Turkish J. Eng. Env. Sci.
26 (2002) , 345 – 352.

Mechanical Properties of Spray Cast 7XXX Series Aluminium Alloys

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Received 14.06.2001

Abstract

Mechanical properties of spray deposited and extruded 7xxx series aluminium alloys were investigated in peak aged condition. To study the influence of Zn additions on the mechanical behaviour of spray deposited materials, three alloy compositions were selected, namely: SS70 (11.5% Zn), N707 (10.9% Zn) and 7075 (5.6% Zn). After ageing treatment, notched and unnotched specimens of spray deposited alloys were subjected to tensile tests at room temperature. Experimental results showed that the SS70 alloy exhibited the highest strength. Spray deposited Al alloys showed a very high strength as compared to conventionally processed 7xxx series Al alloys. Compared with the PM processed 7xxx series Al alloys, fracture toughness values of these alloys were higher.

Key words: Spray deposition, 7xxx series Al alloys, Strength, Fracture toughness.

Introduction

For 70 years, aluminium alloys have been the materials of choice for both military and commercial aircraft structures. The ingot metallurgy (IM) alloys of the 2000 (Al-Cu-Mg) and 7000 (Al-Zn-Mg-Cu) series used thus far show several disadvantages caused by the production process. Such problems are primarily coarse intermetallic constituent phases, coarse grains, and macrosegregation, resulting in low fracture toughness. Recent advances in aluminium alloy and temper development are maintaining aluminium alloys as the materials of choice for future commercial aircraft structures to meet cost and weight savings objectives. Aluminium producers have increased research activity in the area of advanced aluminium alloys to provide improved performance characteristics. During the past decade increased efforts have been made to improve the structural efficiency and properties of aerospace materials through the development of lighter weight, stiffer and stronger materials via rapid solidification processing (RSP) (Duan *et al.*, 1993). Rapid solidification processing improves the mechanical properties of many alloys in terms of increased tensile strength, ductility and fatigue and crack propagation resistance (Sanctis, 1991). Such improvements are mainly associated with large solid solubility extensions of alloying elements, reduced macrosegregation, refinement of the alloy grain size and changes in the second phase particle size, shape and distribution due to high cooling rates (possibly exceeding 10^6 K s^{-1}).

There are a number of well established techniques that may be readily utilized for rapid solidification. Alloys produced by atomization, one of the rapid solidification techniques, followed by powder metallurgy (PM) consolidation overcome the formation of coarse grains, coarse constituents, and macrosegration because of the high cooling rates. Therefore, these RS-PM alloys are characterized by very fine, homogeneous, and segregation free microstructures combined with a fine distribution of intermetallic particles. On the other hand, all PM alloys, without exception, typically contain fracture inducing oxides that form on the powder surface and do not disappear during consolidation.

Recently, the spray deposition technique has been developed to produce high density, near net-shaped preforms of materials directly from the liquid state as an alternative production method to PM. Spray casting was developed from work carried out by Singer at the University of Swansea, UK, during the early 1970s (Singer, 1970, Singer, 1972). The process was explained schematically in detail by Salamcı (2001) Spray deposition processing generally consists of two-steps: the energetic disintegration of a molten metal by inert gas jets into micron-sized droplets (atomization) and subsequent deposition of a mixture of solid, liquid, and partially solidified droplets on a surface (deposition) (Lengsfeld *et al.*, 1995). The spray deposition technique differs from established PM technology in that both the atomization and consolidation processes are combined in a single operation. The reduction in the number of manufacturing steps can lead to significant economic savings. Furthermore, this process is carried out under an inert (typically nitrogen) atmosphere and therefore the embrittling oxide content can be reduced and thus the ductility and fracture toughness can be improved.

