24th EUROPEAN ROTORCRAFT FORUM

Marseilles, France. 15th - 17th September 1998

REFERENCE : SM04

TITLE : The EH101 - An aluminium-lithium helicopter

AUTHOR : Dr. Alan F Smith
GKN Westland Helicopters Ltd.,
Yeovil, Somerset, England. BA20 2YB

The first full-scale production and industrial use of aluminium-lithium based alloys occurred in the early 1960's when the enhanced stiffness and compressive strength of alloy AA2020, rather than reduced density, led to its incorporation in the RA-5C Vigilante high performance, Mach 2, attack and reconnaissance aircraft. Whilst this aircraft was in active operational service with the US Navy for over twenty years, the potential use of alloy AA2020 in other projects at that time did not materialize and it was not until the late 1970's that the aerospace industry's interest in aluminium-lithium technology was re-activated. This time, however, it was primarily the potential for reduced density which was the initial attraction. One of the first of these new "reduced density" alloys to reach full commercial status emerged in the early 1980's and was subsequently registered as alloy AA8090. The widest application to date is as a route to significant structural weight reduction on the Anglo-Italian EH101 helicopter.

This paper briefly charts the history of aluminium-lithium based alloys, in order to answer the question as to why such alloys have apparently taken so long to reach full commercial status, whereas other aluminium alloys have been available and used in the aerospace industry for some seventy years or so. The specific and pioneering use of aluminium-lithium alloy AA8090 on the EH101 helicopter will be discussed and finally, some areas will be indicated where it is perceived that further research and development may lead to industrially exploitable technologies.

1. BACKGROUND

Lithium has always been of interest to research metallurgists since it is one of only eight elements whose solid solubilities in aluminium exceed 1 atomic percent, thereby offering the possibility that useful engineering alloys could be developed. The first two decades of the twentieth century saw significant interest in adding lithium to aluminium, but the development of wide scale industrially exploitable alloys was relatively unsuccessful. This was essentially due to incomplete understanding of the physical metallurgy of aluminium-lithium based alloys, particularly hampered by the lack of high resolution electron microscopy and microstructural techniques available today. Alloys were made which contained only lithium as the major alloying element but these were brittle and of relatively low strength. Other attempts consisted of adding small amounts of lithium to alloys containing higher levels of other soluble elements such as copper and zinc but, again, the resultant properties were generally inferior to other aluminium alloys and particularly the aluminium-copper based compositions being developed in the late 1920's and 1930's. It was not until the 1940's when workers at the then ALUMINIUM COMPANY of AMERICA (now

ALCOA) discovered that certain combinations of copper and lithium in aluminium resulted in alloys which could be heat treated to produce industrially useful strength levels. Further property enhancements could be achieved by the additional incorporation of relatively low levels of other elements. Unfortunately for these alloys, history partially repeated itself whereby, as with aluminium-copper in the 1920's/1930's, these new aluminium-lithium developments were overshadowed by the superior properties being exhibited by the newly emergent aluminium-zinc- magnesium alloys of the mid 1940's.

Industrial interest in aluminium-lithium alloys was renewed yet again, in the mid-late 1950's when workers at ALCOA realised that lithium additions in excess of approximately one weight percent resulted in typically 8 - 10% increase in stiffness. This, together with the potential for high strength in the additional presence of copper, prompted ALCOA to renew their efforts to develop industrially viable alloys of this type, this culminated in 1957 with the announcement of alloy AA2020 of nominal composition Al-4.5Cu-1.1Li-0.5Mg-0.2Cd. With a particular application in mind, this alloy composition was optimized to exhibit maximum compressive strength and stiffness. ALCOA spent the following few years implementing the full production plant and developed the optimum processing parameters to enable AA2020 sheet and plate to be manufactured to established aerospace standards. This led to considerable interest from the aerospace industry, particularly when further evaluation found that alloy AA2020 did not exhibit the widespread exfoliation and stress corrosion cracking problems being experienced with other high strength aluminium alloys at that time. Furthermore, compared to those other aluminium alloys whose perceived superior mechanical properties had earlier prevented it's commercialisation, it became apparent that alloy AA2020 retained a higher proportion of its strength at the elevated temperatures being induced by aerodynamic heating. Since interest was growing in faster aircraft of Mach. 2.5 and above, this finding was of major importance. Thus, after all the setbacks of the previous few decades, it appeared that aluminium-lithium had finally reached full commercial status and had found a very important niche in the aerospace industry.

