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Mechanical and physical properties of sintered aluminum powders

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Properties

ABSTRACT

Purpose: The purpose of the work is to compare the physical and mechanical properties for argon atomized Al-1wt-%Mg powders with and without lubricant 1wt% Acrawac. Pure nitrogen sintering was performed and the effect of sintering atmosphere for the mixed Al-1%Mg powder compacts was investigated.
Design/methodology/approach: One weight percent Acrawax was premixed with the powder as a lubricant for the first group samples. However, no wax was used for the second group specimens. As a sintering aid, 1wt% Mg was added for both group materials. Compaction of the specimens was performed using a hand operated Carver hydraulic press and a floating rectangular die. First group specimens were pressed to green densities of 91.5 and 92.5% using pressures of 435 and 490 MPa, respectively. In the second group (no wax) samples, 93% green density was obtained using the similar compaction pressures. Sintering and delubrication occurred in a horizontal tube furnace with a high purity nitrogen atmosphere. The nitrogen flow rate was : 1.5 l min^{-1}. The heating rate from the dewaxing to sintering temperature was 10°C min^{-1}. While the sintering temperature kept at 640°C, sintering time varied between at 2 h and 6 h. Three point bending samples were examined using Instron machine using 25.4 span between the lower supports and 2 mm/min strain rate.
Findings: Green and theoretical density increased with the increment of compaction pressure. Although Acrawax lubricant provides a reasonable green density, it had a deleterios effect on sintered density mainly owing to its wide burn off range and hence incomplete removal during sintering leaving some black residue.
Research limitations/implications: Residual macro- and microporosity was present in all sintered samples under every sintering condition. Medium sized pores and small interconnected micro-pores at grain boundaries were visible when lubricant was added which reduced the sintered densities due to a wide burn off range leaving residual porosity.
Originality/value: Mechanical and physical properties of sintered aluminum powders were evaluated.
Keywords: Powder metallurgy; Aluminum; Sintering; Microstructure; Mechanical properties

1. Introduction

A lot of smart possessions are reported for the engineering implication of Al and its alloys. They are mentioned as good mechanical strength and corrosion resistance, low density and cost advantage depending on the manufacturing method, higher thermal and electrical conductivities [1]. The claim and fabrication of light weight and near net shape high quality Al alloys by powder metallurgy (PM) practice has enlarged, in particular, for the aerospace and automotive purposes [2]. Nevertheless, there are a number of complexities in the straight compaction and sintering of almost every series of Al powder. This complexity is essentially as a result of the existence of a firm and intense oxide layer covering the powder particles and therefore dropping both compressibility and sinterability of the powder. Diverse efforts have been made effectively to develop the compressibility and the sintering response in different way, and for diverse series of Al alloys. It is stated that an addition of 0.1-1 wt-%Mg facilitates to break up the surface oxide layer through the

development of a $MgAl_2O_4$ phase [3]. This improved the sintered density by 9% with 1 wt-%Mg content, and for this reason enhanced the mechanical features [4]. The other researchers [5] have concluded that rising the Mg content equal to 3.5 wt-% in 7xxx series, enhanced the mechanical strength better than the present commercial alloy. Besides, it was mentioned [6] that at elevated Mg contents, the inferior phase could not be completely dissolved in solid solution and therefore stayed as a complex at the grain boundaries resulting embrittlement of the alloy.

On the other hand, major developments in the sinterability of diverse Al alloys (primarily 7xxx and 2xxx series) have been published [6-7]. This was achievable by a liquid phase sintering (LPS) course resulting to enhanced densification of the alloys. In the reported papers, the cause of trace addition of chosen elements such as Pb, Sn and Sb on the sinterability of Al alloys was examined [5-10]. It was realized that microalloying with 100 ppm of Pb (0.12 wt-%Pb) supplied the superlative sintering reaction and enhanced the ultimate tensile strength (UTS) by 36% from 214 to 427 MPa of an Al-Zn-Mg-Cu alloy formed from premixed elemental powders [10]. It was stated that the admixed elements such as Pb and Sn had low solubility in the base Al matrix and consequently stayed segregated at the liquid/vapor interface.