Solidification during spray deposition is complicated by the extreme differences in thermal environments prior to and after impact. For example, whereas a typical 80 μm aluminium droplet is exposed to relatively high cooling rates (0.4 to 1×10^4 K/s) during flight, the cooling rate after impact is relatively slow (10 to 20 K/s) (Lengsfeld *et al.*, 1995). It should be noted, therefore, that in the spray deposition process the achievable cooling rates during deposition are not high. Even during the atomization stage of the spray deposition process, the cooling rates (10^3-10^4 K/s) are not as high as those achievable in typical atomization techniques employed in the RS-PM route (up to 10^6 K/s) owing to the much larger droplet sizes in spray deposition (Machler *et al.*, 1991).

The objective of the present work was to study the mechanical behaviour of spray deposited 7xxx series aluminium alloys and the results are presented and discussed for three alloys. The alloys investigated in the present study were produced by Alcan Cospray Ltd. at Banbury, Oxon. using the spray deposition process to study the effects of spray casting on the mechanical properties of two developmental alloys, SS70 and N707, which have higher solute contents and 7075 aluminium alloy. To evaluate the influence of Zn additions on the mechanical behaviour, three alloy compositions were studied in detail: Al-11.5% Zn-2.64 Mg-1.16 Cu-0.26 Zr, Al-10.9 Zn-2.16 Mg-1.01 Cu-0.22 Zr and Al-5.6 Zn-2.5 Mg-1.6 Cu-0.2 Cr (all compositions in wt.%). The main strengthening mechanism in these alloys is precipitation hardening by structural precipitates formed during artificial ageing (intermediate η' and equilibrium η ($MgZn_2$)). A practical limit of about 8 wt.% Zn is imposed for conventional cast materials because of inherent foundry problems (solute macrosegregation and cracking) (Sanctis, 1991). The spray deposition technique enables the level of Zn in the alloys to be increased. This increases the volume fraction of hardening precipitates, thus leading to an improvement in strength.

Experimental Method

The alloys, namely SS70, N707 and 7075, investigated in the present study were produced by Alcan Cospray Ltd. at Banbury, UK using the spray deposition process. SS70 was spray cast as a cylindrical preform with a diameter of 240 mm and height of 1100 mm and extruded down to a 25 mm diameter rod. The N707 was also spray cast as a preform, which was 235 mm in diameter and 790 mm in height, extruded down to a 63 x 25 mm rectangular section. The 7075 alloy was similarly processed; i.e. spray cast to a ~240 mm diameter cylindrical preform and extruded to a 65 x 30 mm rectangular section.

Table 1. Chemical composition of SS70, N707 and 7075 alloys (weight percent).

Alloy	Zn	Mg	Cu	Zr	Cr	Fe	Si	Mn	Al
SS70	11.50	2.64	1.16	0.26	<.01	0.05	0.02	-	bal.
N707	10.90	2.16	1.01	0.22	<.01	0.03	0.01	-	bal.
7075	5.6	2.5	1.6	-	0.2	0.4	0.5	0.3	bal.

The chemical compositions of the alloys are given in Table 1. Compared to 7075, the zinc contents of SS70 and N707 were significantly increased from 5.4% to 11.5% and 10.9%, respectively, in order to increase strength. In order to control recrystallization and grain growth 0.2% Zr was added to SS70 and N707 instead of Cr, which was used in 7075. SS70 had a slight increase in Zn and Mg content compared to N707. The SS70 and N707 had lower iron and silicon contents (around 0.05-0.03% Fe and 0.02-0.01% Si) compared to the conventional 7075 alloy.

It was not possible to perform all of the mechanical tests which would have been desirable because the SS70 alloy was available only as a rod of 25 mm diameter and the N707 and 7075 were a bar which had a 63 × 25 mm rectangular section. Thus it was not feasible to make compact tension (CT) specimens from the SS70 alloy and so it was decided to use the notched tensile test (ASTM E 602) for the three materials to estimate the fracture toughness of these alloys.