Following extensive evaluation, alloy AA2020 plate replaced that of AA7075-T651 in the North American Aviation RA-5C Vigilante, a high performance, Mach 2 aircraft designed for both attack and reconnaissance. From 1958, a total of 177 aircraft were constructed with AA2020 on the upper and lower wing skins and horizontal stabiliser, leading to a weight saving of 73Kg compared to the use of alloy AA7075-T651 as specified on the original design. Design and construction procedures were modified to address AA2020's deficiencies of notch sensitivity, low toughness and low ductility which were identified at an early stage of it's development. These aircraft have now seen more than 25 years active and operational service with the US Navy without any major problems associated with the alloy AA2020.

A number of major programmes subsequent to the Vigilante, evaluated alloy AA2020, but the above deficiencies led to difficulties in meeting the increasing damage tolerant requirements of airframe design imposed by several countries' airworthiness authorities. Insufficient demand for AA2020 eventually led to ALCOA's decision to cease production in the late 1960's. The overriding need in the early 1970's to resolve the stress corrosion cracking and, to a lesser extent, fracture toughness problems of the widely used Al-Zn-Mg-Cu (AA 7XXX) series alloys took precedence at ALCOA. Accordingly minimal effort was devoted to improving the damage tolerant properties of alloy AA2020.

In parallel with the above, it is believed that independent developments have taken place in the then USSR for many years and that extensive use has been made of aluminium-lithium alloys in both fixed and rotary wing aircraft. However, as far as is known, the approach has differed to a degree, with aircraft design and particularly welded structures having been tailored to the use of low strength, aluminium-magnesium-lithium alloys whose compositions and properties have not, to date, received much attention in the West.

Interest in aluminium-lithium alloys was re-awakened yet again in the early 1970's although it was the potential weight saving which was the primary attraction. This emanated from a) significant and perceived permanent increases in oil prices, which prompted civil aircraft manufacturers and operators to place greater emphasis upon seeking structural weight reductions and b) the increasing popularity and use of lightweight organic based composite materials had begun to make serious inroads into the traditional aerospace markets of a number of major aluminium alloy manufacturers. In order to avoid the deficiencies which led to the demise of alloy AA2020, the initial belief was that compositions would be needed which could only realistically be made by rapid solidification/powder metallurgy techniques and this route was actively pursued, particularly in the USA.

Meanwhile, advances in the fundamental understanding of sub-microscopic strengthening mechanisms in aluminium-lithium alloys were made, particularly in the UK and France, which led workers in these countries to believe that aluminium-lithium compositions to give properties superior to AA2020 could be developed, but which were still amenable to manufacture by the "ingot metallurgy" route, widely used for aluminium alloys including AA2020. Work carried out independently at the Defence and Evaluation Research Agency (DERA), formerly the Royal Aerospace Establishment (RAE) at Farnborough, UK and Cégédur Péchiney, Voreppe, France eventually led to registration of an Al-Li-Cu-Mg-Zn alloy designated AA8090. The RAE licenced British Alcan at that time to commercially manufacture this alloy, whilst Péchiney also produced it independently. In subsequent years, both companies developed further aluminium-lithium alloys, with AA8091 coming from British Alcan whilst Péchiney produced AA2091 and CP276. Meanwhile, a number of US aluminium producers also reverted to use of the "ingot metallurgy" route for aluminium-lithium manufacture and the alloy AA2090 was developed by ALCOA. Of all the above alloys, only AA8090 survives to this day.

2. CURRENT COMMERCIAL ALUMINIUM LITHIUM ALLOYS

The amount of lithium in the AA8090 composition is such that density is reduced by approximately 10% with a similar percentage increase in stiffness, compared to other aluminium aerospace alloys. As such, AA8090 may be described primarily as a "reduced density" alloy, as were the now-defunct AA8091, AA2090, AA2091 and CP276 alloys described above. The work of recent years has shown, however, that lithium additions can also enhance certain other properties, depending upon alloy compositions, and this has led to the development and commercialisation of several further alloys in which density reductions are slightly less and of secondary importance. Table 1 details all aluminium-lithium alloys currently commercially available in the West.

