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Combined effect of hot extrusion and heat treatment on the mechanical behavior of 7055 AA processed via spray metal forming

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ABSTRACT

The mechanical properties of 7xxx series alloys can be tailored by subjecting them to deformation processing and heat treatment. In the present study dealing with spray forming of 7055 AA, extrusion and heat treatment involving solutionizing followed by peak aging resulted in improved mechanical behavior. The strength and ductility obtained are comparable to that of extruded and heat treated as-cast 7055 AA (Mondal et al., 2011) [1]. Spray forming offers an alternate route to develop high strength aluminum alloys and the current study is an attempt that draws closer to the target value of 1GPa strength and 10% ductility for high strength aluminum alloys.

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1. Introduction

7055 AA is a prominent member of 7xxx class of aluminum alloys and is a widely used aircraft alloy due to its high fracture toughness, enhanced fatigue and corrosion resistance and excellent formability [1–6]. Recent ballistic resistance studies indicate that 7055 AA also offer an unprecedented ballistic penetration resistance [3]. Being age hardenable, the high strength of 7055 AA alloy is attributed to the uniform distribution of coherent GPI, GPII and metastable η′ phases. As in most age-hardenable alloys, metastable η′ is responsible for peak hardening and coarsening of the stable but non-coherent η phase leads to the decrease in the strength of 7055 AA [4].

7xxx class of aluminum alloys in general and 7055 AA in particular have been processed via ingot and powder metallurgy [1]. In the current study, spray forming was chosen as a processing route to develop light weight high strength alloy with good ballistic properties. Spray forming is a rapid solidification technology used for producing semi-finished tubes, billets, plates and other simple configurations in single integrated operation. Spray Metal Forming (SMF), also referred to as spray casting or spray deposition involves use of high pressure nitrogen to atomize a molten stream of metal into a spray of liquid droplets. The atomization process takes place in a chamber that is purged with nitrogen and produces a distribution of droplets sizes. The spray parameters are set in such a manner that the depositing droplets have sufficient liquid content to flow and completely wet the surface. The metal then solidifies into an fully dense preform with a fine, uniform microstructure. In gas atomized spray forming (GASF), the dense mass of equiaxed grains occasionally include shrinkage pores [7]. Typical microstructures generated via vacuum plasma, air plasma and electric arc spray forming (VPSF, APSF and EASF) have markedly different microstructure than the microstructure in the materials processed via GASF [7–12]. In the study involving Al–Zn–Mg–Cu alloy processed via spray atomization and deposition technique, the microstructure is found to be composed of aluminum matrix dispersed with Al7Cu2Fe, Al9FeNi phases [13]. The spray formed Al–Zn–Mg–Cu alloy in T6 temper condition exhibit super strength due to the presence of coherent GP zones [13]. The metal forming due to the low deposition temperature is a viable technique that can be utilized to produce range of aluminum alloys including 7055 AA [6]. As mentioned earlier, there is always small amount of porosity associated with metals and alloys formed via spray forming. As a result spray formed materials have to be extruded/forged to eliminate the porosity. The objective of the present study is to process 7055 AA via spray forming and study the effect of hot extrusion and heat treatment on the mechanical behavior of spray formed 7055 AA.

2. Experimental procedure

2.1. Spray forming of 7055 AA

The 7055 AA was processed via spray forming technique. The spray forming experiments were conducted in a specially designed spray chamber. To begin with, 30–70 lb of alloy was superheated to temperatures between 850 and 1000 °C in a fiber crucible using an induction apparatus. The spray chamber was purged with