Some scientists[11], have measured the densification behavior of the 2xxx, 6xxx and 7xxx series Al powder mixtures under various sintering circumstances including temperature, time and atmosphere as well as diverse heat treatment. It was established that the 2xxx series compacted at 400 MPa presented a little higher density (95% TD) when sintered under vacuum as compared with sintering in nitrogen (92% TD). Conversely, both the 6xxx and 7xxx series Al powder mixtures also pressed at 400 MPa, illustrated much better sinterabilities by sintering in nitrogen and reaching densities of 97% TD. A capable outcome was accomplished [12,13] for degassed 6061 Al prealloyed powder by supersolidus liquid phase sintering (SLPS) subsequent to vacuum degassing of the prealloyed powder, compaction at 380 MPa, and high compaction pressure of 760 MPa by sintering under argon at 585, 605 and 625^{o}C for 30 min. Green and sintered densities in the range of 2.61-2.68 g cm^{-3} and 2.59-2.68 g cm^{-3} were gained, respectively, which resulted in tensile strength of 335 MPa with 7% elongation for the fully heat treated (T6) 6061 alloy.

It has also been informed [14] that segregation and delubrication can be a most important issue with processing of PM Al alloys if a appropriate lubricant has not been used. This can lead to a potentially unsafe surroundings with inhomogeneity and delubrication defects within the sintered product. For that reason, some of the presented lubricants used for the Fe based PM alloys are not appropriate for the Al based powders due to their burning properties reasoning undesirable reactions by products.

It was reported that the compaction, sintering and mechanical properties of the premixed elemental 6061 Al powder with and without addition of sintering aids (Pb, Sn or Ag) [15]. In this paper it was obtained that by normal compaction at 340 or 510 MPa, and sintering under pure nitrogen (30 min or 1 h), sintered densities of ≥2.68 g cm^{-3} (98% TD) were accessible, which resulted in UTS of 305 MPa and 6-8% elongation for the (sintered and) fully heat treated (T6) 6061 Al alloy. The premixed elemental powder caused the development of two types of liquid phase during sintering. It was obtained that an effective densification achieved by a proper LPS process with addition of sintering aids (mainly 0.12%Pb) during which the molten liquid phase penetrated through the broken oxide film causing improved particle bonding and sinterability.

Recently, two papers has been published about physical and mechanical properties of the as received (gas atomized) and degassed 6061 Al prealloyed powders with and without additions of solid or liquid lubricants and sintering aids (Pb, Sn or Ag). Both vacuum and pure nitrogen sintering were carried out for compaction at 340 or 510 MPa and also to investigate the effect of sintering atmosphere for the prealloyed 6061 Al powder compacts[16]. Highest sintering densities of ~98-99% of theoretical were obtainable for the prealloyed (and degassed) Al compacts by sintering under pure nitrogenwith an addition of paraffin wax, liquid paraffin, or a Pb addition as sintering aid and no lubricant. It was found that additions of solid lubricants such as lithium stearate and acrawax to both the premixed and prealloyed powders reasonable green densities, but had deleterious effect on sintered densities and microstructures. Other lubricants such as zinc stearate, stearic acid and liquid paraffin provided similar green densities, but higher sintered densities and less porous microstructures. It is cocluded that both lubricant type and sintering atmosphere will have a major effectr on the sintered properties of the 6061 Al powder. Sintering under pure nitrogen resulted in higher sintered densities, but the higher tensile properties were obtained from the degassed and vacuum sintered prealloyed powder compacts.

In this study, the physical and mechanical properties are compared for argon atomized Al-1wt-%Mg powders with and without lubricant 1wt% Acrawac. Pure nitrogen sintering was performed and the effect of sintering atmosphere for the mixed Al-1%Mg powder compacts was investigated.

2. Experimental procedure

2.1. Mixing

Argon atomized Al and 1%Mg and also adding 1 Acrawax (all w/o) in the secind group samples are mixed in a jar and shook for 20 minutes. The properties of the used materials and lubricant are shown in Table 1.

The shape and morphology of the metal powders were also inspected using SEM and representative particle morphologies are shown in Figure 1.

Table 1.
The properties of the used materials and lubricant

Material	Company	Properties
Al	Cerac	Composition: 99.5 % (purity) Particle size: -100/+200 mesh (-150/+75 μm)
Mg	Cerac	Composition: 99.6 % (purity) Particle size: -200/+325 mesh (-75/+45 μm)
Acrawax	Lonza Inc.	Material: Acrawax C Lubricant
		Density: 0.97 g/cm^3
		Melting point: 140-145 ^{o}C