The greatest use of aluminium lithium to date is that of alloy AA2195, used in the construction of the external fuel tanks for the US Space Shuttle. In order to impart the ultra high strength, enhanced cryogenic properties (particularly fracture toughness) and weldability, the copper-lithium ratio is such that the resultant density reduction is slightly lower than alloy AA8090. Nevertheless, replacement of AA2219 plate by AA2195 has resulted in an approximate 3600 Kg weight saving per fuel tank. The second widest use of aluminium-lithium is in Europe, where AA8090 is used extensively to provide structural weight savings on the EH101 helicopter, designed and manufactured jointly by GKN Westland Helicopters of the UK and Agusta S.P.A. of Italy. Thirdly, alloy AA8090 sheet is also used for a non-structural application on the Boeing 777 aircraft. Further aluminium-lithium programmes are also currently in progress.

3. USE OF ALLOY AA8090 ON THE EH101 HELICOPTER

The initial design of the EH101 took place in the early 1980's and, since this pre-dated the full commercialisation of the post - AA2020 generation of aluminium-lithium alloys, was based upon 'conventional' Al-Cu-Mg, Al-Zn-Mg-Cu and Al-Si-Mg alloys. During the prototype stage, the decision was made to introduce alloy AA8090 as this became commercially available in the late 1980's. Full EH101 productionisation commenced in 1995 when the first order for 44 aircraft was received from the Royal Navy and it is on these and future EH101's that full use of aluminium-lithium is and will be made, accounting for over 90% of all aluminium alloys used in construction of the airframe. Table 2 summarises the AA8090 tempers and product forms used on the EH101 and indicates the corresponding 'conventional' alloy specified in the original design. A major proportion of the weight saving on the aircraft derives directly from the reduced density of alloy AA8090 (9 - 10%) whilst a further contribution (2 - 3%) is provided by exploitation of the increased elastic modulus of this alloy. In order to retain the optimised vibration characteristics of the original design, numerous components have been reduced in gauge, hence reduced weight, to maintain equivalence of elastic modulus: Strength has been adjusted by selection of appropriate artificial ageing parameters. Table 3 indicates areas and types of application of alloy AA8090 on the EH101. A major contribution to the weight saving is provided by AA8090 die forgings of which the entire main cabin frame is constructed, Figures 1 and 2.

3.1 Advantages of alloy AA8090

In addition to the reduced density and increased elastic modulus, the use of aluminium-lithium alloy AA8090 has the following advantages compared to "conventional" aluminium alloys:

a) Significantly lower fatigue crack growth rate, hence improved fatigue life.

b) Due to the formation of submicroscopic strengthening precipitates during natural ageing, "conventional" aluminium alloy sheet such as AA2024 and AA2014A generally requires solution heat treatment within 2 hours prior to forming if adequate cold formability is to be achieved. Alternatively, the sheet may be supplied in the annealed condition with solution heat treatment applied to the formed part, but with possible distortion and grain growth problems. In contrast, natural ageing effects are essentially absent in solution heat treated and stretched AA8090 sheet. For all but the most complex of components, this facilitates cold forming in the as-supplied T3 temper without the need for re-solution heat treatment, thereby conferring clear advantages for costs, production planning and logistics.

c) Although technically possible, the superior corrosion resistance of AA8090 precludes the need to clad this alloy.

d) AA8090 combines the high strength of "conventional" aluminium alloys such as AA2014A and the weldability of low strength aluminium-silicon-magnesium alloys such as AA6082.

e) Partially because of the higher processing temperature which AA8090 can withstand, extrudability is significantly enhanced compared to "conventional" aluminium alloys of similar strength, such as AA7075. A number of complex one piece extrusions such as hollow seat tracks and floor beams are used on the EH101 and further weight reductions are achieved since these would not be possible in AA7075; this alloy would have required adhesively bonding together several constituent sections.

f) Alloy AA8090 sheet can be superplastically formed, thereby offering the possibility of manufacture of complex shapes. Special

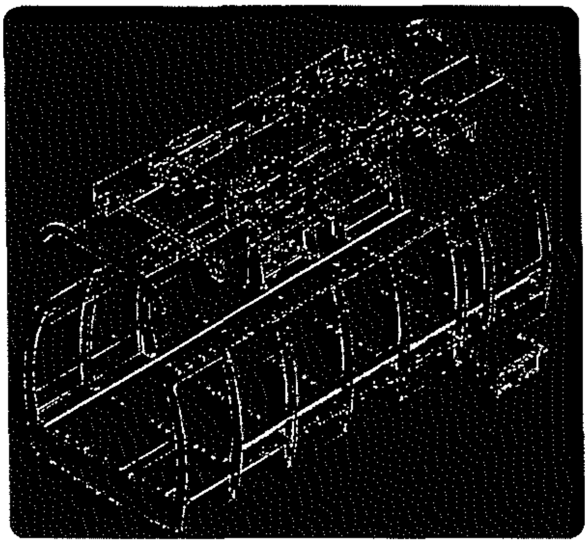

Figure 1. Schematic diagram showing the EH101 main lift frame components which are machined from AA8090 cold compressed die forgings.