Tensile test specimens were prepared according to British Standard BSEN 10002-1:1990. The tensile test specimens used in this work had a gauge length of 25 mm and diameter of 5 mm. A photograph of one of the specimens is shown in Figure 1. Specimens were machined from the extrusions in the longitudinal (L) direction, which was parallel to the extrusion direction, and in the transverse (T) direction, perpendicular to both the extrusion direction and the shortest side of the billet (Figure 2). Notched tensile test specimens were prepared according to ASTM E 602-91; a photograph and drawing of the specimen are shown in Figure 3. Specimens were machined from the extrusions in the longitudinal and transverse directions. The tensile and notched tensile tests were performed at room temperature with a crosshead speed of 1 mm min^{-1} using an Instron 1185 testing machine. The fracture toughness K_{IC} values were obtained using the results gained from the notched tensile test specimens. The notch yield ratio (NYR), which is the ratio of notched tensile strength (NTS) to tensile yield strength (TYS), was calculated. The correlation between the notch yield ratio and the plane strain fracture toughness K_{IC} for 7xxx aluminium alloys is demonstrated in Figure 4 (Kaufman, 1979). Fracture toughness K_{IC} values were obtained using this figure for each notch yield ratio (NYR).

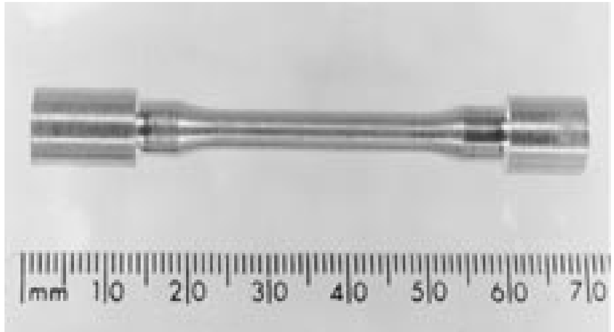

Figure 1. Photograph of a tensile test specimen used in this work (to BSEN 10002-1: 1990).

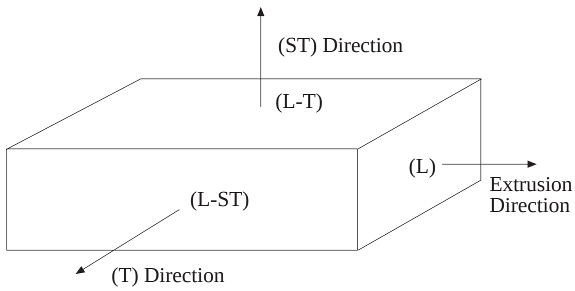

Figure 2. Schematic presentation of the faces and directions of an extruded bar.

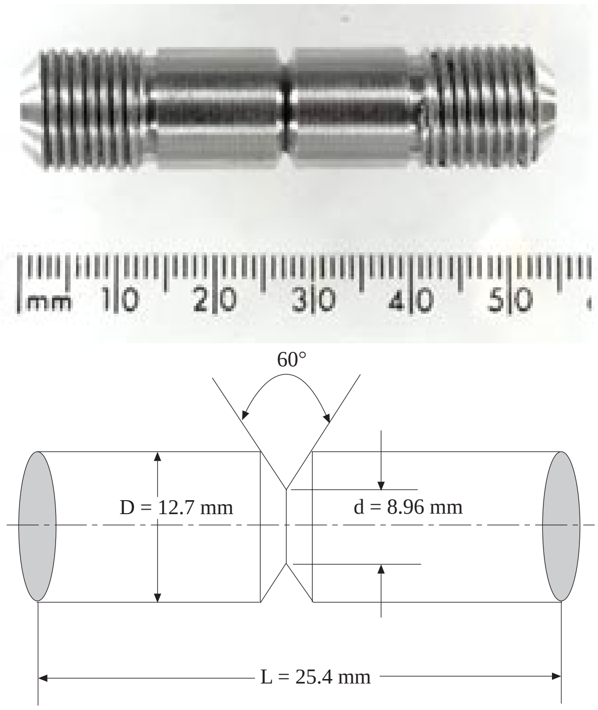

Figure 3. Notched tensile specimen used in this work (to ASTM E 602-91): (a) photograph of a specimen against a scale (b) drawing showing test section.