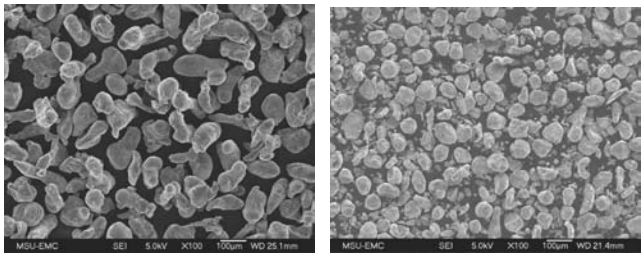

Fig. 1. Representative particle morphology of argon atomised Al powder (left) and Mg powder (right); sieved below 150 µm showing rounded but irregular Al particles and sieved below 75 µm showing mostly spherical Mg particles

2.2. Compaction and sintering

For each compaction, ~3.5 g of powder was used and pored into the die cavity. Care was taken to make sure that the powder was dispersed properly within the die cavity. Rectengular specimens with the size of 31.8x12.7x3.5 mm (3.5 g of powder) were pressed at pressures in the range of 330-490 MPa for the mixed powders in order to study the compaction properties and consequently to observe the best compaction pressure for sintering. Also, these rectangular bars were used for mechanical testing. A single performing hydraulic press (22 ton Carver) was employed for compaction. Sintering was carried out under pure nitrogen atmosphere (about -50°C dew point) in a standart Carbolite gas atmosphere, recrystallized alumina tube furnace (controlled by a Eorotherm 2404 controller) at a temperature of 640°C for 2 or 6 h. The green and sintering densities were calculated by measuring the dimensions and weight of the specimens to on accuracy of 0.001 mm and 0.0001 g, respectively.

2.3. Metallography and mechanical testing

Same sized specimens were used for the three point bending machine. To do this INSTRON 5869 machine having the 1000 kN maximum load was employed using 25.4 span between the lower supports and 2 mm/min strain rate. Microstructural examination of the Al-1Mg alloy was conducted using a Zeiss Axiovert 200M optical microscope and JEOL JSM-6500F scanning electron microscope (SEM). The quantitative analysis of the microstructure within the as sintered specimens was performed using the SEM equipped with an energy disperive spectroscopy (EDS). Metallographic samples were prepared conventianally, and then polished using 6 mm and finished with 1 mm polish. No etching was carried out.

3. Results and discussion

3.1. Compaction behaviour

The mixed Al-1%Mg powders with and without wax were compacted at different pressures in the range of 330-490 MPa to study their comressibility. The admixed lubricant has improved the green density from ~2.41 g cm^{-3} (without lubricant mixed powder) to ~2.45-2.48 g cm^{-3} as expected. The mixed powders with 1 Acrawax (w/o) pressed at 435 and 490 MPa, and sintered at 640°C for 2 h under pure nitrogen atmosphere. Same conditions were used for no wax samples except longer sintering time (6 h). Figure 2 shows the compaction graph by plotting green density versus compaction pressure. It is seen from Fig. 2 that green and theoretical density increased with the increment of compaction pressure. This is consistent with the previous work [16-18].

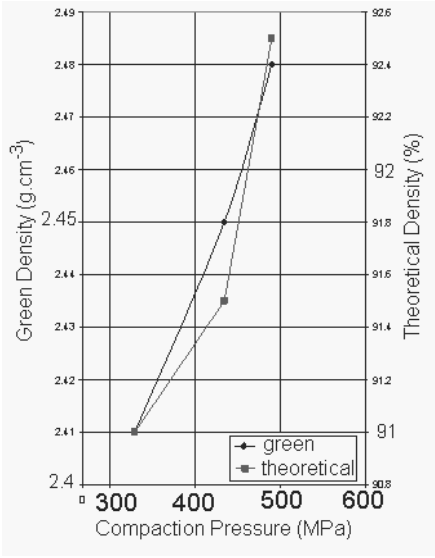

Fig. 2. The relationship between compaction pressure and green/theoretical density for various Al - 1%Mg compacted samples

In the present study, the theoretical density (density of loose Al-Mg-Acrawax powder) was found as 2.6852 (±0.0043) g/cm^3. According to this value, the average calculated green density of the wax included samples is obtained as 2.4564 g/cm^3 using 435 MPa compression pressure, it means that the material is 91.5% dense (8.5% porosity) in the present work. In 490 MPa compression pressure, the average calculated green density of the samples is obtained as 2.4840 g/cm^3, it means that the material is 92.5% dense (7.5% porosity) in the present study.