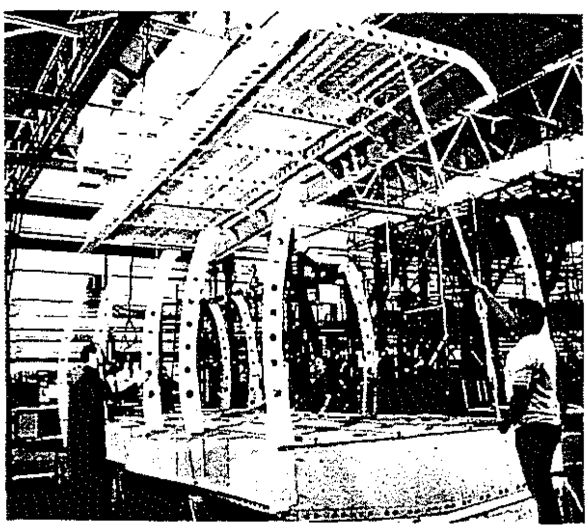

Figure 2. Assembly of EH101 main cabin showing frames machined from AA8090 cold compressed die forgings.

processing of the sheet is required if this characteristic is to be optimised.

h) The electrical conductivity of alloy AA8090 is approximately half that of "conventional" aluminium alloys, thereby providing a convenient means of differentiation if alloys become inadvertently mixed.

3.2 Disadvantages of alloy AA8090

Whilst the positive aspects of alloy AA8090 are such that extensive use is made on the EH101, there nevertheless are some disadvantages which should be noted:

a) The attainment of 'medium' and 'high' strength levels is critically dependent upon the application of a degree of post-solution heat treatment cold work. This arises because the presence of lithium inhibits the nucleation of sub-microscopic strengthening precipitates during artificial ageing but this can be overcome by cold work-induced dislocation networks. Cold working may be readily applied to sheet, plate and extrusions by stretching, although in most cases this can only be carried out by the metal manufacturer. Whilst this is not usually problematic for plate and extrusions which are frequently supplied in the fully heat treated condition, it does have the implication that if any re-solution heat treatment is necessitated for the forming of a complex part in sheet, then it will usually be impossible to uniformly apply the post-solution heat treatment cold work, necessary to achieve 'medium' and 'high' strength levels upon subsequent artificial ageing. This drawback is partially countered by the minimal or absent natural ageing effects in AA8090, as discussed earlier, such that all but the most complex of components can generally be made by cold forming sheet in the stretched (T3) condition. Minor manipulation of extrusions, such as joggling, is also possible in the T3510/T3511 tempers.

   In the case of forgings, post-solution heat treatment cold work can be introduced by cold compression, but this will only be effective if adequate plastic deformation occurs in order to shear the metal relatively freely without undue constraint by adjacent regions in the components. These requirements place limits on the configuration and section size of die forgings which can be effectively cold compressed. (Triaxial compression techniques such as HIPing would not achieve the desired effect since metal shearing does not occur). Whilst the configuration of the forgings for the EH101 cabin frame are such that special cold compression dies can impart sufficient cold deformation, (albeit with increased tooling costs), components of a more 'bulky' nature such as undercarriage cylinders would not respond to the same degree and therefore remain in the heavier 'conventional' alloy (AA7010-T74).

b) Metallic lithium is an inherently costly material and inevitably the price of the final aluminium-lithium alloy is significantly higher than that of 'conventional' aluminium alloys. However, although often difficult to quantify, this can be partially offset against both the design and manufacturing advantages of the alloy. Furthermore, it should be remembered that material cost is frequently only a fraction of that of the completed component when the cost of manufacture is accounted for.

c) It is necessary to segregate aluminium-lithium scrap from that of 'conventional' aluminium alloys. This arises from the fact that mixed aluminium alloy scrap is generally reprocessed by a secondary aluminium smelter to produce relatively pure aluminium ingots, which are generally used in the non-aerospace foundry industry. Most impurities and particularly lithium are removed during melting and filtration, with the remaining low levels generally having no discernable effect upon properties. However, it has been shown that even very low levels of residual lithium can lead to significant deterioration in the castability of the aluminium-silicon-magnesium alloys widely used for general engineering applications.