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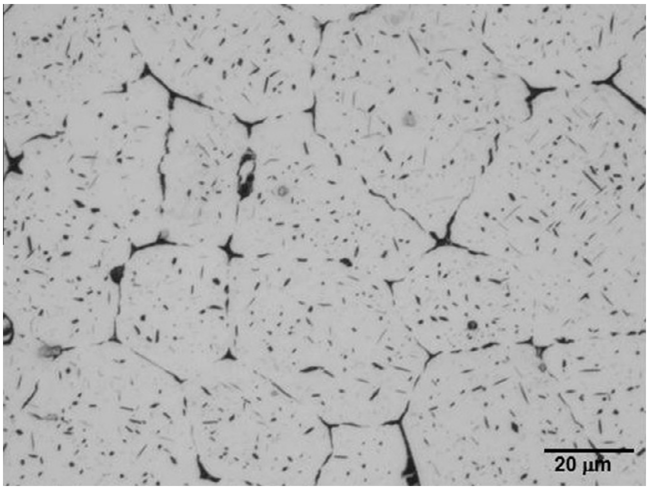

Fig. 1. Micrograph of spray formed 7055 AA showing coarse grain structure.

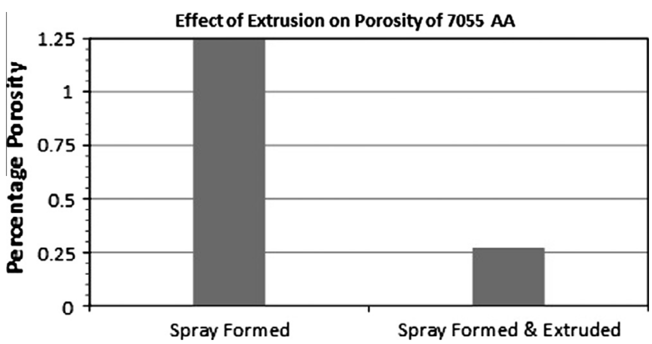

Fig. 2. Effect of extrusion on the porosity of spray formed 7055 AA.

nitrogen until there was a very low level of oxygen present. Next a stopper rod was lifted to allow the superheated alloy melt to flow through the nozzle in the bottom of the crucible. Pressure in the crucible was increased to maintain a constant metal flow rate. The metal stream was delivered to an atomizer where high-pressure nitrogen jets, at near-sonic velocity, atomized the molten stream into a fine dispersion of micrometer-sized droplets. After atomization, the distribution of partially solidified droplets was collected on a rotating substrate (rotation 3 Hz) positioned at approximately 700 mm from the gas atomizer (scan speed 19–21 Hz). To maintain the atomizer-substrate distance, the substrate was displaced vertically during spraying at a withdrawal rate of 0.7–1.04 mm/s. This ensures the microstructure and the precipitates are uniform in size and distribution throughout the entire billet.

2.2. Heat treatment of spray formed 7055 AA

The spray formed 7055 AA billets were homogenized at 450 °C for 1 h and extruded at 450 °C using an extrusion ratio of 10:1. Age hardening treatment of the spray formed 7055 AA specimen before and after hot extrusion included solution treatment at 450 °C for 1.5 h followed by water quenching and two step peak aging [1]. Artificial aging process was carried out by initially exposing the solution treated specimen at 100 °C for 8 h and then at 120 °C for 24 h.

2.3. Characterization of spray formed 7055 AA

Metallographic examinations were carried after etching the samples using chemical etching technique. The etchant used was Keller's reagent.

The phase changes occurred during heat treatment and extrusion of the spray formed 7055 AA were followed using PANalytical Empyrean X-ray powder diffractometer (Cu Kα radiation, 45 kV, 40 mA). All measurements were performed at room temperature. Crystallite size was estimated by Scherrer method using PANalytical HighScore software. The intensity data were corrected for background scattering, absorption and detector efficiency.

Tension test on the cold spray formed 7055 AA specimens in various condition were performed using an Instron 5500 R tensile testing machine. These tests were performed as per ASTM E8. The toughness values for each cold spray formed 7055 AA sample was computed by integrating the area under the stress strain diagram. This was done by summing the complementary stress–strain data points using numerical integration by the trapezoidal rule. The fractured surfaces of the spray formed specimen failed during the tension test were studied by performing Field Emission Scanning Electron Microscopy (FESEM) imaging.

3. Results and discussion

Unlike casting technologies that result in macro-segregation and coarse grained microstructure, spray forming lead to 7055 AA with fine grained, and chemically homogeneous microstructure. Fig. 1 is an optical micrograph of spray formed 7055 AA showing the grain structure in the spray formed material.