In the present study, the theoretical density (density of loose Al-Mg) was found as 2.7125 (±0.0030) g/cm^3. According to this value, the average calculated green density of the Al-Mg (no wax) samples is equal to 2.5186 g/cm^3 using 435 MPa compression pressure, it means that the material is 92.8% dense (7.2% porosity) in the current study. The average calculated green density of the samples is obtained as 2.5103 g/cm^3 in case of employing 490 MPa pressure, it means that the material is 92.5% dense (7.5% porosity) in the present work.

3.2. Sintering effect

Al-1Mg powders with wax specimens were sintered in two steps within nitrogen atmosphere: First, specimens were heated to

350°C for 2 hours for polymer burn out and then temperature ramp up to 640°C for 2 hours, and finally furnace cooled down to room temperature. The heating and cooling speed was 10°C /min and the dew point of N_2 was about -40°C. The Eurotherm 2404 temperature controller was used in the muffle furnace. Figure 3a depicts the temperature and sintering time relationship for the present study.

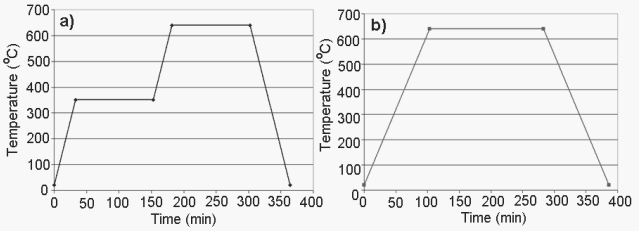

Fig. 3. Sintering time versus temperature for: a) Al-1%Mg-1%Acrawax compacts, b) Al-1Mg (all w/o)

Al-1Mg compacts (no wax) were sintered in the same furnace at the same atmosphere (N2), but in one step process. Specimens were heated at the same temperature (640°C), but longer (6 hours) than the others, and finally furnace cooled down to room temperature (Figure 3b). The heating and cooling speed was slower than before (3°C/min).

In wax added specimens applying 435 MPa compression pressure, average sintering density is equal to 2.2698 g/cm^3 which is 84.5% density (15.5% porosity). It means that porosity is doubled during the sintering process comparing to the green one. The large porosities reduced the sintering densities due to a wide polymer burn off range leaving residual porosity. In addition, sinterering density decreased in 10%. In case of using 490 MPa pressure (Table 3), the obtained average sintering density is identical to 2.2707 g/cm^3 which is 84.5% density (15.5% porosity). It represents that porosity is twofolded during the sintering route comparing to the green one. This is due to formation of large porosities during the sintering stage for the polymer burn out and as a result material is expanded, volume increased and density decreased.

Comparing Al-1Mg powders with and without wax, unwaxed samples gave better green and sintred density for both pressures (Table 2). Although Acrawax lubricant provides a reasonable green density, it had a deleterios effect on sintered density mainly owing to its wide burn off range and hence incomplete removal during sintering leaving some black residue. The previous workers [16] reported that the best green and sintered densities were obtained with paraffin wax and liquid paraffin which had a shorter burn off range leaving no residue after sintering and hence a cleaner end product. They concluded that the higher the molecular weight, the wider the burn off range, and the more reactive with Al the less suitable the lubricant. The present results are consistent with the previous works [16-18].

In Table 3, mass, density and volume changes of Al-1Mg powders with or without wax are tabulated for both pressures. It is seen from this table that while mass decreased as 0.5% with waxed samples due to wax burn out during the sintering at 350°C, it increasedas 4 to 5% due to AlN formation in nitrogen atmosphere. Similarly, density decreased due to wax burn out as explained above, it increased owing to the AlN formation. Because, sintering under nitrogen was beneficial for its reducing atmosphere, protection against further oxidation, reducing the oxide content of the Al powder particles and formation of AlN [19] which improves the densification as ~2.60 g cm^{-3} (~95.8% TD) pressed at 435 MPa.

Table 2.
Green and sintered densities of Al-1Mg (with and without wax) pressed at 490 MPa and 435 MPa

Powder type	Compacting Pressure, MPa	Theoretical density, g cm^{-3}	Green density		Sintered density	
			g cm^{-3}	% TD	g cm^{-3}	% TD
Al-1Mg-1wax	490	2.6852	2.4840	92.5	2.27	84.5
Al-1Mg		2.7125	2.5103	92.5	2.57	95.1
Al-1Mg-1wax	435	2.6852	2.4564	91.5	2.26	84.5
Al-1Mg		2.7125	2.5186	92.8	2.59	95.8

Table 3.
Percentages mass, density and volume changes for Al-1Mg powders with and without wax pressed at 435 MPa and 490 MPa