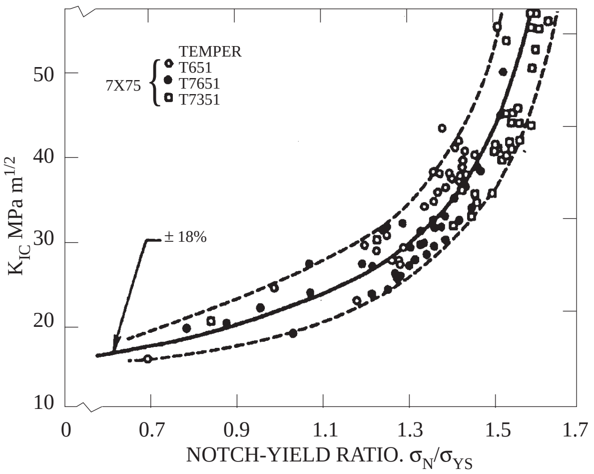

Figure 4. Correlation of plane-strain fracture toughness with notch-yield ratio for 7075 and 7475 plate [after Kaufman (1979)].

After machining, all materials were solution heat treated at 470°C for 0.5 h and then aged to the T6 condition (at 120°C for 24 h) before testing. At least four samples were tested. The point counting method has been applied to determine the volume fraction of ageing precipitates in the T6 microstructure (Vander Voort, 1984, ASM Handbook, 1992). The technique has been used with a point-count grid. The test grid was placed as a plastic overlay on the micrographs. The number of points which are the intersection of the crossed lines lying in the precipitate was counted. Points lying on the precipitate boundary were counted as one-half.

Results and Discussion

The mechanical properties of the three alloys, SS70, N707 and 7075, at room temperature, aged to the T6 condition are summarized in Tables 2 and 3 and Figure 5. The results were obtained in the longitudinal (L) and long transverse (T) directions for N707 and 7075 and (T) direction for SS70 alloy. Figure 6 shows bright field transmission electron microscopy (TEM) micrograph typifying the general microstructure of alloy SS70 in the solution heat treated condition (at 470°C for 0.5 h). The matrix grains contain a number of dislocations and smaller dispersoids. Figure 7 shows bright field images of SS70 in the T6 temper condition (at 120°C for 24 h). The precipitates which formed during ageing (η' and η ($MgZn_2$)), appear to be plate-shaped. The volume fraction of precipitates was found to be 25% by using the point counting method. Similar to SS70, the ageing precipitates were detected in the N707 and 7075 alloys.

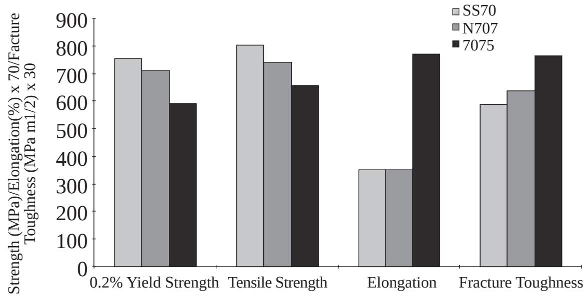

Figure 5. Comparison of mechanical properties of spray deposited extruded and peak aged (T6 temper) SS70, N707 and 7075 alloys.