The porosity in the spray formed 7055 AA before and after extrusion was measured using image analyzer and is shown Fig. 2. After extruding as-sprayed 7055 AA using extrusion ratio of 10:1, the average porosity is found to decrease from 1.25 % to 0.25 %.

The as spray formed 7055 AA has a coarse grained microstructure as seen in Fig. 1. This granular structure was observed by etching the polished spray formed 7055 AA using Keller's reagent. Optical micrographs of the spray formed 7055 AA following extrusion and peak aging observed using same chemical etchant are shown in Fig. 3. In Fig. 4 what appears as a two phase microstructure essentially reveals the onset of recrystallization in the peak aged extruded spray formed 7055 AA.

As seen in Fig. 4 the spray formed 7055 AA extruded using extrusion ratio of 10:1 upon peak aging undergoes substantial recrystallization. The intermetallic particles (seen here as black particles) that line up along the original grain boundaries tend to

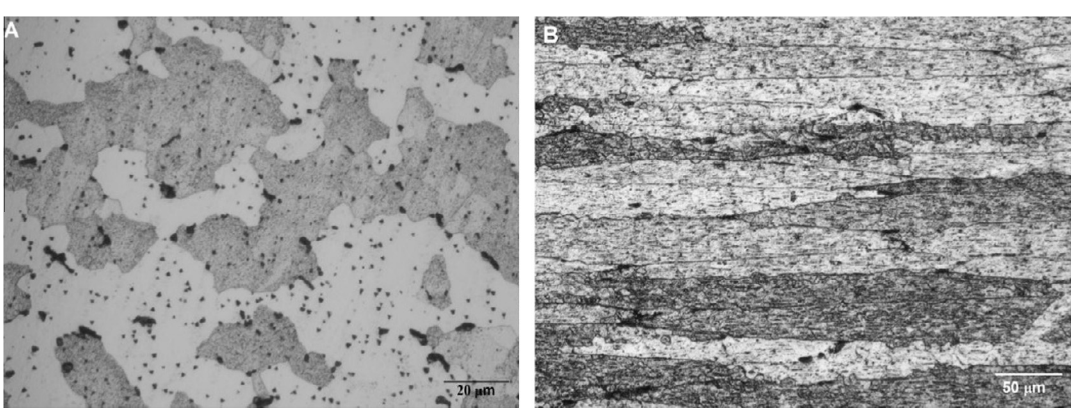

Fig. 3. Photographs of spray formed 7055 AA following extrusion showing microstructure (A) across the cross section and (B) along the extrusion direction.

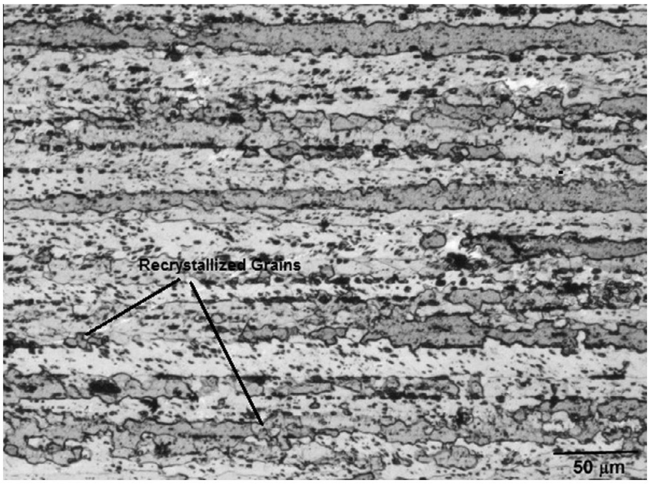

Fig. 4. Photographs of spray formed and extruded 7055 AA in peak aged condition showing the microstructure along the extrusion direction.

