[00119] Table 6: Evaluation results of the mechanical properties of the additively manufactured products (B1~B5)

No.	Ultimate Tensile Strength (MPa)		Yield Strength (MPa)		Elongation (%)	
	X-Y	Z	X-Y	Z	X-Y	Z
B1	107	-	-	-	0.69	-
B2	317	-	270	-	23.9	-
B3	292	281	279	255	14.8	11.4
B4	302	287	299	269	11.2	10.8
B5	344	327	246	318	6.0	10.1

[00120] Table 7: The mechanical properties of conventional Al6061 material (standard material)

No.	Ultimate Tensile Strength(MPa)	Yield Strength(MPa)	Elongation(%)
Reference ASTM Al6061-0	150	85	16
Reference ASTM Al6061-T4	205	110	16
Reference ASTM Al60601-T6	290	240	10

[00121] Table 8: Crack evaluation and porosity of the additively manufactured products (B1~B5)

No.	B1	B2	B3	B4	B5
Cracking (Yes/No)	Yes (FIG. 17)	No (FIG. 18)	No (FIG. 19)	No (FIG. 20)	No (FIG. 21)
Porosity (%)	2.13	**0.05**	0.06	0.03	0.01

[00122] From the results and comparison shown in Table 6 above, it can be seen that the additively manufactured products B2~B4 exhibited excellent mechanical properties for tensile strength, yield strength and elongation. In comparison, as shown in the additively manufactured product B1 (whose microscopy image is illustrated in FIG. 17), the mechanical properties were inferior, and crack was observed in the manufactured product. The reason for this was that B1 uses a powder composition P1, which includes Sc/Zr in amounts outside the scope of the present disclosure (Sc: 0.46~0.80 mass%; Zr: 0.15~0.4 mass%). Furthermore, as shown in the additively manufactured product B5 (whose microscopy image is illustrated in FIG. 21), when Sc/Zr are included in amounts higher than the scope of the present disclosure, although the tensile strength is high, the yield strength and elongation will also be lowered as compared to the additively

manufactured products B2~B4 (including composition within the scope of the present disclosure).

[00123] In addition, by further comparison with the mechanical properties of conventional A6061 material shown in Table 7, it can be seen that the mechanical properties of the additively manufactured products B2~B4 are further improved as compared to the conventional materials. Moreover, as shown in Table 8, it can be seen that the porosity of the additively manufactured products B2~B5 are further lowered as compared with the additively manufactured product B1. The additively manufactured products B2~B4 are also shown to be crack-free (see FIGs. 18-20).

[00124] The reasons for the crack-free is due to the formation of the ultrafine grains in the melt pool boundaries, which interferes with the epitaxial growth of the long columnar grains in the alloys without the additional modification, decreasing the crack sensitivity. Further evaluation of the microstructures, and the effects of performing heat treatments was evaluated by using the aluminum alloy powder P2 as an example.

[00125] By using the aluminum alloy powder P2 as the raw material (composition including elements within the claimed range), the microstructures of the as-built additively manufactured product (without further heat treatment) are further evaluated and shown in FIG. 22 and FIG. 23. The two examples demonstrate distinct ultrafine grain fractions, which corresponding to a relatively low energy density (FIG. 22) and a relatively high energy density (FIG. 23). The ultrafine grain size is less than 1 μm.

[00126] The microhardness of the samples demonstrated in FIG. 22 and FIG. 23 are 84-103 $HV_{0.1}$. The tensile properties of the samples demonstrated in FIG. 22 and FIG. 23 are listed in Table 9.

[00127] Table 9: Tensile properties of the as-built (additive manufactured) samples.

Sample	Yield strength (MPa)	Ultimate tensile strength (UTS) (MPa)	Total elongation (%)
Example E1	265-270	316-318	23-25
Example E2	294-310	322-334	20-22

[00128] The strengthening contribution for the as-built samples comes from the grain boundaries the most. The precipitates will provide one of the major parts for the strength of aluminum alloys. Therefore, precipitate manipulation is important for controlling the properties. The manipulation of the precipitates is realized by the heat treatment control. There are two ways to program the heat treatment for this alloy, which includes DA and STA as mentioned above.