Material type	Compacting Pressure, MPa	Mass change, %	Density change, %	Volume change, %
Al-1Mg-1wax	435	-0.5	-10	9.5
Al-1Mg		5.2	3.5	-4.4
Al-1Mg-1wax	490	-0.5	-9.8	9.3
Al-1Mg		4.3	2.8	-3.1

3.3. Microstructural evaluation

Specimens of the as sintered in pure nitrogen mixed Al-1Mg samples with lubricant, pressed at 435 or 490 MPa and sinteredat 640°C for 1 or 2 h, were prepared conventionally for metallographic examination using scanning electron microscope. Porosity content, pore size, shape and distribution within the as sintered samples were inspected using SEM equipped with EDS analysis. Residual macro- and microporosity was present in all sintered samples under every sintering condition. Medium sized pores and small interconnected micro-pores at grain boundaries were visible when lubricant was added which reduced the sintered densities due to a wide burn off range leaving residual porosity.

Fracture surfaces

After three point bending test, the fracture surfaces are examined in SEM using different magnifications. It is observed that sintering is quite successful in outer side of the specimens, it is not properly sintered the inner side of the specimens for both group specimens. The reason is could be due to insufficient sintering time or the rapid heating rate of 10°C/min. Most probably, diffusion is not sufficiently completed within such a ramp rate condition at 640°C for 2h. The representative SEM micrographs are shown in Figure 4 for both group samples.

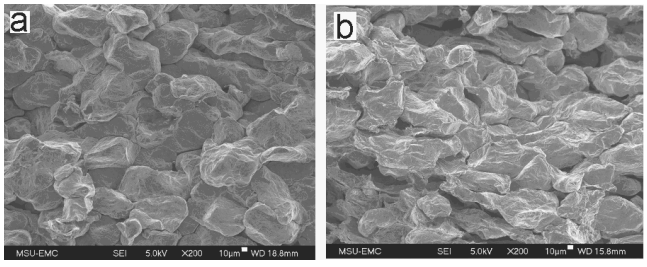

Fig. 4. SEM micrographs of Al-1Mg-1wax specimens for fracture surfaces after three point bending test. Image a belongs to 435 MPa and image b belongs to 490 MPa compression pressure. Some porosities and cracks are seen. Sufficient sintering in outer sides and less in the inner side (Scale bars show a distance of 10 µm)

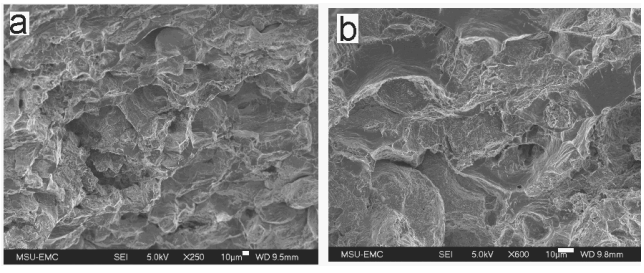

Fig. 5. SEM micrographs of Al-1Mg specimens for fracture surfaces after three point bending test. Some porosities and cracks are seen. Sufficient sintering is visible in everywhere. Image a belongs to 435 MPa and image b belongs to 490 MPa compression pressure (Scale bars shows a distance of 10 µm)

However, ductile fracture is clearly visible in Figure 5 for both pressured samples due to perfect diffusion at slower heating rate (3°C /min) and also longer sintering time (6 h) at the same sintering temperature (640°C) in nitrogen atmosphere.

Surface polished samples

Specimen surfaces are polished in conventional method and not etched for SEM investigations. In Figures 6 and 7, SEM micrographs are illustrated for both group materials. It is seen from Figs. 6-7 that irregular porosities mainly in grain boundaries and also bulk porosities on the surface are clearly observed.

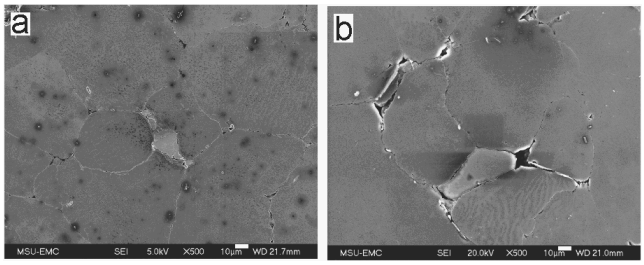

Fig. 6. SEM micrographs of Al-1Mg-1wax surface polished samples. Some irregular porosities mainly in grain boundaries and also bulk porosities are seen as black spots. Micrograph a belong to 435 MPa and b belong to 490 MPa compression pressures