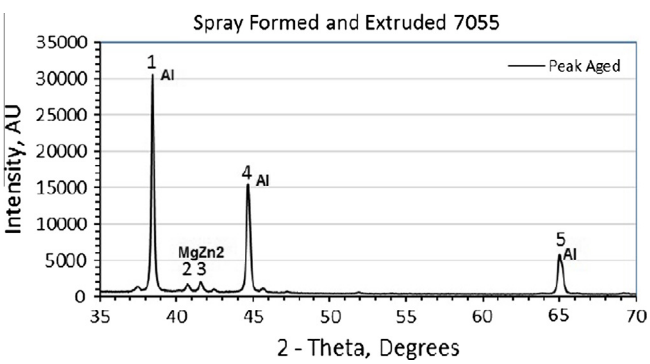

Fig. 5. X-ray diffraction pattern of spray formed and extruded 7055 AA.

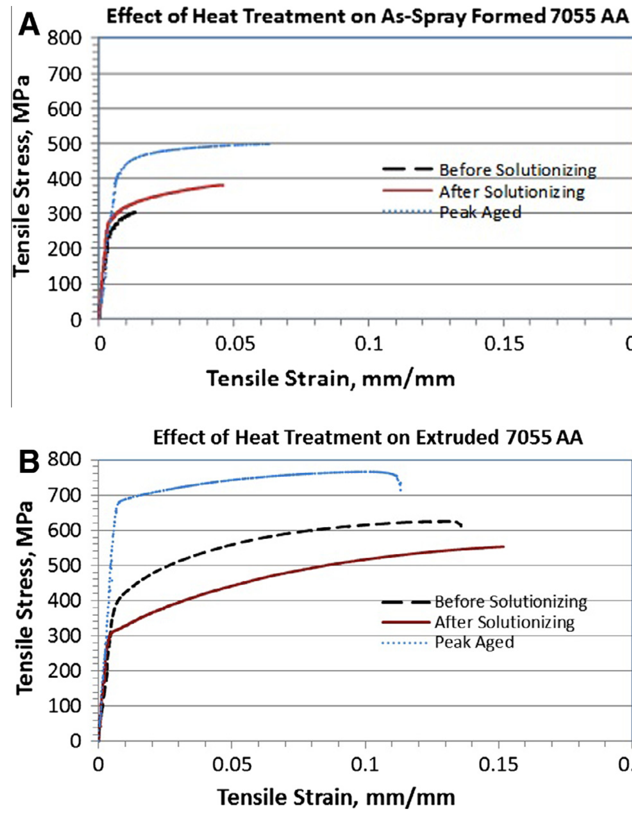

Fig. 6. Effect of heat treatment on the tensile behavior of spray formed 7055 AA before and after extrusion.

restrict the migration of recrystallization front. The presence of intermetallic equilibrium η ($MgZn_2$) phase was observed in the XRD pattern of extruded spray formed 7055 AA as seen in Fig. 5. Peaks representing the η ($MgZn_2$) phase are not as distinct in the XRD pattern of as spray formed material because the amount of this phase is probably beyond the detection limit of the X-ray diffractometer.

Table 1 shows the effect of extrusion on the crystallite size of aluminum and η ($MgZn_2$) phase of in case of spray formed 7055 AA. Extrusion of spray formed 7055 AA carried out at 450 °C using an extrusion ratio of 10:1 tends to increase the size of aluminum crystallite while the η ($MgZn_2$) phase crystallite show a reverse trend.

Fig. 6A shows the stress strain relationship in as formed 7055 AA tensile specimen before and after the heat treatment. As per Fig. 6A, heat treatment that involves solutionising followed by peak aging has substantial influence on the tensile properties of as-sprayed 7055 AA. The relatively lower strength and ductility of as-sprayed 7055 AA can be partially attributed to the presence of porosity.

When we compare Fig. 6A and B that represent stress strain curves of spray formed 7055 AA before and after extrusion, we observe strong influence of extrusion on the tensile behavior of the material as shown graphically in Fig. 7. Effect of extrusion alone and in combination with heat treatment on yield strength of spray formed 7055 AA is shown in Fig. 7A. Percentage increase in the yield strength of spray formed 7055 AA brought about by extrusion and heat treatment alone is almost identical (~60%). While increase in yield strength brought about by extrusion alone is due to pore closure, the 60% rise due to heat treatment alone could be attributed to the evolution of fine grain as a result of recrystallization the material undergoes during heat treatment.