[00129] (1) Relying on the precipitates which consist of additional elements, i.e., Sc and Zr, the precipitate will be $Al_3(Sc,Zr)$. To achieve this, moderate temperature (250 to 450 °C) needs to be

applied. The duration can change from 5 mins to 100 h, depending on the original microstructure and which properties are needed. This method is referred as direct aging (DA).

[00130] (2) Relying on the precipitate which consist of original elements, i.e., Mg and Si, the precipitate will be Mg_xSi_y. To achieve this, the solution treatment needs to be applied first. The solution treatment is performed at high temperature (460 to 550 °C) for 5 mins to 10 h. After holding, the parts will be water quenching. After solution treatment, the parts will be subjected to aging treatment, which will be performed at low temperature (140 to 220 °C) for 30 mins to 100 h. This method is referred as solution + aging treatment (STA).

[00131] When DA is conducted on the sample of example E2, the DA is being held at 400 °C for 1 h (referred as example E3), the TEM results in FIG. 24 show the coherent secondary $Al_3(Sc,Zr)$ as the strengthen phase in the samples. When STA is conducted on the sample of example 2, the STA is being held at 550 °C for 0.5 h, water quenched, and then being held at 175 °C for 8 h (referred as example E4), the TEM results in FIG. 25 show the needle-liked precipitates nucleate in the samples. These needle-liked precipitates are Mg_xSi_y.

[00132] The microhardness of the DA samples depends on the temperature and duration. The highest microhardness can be larger than 120 $HV_{0.1}$. The microhardness of the STA samples depends on the temperature and duration. Example E4 shows a microhardness of ~110 $HV_{0.1}$.

[00133] The tensile property examples of the heat-treated samples are listed in Table 10 below. Besides example E3 and example E4, the following examples are also included for comparison:

[00134] Example E5: sample with the microstructure shown in Example E1 – Direct aging at 400 °C for 1 h.

[00135] Example E6: sample with the microstructure shown in Example E1 – Solution treated at 520 °C for 0.5 h, water quenched, and then being held at 175 °C for 8 h.

[00136] Table 10: Tensile properties of the heat-treated samples.

Sample	Yield strength (MPa)	Ultimate tensile strength (UTS) (MPa)	Total elongation (%)
Example E3 (DA)	348-378	358-391	8-12
Example E4 (STA)	288-300	334-344	13-17
Example E5 (DA)	321-327	345-351	17-23
Example E6 (STA)	331-335	373-377	13-15

[00137] By comparing the microstructures and tensile properties shown in Table 10 above, the strengthening mechanism for the heat-treated samples depend on the contribution from both the grain-boundary strengthening and the precipitate strengthening. For DA samples, coherent secondary $Al_3(Sc,Zr)$ precipitates are the main contributors. For STA samples, coherent $Al_3(Sc,Zr)$

and needle-liked precipitates are the main contributors.

[00138] Based on the examples above, for the as-built additively manufactured product (without further heat treatment) using the LPBF process, the bi-modal grain size distribution with ultrafine grains with the size less than 1 μm and possible columnar grains with the size larger than 1 μm can be obtained, and microhardness of 84 $HV_{0.1}$ or higher can be achieved. Furthermore, when the designated amounts of aluminum, magnesium, copper, chromium, silicon, scandium, and zirconium are included in the aluminum alloy powder P2, which is used as a raw material for manufacturing the additively manufactured product, the obtained product will be crack-free, the yield strength and ultimate tensile strength will be 250 MPa or higher, and the elongation will be 16% or higher.

[00139] For the DA treated samples, nanosized $Al_3(Sc, Zr)$ precipitates are observed with a transmission electron microscopy, which are the main strengthening precipitates in this state, and the ultrafine grains are maintained to be 1 μm or less. Similarly, for DA treated samples, the yield strength and ultimate tensile strength will be 300 MPa or higher, and the elongation will be 3% or higher. For STA treated samples, nanosized $Al_3(Sc, Zr)$ precipitates and needle-liked precipitates are observed with the transmission electron microscopy, which are the main strengthening precipitates in this state, and the grain size ranges from 100 nm to 200 μm. Similarly, for STA treated samples, the yield strength is 270 MPa or higher, while the ultimate tensile strength is 330 MPa or higher.

Industrial Applicability:

[00140] The alloy powders (Al6xxx and Al7xxx) and laminated molded product (additive manufactured product) of the present disclosure can be used in different engineering applications, ranging from aerospace, automobile and semiconductor to marine and defense industries.