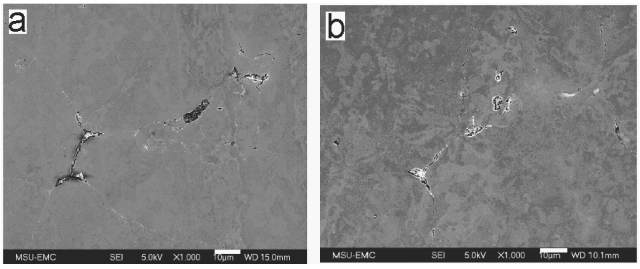

Fig. 7. SEM micrographs of Al-1Mg surface polished samples. Some irregular porosities mainly in grain boundaries and also bulk porosities are seen as black spots. Micrograph a belong to 435 MPa and b belong to 490 MPa compression pressures

In general, the microstructural studies using both optical and scanning electron microscopes illustrated similar stuffing for both with and without lubricant specimens sintered under nitrogen atmosphere. These consistent of Al matrix, a number of identical second phases and pores differing only in the proportions in both with and without wax powders.

3.4. EDS analysis

The elemental microanalysis of various grain boundaries and also matrix were conducted using EDS analysis (Tables 4-5 and Figures 8-9). It is seen from these Tables and Figures that, the structure contains basically Al and Mg (Fig. 8). However, it can also be observed that some impurities such as Si in the structure

(Fig. 8). In addition, O can also be observed due to high affinity of Al and Mg in the ambient temperature.

The presence of grain boundary solidified liquid phases, analysed by EDS system was almost consistent in all the sintered compacts, i.e. light grey structures of Al-Fe-Si phase are exposed at grain boundaries with iron being one of the main impurities of the as received Al powders. A dark grey phase, mostly at grain boundaries was analysed as mainly Mg2Si which forms due to rapid solidification of the gas/air atomized Al powder reasoning supersaturation of Mg/Si in the solid solution and precipitating in the form of fine Mg2Si upon exposure to high temperatures during sintering [17]). Presence of this phase has also been confirmed from the Al-Mg-Si phase diagram by other researchers [20]. Some fine black areas also appeared in both group samples also appeared in both alloys as remaining fragments of the aluminium oxide of the starting Al powder.

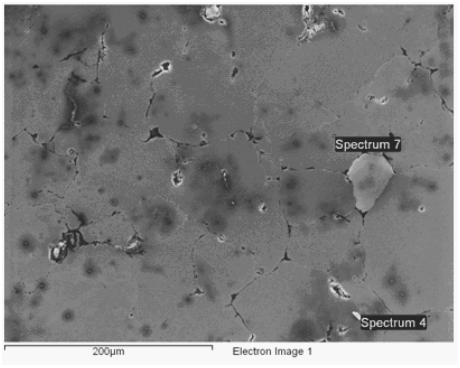

Fig. 8. SEM micrograph and EDS analysis points in Al-1Mg-1Acrawax, compaction under 490 MPa and sintered at 640°C for 2 h

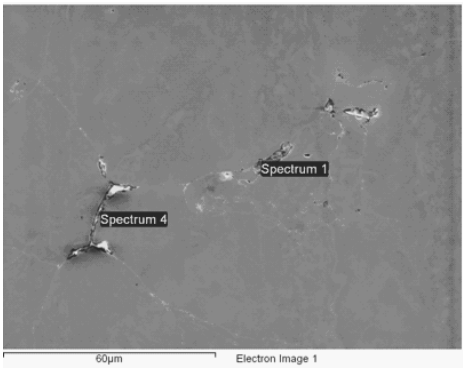

Fig. 9. SEM micrograph and EDS analysis points in Al-1Mg compaction under 435 MPa and sintered at 640°C for 6 h, illustrating Mg2Si phase in grain boundary

Table 4.
EDS analysis in Al-1Mg-1Acrawax compaction under 490 MPa and sintered at 640°C for 2 h (spectrum 4 and 7)

Spectrum Point	Elements (% wt)			
	O	Mg	Al	Si
Point 7	0.21	0.08	99.71	-
Point 4	0.25	0.10	95.94	3.71

Table 5.
EDS analysis in Al-1Mg compaction under 435 MPa and sintered at 640°C for 6 h (spectrum 1 and spectrum 4), implying Mg2Si phase in grain boundary

Spectrum	Elements						
Point	O	Mg	Al	Si	C	N	Fe
Point 1	37.4	34.9	22.9	0.8	1.78	3.13	-
Point 4	16.0	3.25	63.3	5.6	0.83	1.89	8.5

3.5. Dilatometer and dimensional change

Two green compact specimens were tested in nitrogen atmosphere to check the dimensional changes by a vertical push rod dilatometer using 10°C/min ramp up to 640°C for the 30 min dwell time in a two channel and then a cool down to room temperature at 10°C/min in nitrogen. The specifications of the dilatometer is as follows: Unitherm Model 1161 Dilatometer System , 600°C max capacity, Two channel system.