Table 1
Effect of extrusion on the size of Al and $MgZn_2$ crystallites.

Sample	Peak No.	2 – Theta (°)	*d* Spacing (A°)	FWHM (°)	Crystallite size (A°)
Spray formed 7055 AA	1 – [Al(111)]	38.45	2.34	0.169	660
	2 – [MgZn2–1]	40.72	2.21	0.23	432
	3 – [MgZn2–2]	41.59	2.17	0.224	449
	4 – [Al(200)]	44.68	2.02	0.210	492
	5 – [Al(220)]	65.02	1.43	0.228	492
Spray formed and extruded 7055 AA	1 – [Al(111)]	38.46	2.33	0.130	898
	2 – [MgZn2–1]	40.75	2.21	0.422	210
	3 – [MgZn2–2]	41.57	2.17	0.365	250
	4 – [Al(200)]	44.68	2.02	0.142	809
	5 – [Al(220)]	65.06	1.41	–	–

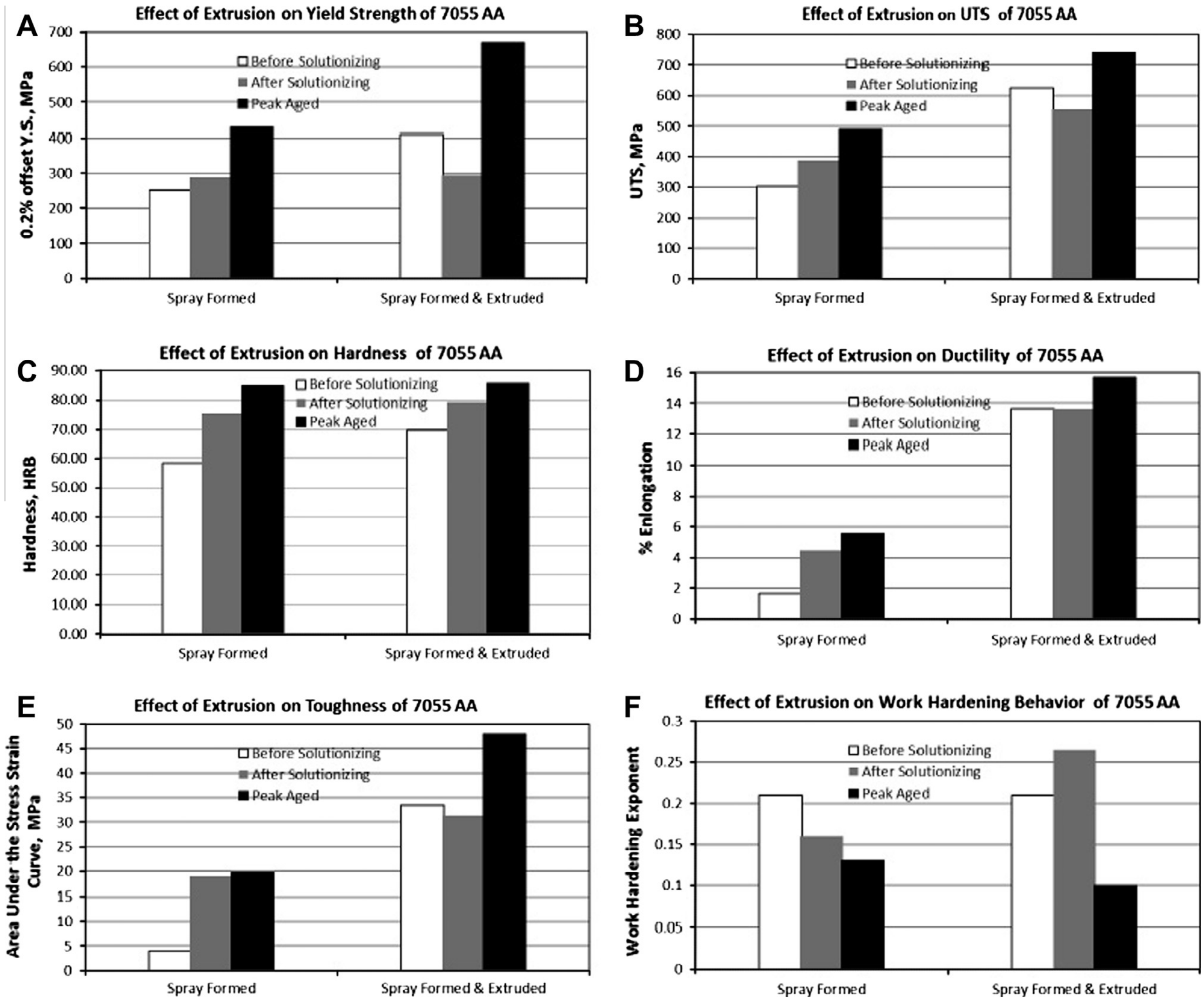

Fig. 7. Effect of extrusion and/or heat treatment on (A) yield strength, (B) UTS, (C) hardness, (D) ductility, (E) toughness and (F) work hardening behavior of spray formed 7055 AA.

In combination, heat treatment and extrusion has much profound effect on the yield strength of spray formed 7055 AA. Combined effect of extrusion and heat treatment leads to nearly 170% increase in the magnitude of the yield strength of spray formed 7055 AA. This large jump in the yield strength is due to combined effect of pore closure during extrusion and recrystallized fine grain as a result of heat treatment. Similar observation can be made when we compare the UTS of 7055 AA under different conditions.

In combination, as seen in Fig. 7B, extrusion and heat treatment bring about similar increase in the ultimate tensile strength (UTS) as the yield strength. Extrusion alone nearly doubles the UTS of the spray formed 7055 AA.

The hardness of the spray formed 7055 AA samples do not show a similar trend as UTS. Fig. 7C shows the hardness variation in spray formed 7055 AA samples. What is obvious in Fig. 7C is that peak aging raises the hardness to the same extent whether the spray formed 7055 AA is extruded or not. This could be due to the fact that the porosity in the spray formed 7055 AA is very fine and uniformly distributed.