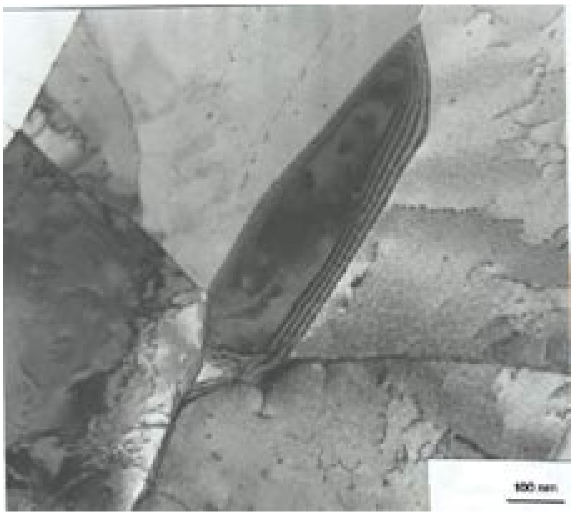

Figure 6. Bright field TEM micrograph showing the general microstructure of the SS70 alloy in the solution heat treated condition (470°C for 0.5 h).

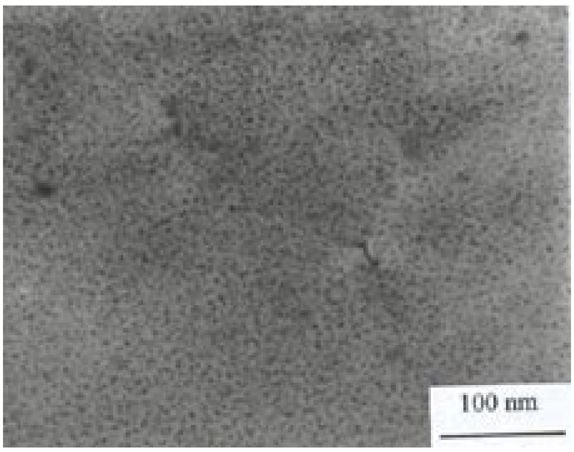

Figure 7. Bright field TEM micrograph of SS70 in the T6 temper.

Table 2. Average room temperature tensile test results of SS70, N707 an 7075 in the T6 condition.

Alloy	Temper	Orientation	σ_{YS} (MPa)	σ_{UTS} (MPa)	Elong. (%)
SS70	T6	L	755	803	5
N707	T6	L	711	740	5
		T	635	673	5
7075	T6	L	590	656	11
		T	524	588	8

Table 3. Average room temperature notch tensile strength results of SS70, N707 and 7075 in the T6 condition.

Alloy	Temper	Orientation	σ_{YS} (MPa)	σ_N (MPa)	σ_N/σ_{YS}	K_{IC} MPa $m^{1/2}$
SS70	T6	L	755	666	0.88	19.6 ± 3.5
N707	T6	L	711	674	0.94	21.2 ± 3.8
		T	635	314	0.5	16.9 ± 3.0
7075	T6	L	590	687	1.16	25.5 ± 4.6
		T	524	560	1.07	23.2 ± 4.2

Table 2 shows the results of the room temperature tensile testing of unnotched specimens. These results indicate that the 0.2% yield strength value for the SS70 is the highest of the three alloys (Figure 5). This is attributed to the fact that this alloy contains the highest concentration of Zn. The N707 alloy, which has a marginally lower Zn content, showed a slightly lower 0.2% yield strength. Finally, the 7075 alloy, with the lowest Zn content, showed a markedly reduced 0.2% yield strength. On the basis of these results, it may be concluded that a higher Zn content increases the strength values of these 7xxx series alloys. This behaviour may be attributed to the fact that increasing the amount of Zn present in the alloys causes an increase in the volume fraction of η' and η precipitates which lead to an improvement in strength. Predictably, alloy ductility, measured by the elongation to fracture, showed the opposite trend, increasing from 5% for SS70 and N707 to 11% for 7075 (Figure 5).