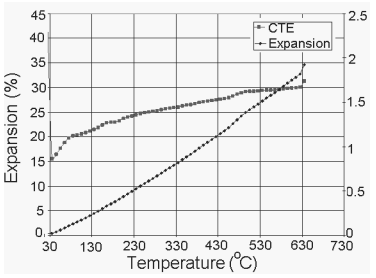

Fig. 10. Expansion and CTE versus temperature for Al-1Mg (w/o) used by dilatometer

Due to similar dimensional change results for both alloys, only Al-1Mg will be reported here. Figure 10 shows the variation in the sintering expansion with temperature obtained from dilatometer. The gas atomised sample when sintered to 640°C for 30 min. in nitrogen exhibits expansion of exproximately 35% and was found to be 95% dense. In addition, the average CTE is found as about $1.7x10^{-6}$/C at 600°C.

3.6. Thermogravimetric analysis (TGA)

Figure 11 shows the thermogravimetric profile of the lubricant (Acrawax): the percentage change in mass was plotted on the ordinate and the temperature on the abscissa. The thetmogravimetric profile provides information on the degradation temperature renge of the lubricant component.

The thermopgravimetric profile was generated by SETSYS Evolution TGA model 7, using SETSOFT 2000 software, coupled with a Pentium 3 compatible computer. The thermo-prolysis behaviour of the lubricant was tested in the temperature range of 30-640°C, using an argon flow rate and heating rate of 20 ml/min and 3°C/min, respectively.

The thermogravimetric profile shows that the lubricant (acrawax) comprises of multi-components. The lubricant starts to degrade at about 200°C and complete the degradation at about

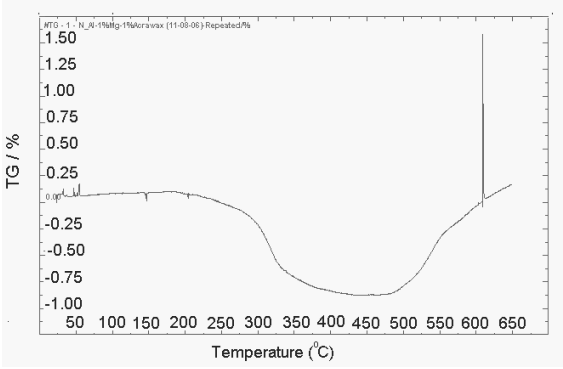

Fig. 11. Thermogravimetric profile of lubricant (Acrawax) in Al-1Mg-1wax alloy

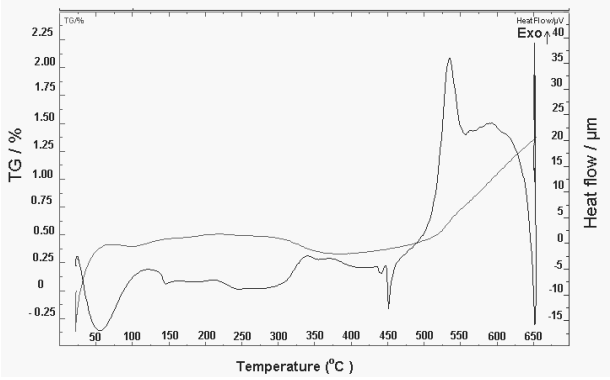

Fig. 12. Thermogravimetric profile of lubricant (Acrawax) in Al-1Mg-1wax alloy

425°C. The loss of weight from 200°C to 300°C is only 0.25%. From 300 to 450°C, the weight loss of the binder rapidly increased to 0.75 %. All the lubricant was removed at about 450°C. A turning point was observed at 450°C and then a fast weight increase occurred up to the 640°C. This is possibly due to hydrating of aluminium for medium dew point of argon atmosphere.