Fig. 7D shows the effect of heat treatment and extrusion on the ductility of spray formed 7055 AA. In combination the extrusion and heat treatment multiply the ductility of spray formed 7055 AA eight times. This combined effect is marginally higher than the increase in ductility caused by extrusion alone. It can be inferred that as far as increase in ductility is concerned, elimination of porosity caused by the extrusion is a major contributor. Generally, in any strengthening mechanism, increase in strength is at the expense of ductility. By comparing Fig. 7A and D, it can be concluded that extrusion of spray formed 7055 AA brings about increase in strength and this increase is not at the expense of ductility. Infact upon extrusion, the ductility also increases with the strength. While strength enhancement can be attributed to lowering of porosity, as seen in Fig. 2, the increase in the ductility is due to the elimination of porosity and to some extent due to the initiation of recrystallization during the extrusion process [5].

Extrusion and heat treatment also have significant influence on the toughness of spray formed 7055 AA. Toughness variations in extruded and heat treated spray formed 7055 AA is shown in Fig. 8E. These toughness values were computed from the tensile stress strain curves using trapezoid rule [1]. Upon extrusion the toughness of 7055 AA exhibit toughness value which is six times that of the as spray formed material. When extrusion is carried out in conjunction with heat treatment, this increase rises to tenfold.