Table 3 shows the results of room temperature notch tensile strength tests of SS70, N707 and 7075. As expected, the 7075, which has the lowest strength, has the highest fracture toughness ($K_{IC} = 25.5 \pm 4.6$ MPa $m^{1/2}$), while SS70, which has the highest strength, has the lowest fracture toughness value of 19.6 ± 3.5 MPa $m^{1/2}$ (Figure 5). On the basis of these results, it may be concluded that as the alloy strength is increased the fracture toughness decreases. Controlling the amount of coarse intermetallic particles and reducing the width of precipitation-free zones (PFZs) which form near grain boundaries depleted of precipitates should lead to an improvement in fracture toughness. The high volume fraction of coarse intermetallic particles increases the probability of the easy initiation of cracks from the particle-matrix boundaries. These coarse particles form during solidification due to low cooling rates and high concentration of transition elements. A reduction in the amount of these elements would decrease the volume fraction of these particles. Therefore, the solubilities of these elements should not be exceeded since all excesses form coarse precipitates. It may be possible to obtain increased toughness by reducing the grain size by controlling composition (e.g. to increase the fine dispersoid concentration) or processing parameters, such as gas atomization pressure, gas to metal mass flow ratios, and amount of hot work before the finishing operation.

A comparison between the mechanical properties of spray deposited 7xxx series aluminium alloys and those reported by other investigators for PM processed and IM processed 7xxx series alloys (Sanctis, 1991; Lengsfeld *et al.*, 1995; Machler *et al.*, 1991; Aluisse-Lonza, 1990; White *et al.*, 1993; Faure and Dubost, 1990; Lavernia *et al.*, 1986; Metals Handbook, 1979) is shown in Table 4 and Figure 8. Table 5 shows the chemical composition of the materials presented in Table 4. As can be clearly seen from Figure 8, the spray deposited 7xxx series aluminium alloys show a very high strength as compared to conventionally IM processed 7xxx series aluminium alloys. Compared with the PM processed 7xxx series aluminium alloys, fracture toughness values for spray

Table 4. Comparison between the room temperature mechanical properties of spray deposited and extruded 7xxx aluminium alloys and conventionally and powder metallurgy processed 7xxx series aluminium alloys.

Alloy	Process	σ_{YS} (MPa)	σ_{UTS} (MPa)	Elong. (%)	K_{IC} (MPa $m^{1/2}$)	Reference
SS70-T6	Spray Cast-L	755	803	5.0	19.6 ± 3.5	This work
N707-T6		711	740	5.0	21.2 ± 3.8	
E1-C-T6	Osprey	790	810	4.9	17.0	Sanctis
E1-PM-T6	P/M	716	735	1.9	13.0	
7150X-T6	Spray Cast	776.5	808.9	14.1	12.7	Lengsfeld *et al.*
7xxx-T6	Osprey	705	719	16	38.2	Machler *et al.*
N707-T6	Spray Cast	760	775	8.0	37.0	Alusuisse-Lonza
SS71-T6	Spray Cast	688	705	13	33.0	White *et al.*
High solute 7xxx-T6	Spray Cast-L	790	805	9.0	20.0	Faure and Dubost
	P/M-(L)	773	773	2.8	7.30	
7075-T6	Spray Cast-L	590	656	11	25.5 ± 4.6	This work
7075-T6	I/M	500	570	11	30.8	Metals Handbook
X7091-T6	P/M	586	614	12	38.0	Lavernia *et al.*
7475-T651	I/M	496	552	12	42.9	Metals Handbook

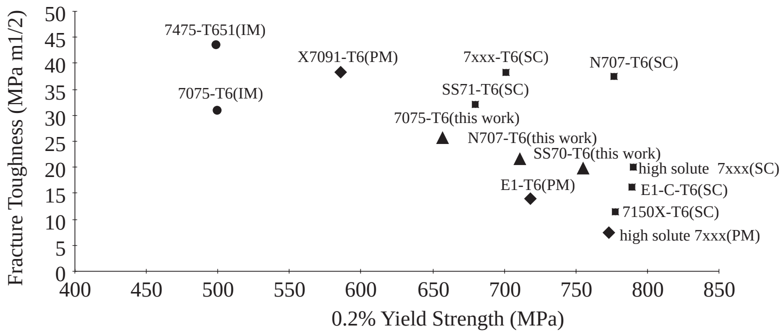

Figure 8. Fracture toughness against 0.2% yield strength in the aged 7xxx series aluminium alloys processed by spray casting, powder metallurgy and conventional ingot metallurgy 7xxx series aluminium alloys.

deposited 7xxx series aluminium alloys are higher. A reasonable explanation for this behaviour would be the higher gas contents (mainly O_2 and H_2) of the PM products; see Table 6 (Sanctis, 1991).