In the second alloy, there was no wax and therefore TGA curve is very stable between 30 to 500°C, however percentage change in mass increased over 500°C possibly due to aluminium hydrating in fairly dried argon atmosphere. In Figure 12, thermogravimetric profile is given for Al-1Mg alloy.

3.7. Mechanical properties

Three point bending test was employed to check the mechanical properties of sintered Al-1Mg compacts using the INSTRON 5869 machine having the 1000 kN maximum load. In the present test, 2 mm/min strain rate was used and the distance (span) between the lower support rods was 25.4 mm which was suggested by the related standard (ASTM D 790-92). The 3 specimens from each group were examined and the average results were reported.

Transverse rupture strength (TRS) was calculated using the equation [21, 22] of as follows:

$$\sigma_T = 3F_BL / 2WT^2$$

Here; σ_T is transfer rupture strength, F_B is failure load, L is distance between the lower support rods, W is the width of the specimen and T is the thickness of the specimen. The calculated results for with and without waxed powders are shown in Tables 6-7 for 435 and 490 MPa compression pressure, respectively.

Table 6.
The mechanical properties of Al-1%Mg-1%Acrawax (all w/o) applied 435 MPa compression pressure and sintered at 640°C 2 h exposed to three point bending test (Span Length 25.4 mm)

Compacting Pressure (MPa)	Specimen no	Failure load N	W mm	T mm	TRS MPa
435	4	80	12.93	3.42	20.2
	5	100	12.93	3.36	26.1
	6	80	12.91	3.34	21.2
490	4	125	12.99	3.83	25.0
	5	110	13.00	3.86	21.6
	6	100	13.00	3.89	19.4

Table 7.
The properties of Al-1Mg (w/o) compacted under 435 MPa and 490 MPa compression pressure and sintered at 640°C 6 h exposed to three point bending test exposed to three point bending test (Span Length 25.4 mm)

Compacting Pressure (MPa)	Specimen no	Failure load N	W mm	T mm	TRS MPa
435	2	550	12.73	2.86	200.93
	3	500	12.77	2.73	200.16
	4	550	12.70	2.75	218.18
490	1	660	12.80	2.84	243.57
	2	630	12.70	2.95	217.18
	3	580	12.74	2.90	206.24

It is seen from Table 6 that the specimens, which were compacted at the pressure of 435 MPA have TRS between 20.2 to 26.1 MPa for the three Al specimens and the average TRS is calculated as 22.5 (±1.97) MPa. It is also noticed that the specimens, which were compacted at the pressure of 490 MPa, have between 19.4 to 25.0 MPa for the three Al specimens and the average TRS is calculated as 22.0 (±1.87) MPa. It shows that their mechanical performance is weak during the transverse rupture (three point bending test) due to insufficient sintering conditions.

It is seen from Table 7 that, specimens which were compacted at the pressure of 435 MPa, have TRS between 200 to 218 MPa for the three Al specimens and the average TRS is calculated as 206.42 (±6.01) MPa. It is also observed from Table 7 that TRS is found as between 206 to 243 MPa for the three Al specimens, which were compacted at the pressure of 490 MPa, and the average TRS is calculated as 222.33 (±12.44) MPa. It shows that their mechanical performance is very good for both pressures during the transverse rupture (three point bending test) owing to enhanced diffusion in the mentioned sintering process.

4. Conclusions

a. Green and theoretical density increased with the increment of compaction pressure. In the present study, green density for wax added sampleswas found as 91.5 and 92.5 for 435 and 490 MPa compression pressure, respectively. However, no wax samples gave a green density of 92.8 and 92.5 for the same pressures.
b. Although Acrawax lubricant provides a reasonable green density, it had a deleterios effect on sintered density mainly owing to its wide burn off range and hence incomplete removal during sintering leaving some black residue.
c. In grain boundary analysis, the light grey structures of Al-Fe-Si phase and a dark grey phase, mostly at grain boundaries was analyzed as Mg2Si which forms due to rapid solidification of the gas/air atomized Al powder reasoning supersaturation of Mg/Si in the solid solution and precipitating in the form of fine Mg2Si upon exposure to high temperatures during sintering.
d. Residual macro- and microporosity was present in all sintered samples under every sintering condition. Medium sized pores and small interconnected micro-pores at grain boundaries were visible when lubricant was added which reduced the sintered densities due to a wide burn off range leaving residual porosity.
e. It shows that the mechanical performance of the sintered samples with lubricant is in weak (~20 MPa) during the transverse rupture stress (TRS or three point bending test). Conversely, TRS improved as 20 times (>200 MPa) in wax free samples.

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