Effect of extrusion and heat treatment on the work hardening behavior of spray formed 7055 AA is shown in Fig. 7F. This behavior, represented in terms of work hardening exponent was assessed using the tensile true stress true strain curves [3]. From Fig. 7F it

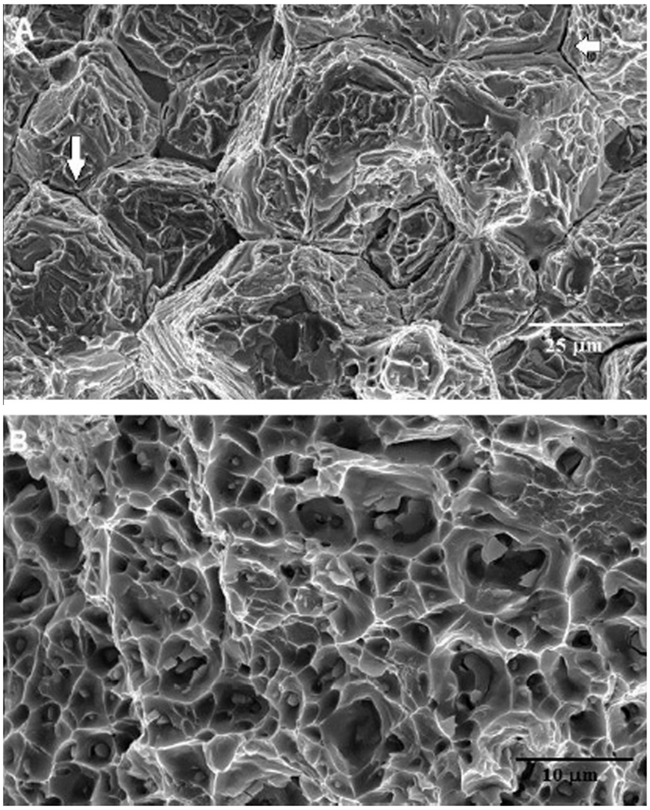

Fig. 8. Fracture surface of spray formed 7055 AA (A) before extrusion and (B) after extrusion.

Table 2
Comparison of mechanical behavior of spray formed and commercially available 7055 AA extrusions.

	Spray formed 7055 AA T6 extrusions	ALCOA 7055 AA T77511 extrusions
0.2% Offset yield strength, MPa	669	669
Ultimate tensile strength, MPa	740	669
% Elongation	15.7	11

appears that extrusion alone has no effect on the work hardening exponent. However, heat treatment tends to lower the work hardening exponent. This decrease in work hardening exponent is steeper when spray formed 7055 AA is extruded and then peak aged. This could mean that extruded and heat treated 7055 AA is probably more prone to dynamic recrystallization that lead to strain softening [5].

Spray formed 7055 AA failed during the tension test were observed under scanning electron microscope to explain the effect of extrusion on the ductility shown in Fig. 8. Fig. 8A is a fracture surface of spray formed 7055 AA. This fracture surface almost appears to be 2D graphical projection of grain structure observed in Fig. 1. The primary feature of the fracture surface seen in Fig. 8A are the splats (formed during spray forming) that are consolidated quite well in spite of rapid cooling except for the strength and ductility limiting cracks left at the splat interface. Occasionally there are also some voids observed at the triple junctions (shown by arrows in Fig. 8A). The intergranular nature of the fracture suggests that the fracture is distinctly brittle. This failure that occurs along the splat interface gives an idea about the size of 7055 AA particles generated during the spray forming process.

In contrast to the brittle failure of spray formed 7055 AA, the extruded sample failed in a ductile manner. Fig. 8B is the fracture surface of extruded spray formed 7055 AA. The dimple structure observed all over the fracture surface is an indication of highly ductile failure.

Table 2 shows the comparison between the commercially available 7055 AA extrusion and the spray formed 7055 AA extrusion. While both extrusion show comparable yield strength, spray formed extrusions exhibit slightly higher UTS and ductility.

4. Conclusions

By subjecting spray formed 7055 AA to deformation processing and heat treatment involving solutionizing and peak aging, it is possible to produce a pore free alloy with substantially improved mechanical properties. The simultaneous improvement in the strength and ductility of spray formed 7055 following extrusion is due to the lowering of porosity and initiation of recrystallization. While extrusion and heat treatment both have drastic influence on the tensile properties of spray formed 7055 AA, the combined effect is much more profound that can lead to an alloy with 740 MPa strength, 16% ductility and excellent energy absorption capability. The strength and ductility of the spray formed 7055 extrusions are comparable to commercially available 7055 AA extrusions.

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