Figure 8 shows that the fracture toughness of the spray deposited high solute 7xxx alloy (K_{IC}= 20 MPa $m^{1/2}$) is remarkably higher than a PM processed high solute 7xxx alloy (K_{IC}= 7.3 MPa $m^{1/2}$). The spray deposited high solute 7xxx alloy also exhibited improvements in elongation (from 2.8% to 9%) over the PM processed high solute 7xxx alloy (Faure and Dubost, 1990).

As can also be seen from Figure 8, the room temperature strength of spray deposited and peak aged (T6) SS70, N707 and 7075 alloys studied in this work is superior to that of commercial 7xxx series aluminium alloys, such as 7075 and 7475, which are commonly used as high-strength alloys in aircraft structures. In spite of achieving excellent strength values, the values of elongation and toughness in peak aged SS70 and N707 were relatively low. However, the elongation and K_{IC} values are considered acceptable for high performance applications.

Figure 8 also shows that the strength values of the spray deposited 7075 alloy [σ_{UTS} = 656 MPa, σ_{YS} = 590 MPa] studied in this work are higher than those of the equivalent 7075 alloy produced by conventional metallurgy [σ_{UTS} = 570 MPa, σ_{YS} = 500 MPa] (Metals Handbook, 1979). Although the conventionally processed 7075 alloy has slightly higher

Table 5. Chemical composition of 7xxx aluminium alloys presented in Table 4 (weight percent).

Alloy	Zn	Mg	Cu	Zr	Fe	Si	Cr	Mn	Al
7150X	12.4	1.94	1.95	0.10	0.09	0.04	-	-	Bal.
7xxx	11.0	2.00	1.00	0.30	< 0.2		-	-	Bal
N707	11.4	2.50	1.20	0.30	-	-	-	-	Bal.
SS71	10.0	2.00	1.00	0.20	-	-	-	-	Bal.
SS70	11.5	2.64	1.16	0.26	0.05	0.02	<.01		Bal.
N707	10.9	2.16	1.01	0.22	0.03	0.01	<.01		Bal.
7075	5.60	2.50	1.60	-	0.30	0.10	0.20	0.30	Bal.
7475	5.70	2.30	1.50	-	<0.05	<0.03	0.22	0.06	Bal.
X7091*	5.80-7.10	2-3	1.1-1.8	0.2-0.6	-	-	-	-	Bal.

* Amount (wt.%) of Co: 0.2-0.6

Table 6. Gas contents for PM billets (after degassing) and SD preforms [after Sanctis (1991)].

Material	Oxygen content (μg/g)	Hydrogen content (μg/g)
SD preforms	50-200	0.1-0.2
PM billets	1000-3000	1-4

fracture toughness than the spray deposited 7075 alloy, the elongation to fracture, at 11%, is identical for the two processing routes.

The SS70 and N707 alloys studied in this work had a lower 0.2% yield strength than that of E1-C, 7150x and N707 (Alusuisse-Lonza, 1990) but higher than that of the 7xxx alloy of Machler *et al.* and SS71 (Figure 8). The fracture toughness and elongation of SS70 are comparable with that of the E1-C and 7150x alloys but lower than that of the 7xxx alloy of Machler *et al.* and SS71.

Conclusions

1. Spray deposited and extruded SS70, N707 and 7075 alloys, in the peak aged (T6) condition gave yield strength values of 755, 711 and 590 MPa with corresponding elongations to fracture of 5, 5 and 11% respectively. Of the three alloys SS70, which has the highest Zn content, showed the highest strength values. This may be attributed to the increase in the volume fraction of η' and η precipitates.

