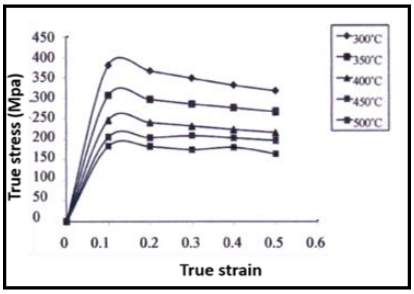

Fig. 20. The flow curves of Al 7075 Vol.20%SiCp (63 μm) for different temperature at constant strain rate of 0.1 s^{-1} [1].

The flow instability took place in two different regions; the first at a lower strain rate of 0.001 s^{-1}, instability occur at 480 - 500°C, while the second occurred at a higher strain rate of 1.0 s^{-1} and a temperature range of (300-340°C). Moreover, the processing map was utilized by Rajamuthamil selvan and Ramanathan [74] to analyse the microstructure and hot working behaviour of Al 7075/ SiCp composite at a vol.%20 with an average grain size of 20 μm. The optimal working parameters for the hot deformation of this composite are a strain rate of 0.1 s^{-1}, a temperature of 400°C, and an efficiency of 40%. The flow curves of this composite at constant temperatures and strain rates are shown in Figs. 21 and 22 respectively.

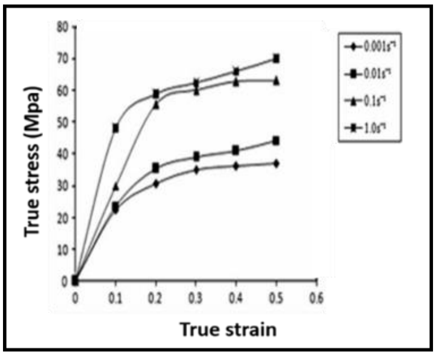

Fig. 21. The flow curves of Al 7075/20% SiCp for different strain rates at constant temperature 400 °C [74].

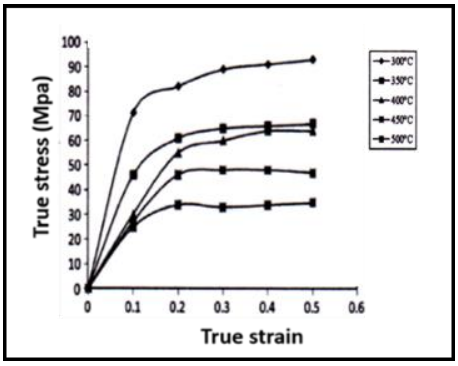

Fig. 22. The flow curves for different temperatures at constant strain rate 0.1 s^{-1} [74].

It can be seen that the flow stress is directly correlated with strain rates and inversely related with temperature. At lower strain rates, flow stress is remarkably lower and strain-hardening rate is relatively high. While at lower temperatures, strain hardening is high, reaching a steady state between 300 - 400°C. The strengthening effect of the reinforcement particles is significantly mitigated as per the increasing temperatures. Finally, Rajamuthamil selvan and Ramanathan [75] proved that the optimum processing parameters for hot working Al 7075 reinforced with 15% of SiCp with an average size of 20 μm are 400°C and 0.1 s^{-1}, with an efficiency of 44%. The Al 7075 15% SiCp composite enhanced hot workability compared to Al 7075, due to increased stiffness and the strength of the matrix via the presence of the reinforcement.

4. Conclusions

The effects of different reinforcement particles on the mechanical properties of Al 7075 are as follows:

- The presence of hard and brittle ceramic reinforcement in AMCs leads to elongation reduction and fracture toughness of the resulting composite.
- Aluminium reinforced with silicon carbide particles is a common particulate composite system. Within this system, several microstructural variables can influence the mechanical properties of the composite like, matrix alloy, aging condition, and volume or weight fraction and grain size of the reinforcement particles.
- Higher strength matrix alloy tends to result in stronger composites. However, for the highest strength matrix alloy, the utilization of reinforcement particles tends to reduce the strength of the resulting composites. In addition, it was found that yield and tensile strengths increased, while toughness and ductility decreased due to increasing volume fraction or weight fraction of the reinforcement particles.
- For a specific volume fraction or weight fraction, tensile properties such as yield stress, tensile strength, and ductility increased with decreasing grain size.
- Ductility loss in most of the MMCs at Large grain size (42 μm) and high volume fractions (21% and 32%) of reinforced particles.
- Reinforcing the Al 7075 with B_4C and AI_2O_3 particles lead to increase the strength of the composite (ultimate tensile, compression, and flexural) within levels greater than the base alloy.

On the other hand, analysing the hot workability of Al 7075 composites reinforced with SiC particles at different volume or weight fraction and grain size can be summarized as following:

- At certain strain rates and temperatures, the flow stress of the aluminium matrix composite is directly proportional to the volume or weight fraction. In addition, the flow stress is inversely proportional to temperature and directly proportional to the strain rate. Moreover, ductility is directly proportional to the temperature and inversely to the strain rate.
- Metal matrix composite can be characterized with a poor hot workability at a high percentage of reinforcement.
- At a high volume or weight fraction, the uniform distribution of the silicon carbide particles was optimum.
- The maximum deformation efficiency is 44%, which can be attained with Al 7075 reinforced with silicon carbide has a grain size of 20 μm and volume fraction of 15%, at a temperature and strain rate of 400°C and 0.1^{-1}, respectively.

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