2. The spray deposited and extruded SS70, N707 and 7075 alloys exhibited excellent strength characteristics with an acceptable ductility level (σ_{YS} = 755 MPa, elongation = 5%; σ_{YS} = 711 MPa, elongation = 5%; σ_{YS} = 590 MPa, elongation = 11%,) compared to many I/M processed 7xxx series aluminium alloys, such as 7075 and 7475, which are commonly used as high-strength alloys in aerospace applications.

3. The spray deposited and extruded SS70, N707 and 7075 alloys had higher fracture toughness values compared to P/M processed 7xxx series aluminium alloys. A reasonable explanation for this behaviour would be the higher gas content (mainly O_2 and H_2) of the PM products.

References

Alusuisse-Lonza Services Ltd Research and Development, N707, June 1990.

ASM Handbook, "Metallography and Microstructures", 9, 9. Edition, 123-126, 1992.

ASTM Standard E 602-91, "Standard Test Method for Sharp-Notch Tension Testing with Cylindrical Specimens".

British Standard BSEN 1990, 10002-1: "Tensile Testing of Metallic Materials, Part 1. Method of Test at Ambient Temperature".

Duan, X., Hao, Y., Yoshida, M., Ando, T., Grant, N.J., "Liquid Dynamic Compaction of Aluminium Alloy 7150", The Int. Jour. Pow. Metall., 29 (2), 149-160, 1993.

Faure, J.F. and Dubost, B., “Analysis of the Spray-Deposited Process as an Approach to Develop Advanced Aluminium Alloys”, Proc. Int. Conf. Advanced Aluminium and Magnesium Alloys, Ohio, 307-315, 1990.

Kaufman, J.G., “Fracture Toughness Testing”, in Application of Fracture Mechanic to Design, Plenum Press, Burke, J.J. and Weiss, V., eds., 36-38, 1979.

Lavernia, E.J., Rai, G. and Grant, N.J., “Rapid Solidification Processing of 7xxx Aluminium Alloys: A Review”, Materials Sci. and Eng., 79, 211-221, 1986.

Lengsfeld, P., Juarez-Islas, J.A., Cassada, W.A., Lavernia, E.J., “Microstructure and Mechanical Behavior of Spray Deposited Zn Modified 7xxx Series Al Alloys”, Int. Jour. of Rapid Solidification, 8, 237-265, 1995.

Machler, R. Uggowitzer, P.J., Solenthaler, C., Pedrazzoli, R.M., Spiedel, M.O., “Structure, Mechanical Properties, and Stress Corrosion Behaviour of High Strength Spray Deposited 7000 Series Aluminium Alloy”, Mater. Sci. Tech., 7, 447-451, 1991.

Metals Handbook, “Properties and Selection: Nonferrous Alloys and Pure Metals”, 2, 9. Edition, 123-139, 1979.

Sanctis, M.D., “Structure and Properties of Rapidly Solidified Ultrahigh Strength Al-Zn-Mg-Cu Alloys Produced by Spray Deposition”, Mater. Sci. Eng., A141, 103-121, 1991.

Salamcı, E., “Ageing Behaviour of Spray Cast Al-Zn-Mg-Cu Alloys”, Turk J. of Engin. & Environ. Sci., 25(6), 681-686, 2001.

Singer, A.R.E., “The Principles of Spray Rolling of Metals”, Met. & Mat., 4, 246-250, 257, 1970.

Singer, A.R.E., “Aluminium and Aluminium Alloy Strip Produced by Spray Deposition and Rolling”, J. Inst. Metals, 100, 185-190, 1972.

Vander Voort, G.F., “Metallography Principles and Practice”, McGraw-Hill, 423-435, 1984.

White, J., Mingard, K., Hughes, I.R., Palmer, I.G., “Aluminium Alloys with Unique Property Combinations by Spray Casting”, Pow. Metall., 37 (2), 129-132, 1994.