4. SPECIFICATIONS

To date, all AA8090 used on the EH101 has been covered by 'in-house' joint GKN Westland-Agusta specifications. However, a number of AA8090 material standards are currently under preparation under the auspices of the European CEN-AECMA standardization system, as summarized in Table 4.

5. FUTURE ALUMINIUM-LITHIUM DEVELOPMENTS

Some perceived future developments which would appear to be potentially exploitable for aerospace applications are as follows:

i) Development of an aluminium-lithium based shape casting alloy: Due primarily to concerns over corrosion of magnesium alloys, all shape castings on the EH101 consist of the aluminium-silicon-magnesium alloy A356. Weight savings could be achieved if use could be made of reduced density aluminium-lithium based castings which, as far as is known, are not commercially available. Particular problems which would need to be resolved would be the propensity of liquid aluminium-lithium to aggressively attack all conventional sand/investment mould materials, as well as being very prone to hydrogen pick-up from the atmosphere, resulting in gross porosity. The DC (Direct Chill) casting route for making ingots for fabrication to wrought products effectively address these issues, but a different system would be needed for pouring into sand/investment moulds. Additionally, alloy compositions specifically amenable to shape casting would need to be developed.

ii) The development of new wrought aluminium-lithium alloys which do not require post-solution treatment cold work: As previously mentioned, the attainment of adequate strength levels in alloy AA8090 is critically dependent upon cold work. This is problematic for die forgings of certain configurations as well as for sheet to be formed into complex shapes. Development of an alloy in which no cold work is necessary would extend the application of aluminium-lithium, particularly into the area of undercarriages, where the forgings typically used cannot be effectively cold compressed.

iii) The development of aluminium-lithium rivets: All rivets used in the EH101 are those commercially available in 'conventional' alloys AA2017 and AA7075. There is scope for further weight savings if lightweight aluminium-lithium based rivets could be produced. The superior fatigue characteristics of aluminium-lithium alloys could be particularly useful, as the integrity of many assemblies is frequently primarily dependent upon the fatigue resistance of the rivetted joint.

iv) Ways to make aluminium-lithium alloys cheaper: As mentioned, these alloys are invariably more expensive than 'conventional' aluminium alloys due to the high cost of elemental lithium. Furthermore, the highest purity lithium must be used, as the standard sodium and potassium impurities in this metal are particularly deleterious to fracture toughness and ductility of the subsequent aluminium-lithium alloy. There may be ways to reduce costs by, for example, using lower grade lithium at the outset, but with casting using vacuum refining techniques to remove the impurities.

6. CONCLUSIONS

Application of advanced microanalytical and microscopical techniques has significantly improved the fundamental understanding of aluminium-lithium metallurgy and has led to the development and commercialisation of several new alloys, with properties superior to the original AA2020 alloy used in the 1960's. One of these, AA8090, is used extensively on the new EH101 helicopter to achieve significant weight savings from both the inherent lower material density and the increased elastic modulus. Additionally, there appears to be further areas for exploitation if further research and development were to be carried out.

TABLE 1

COMMERCIALLY AVAILABLE ALUMINIUM-LITHIUM ALLOYS AS OF MID 1998

Alloy	**Ingot Manufacture** [1]	**Nominal Density (g cm^{-3})**	**Product Forms Available** [2]	**Use**
AA8090	British Aluminium (UK)	2.55 [4]	Sheet, plate, extrusions, forgings	'Reduced density' for 'medium strength' and 'damage tolerant' applications
AA2195	McCook Metals (USA)[3]	2.71 [4]	Sheet, plate	Applications requiring enhanced cryogenic properties, ultra high strength and is weldable. Not designed primarily for reduced density.
AA2097	ALCOA (USA)	2.64 [4]	Sheet, plate	Applications requiring enhanced fatigue resistance. Not designed primarily for reduced density.
AA2197	McCook Metals (USA)[3]	2.64 [4]	Sheet, plate	Applications requiring enhanced fatigue resistance. Not designed primarily for reduced density.

1) Fabrication into wrought products may be carried out by Companies other than the ingot manufacturer.

2) All sheet and plate is unclad.

3) Formed mid 1998 from reorganisation and partial sale of Reynolds Metals.

4) For comparison, typical density of AA2XXX alloys - 2.77 g cm^{-3}
AA7XXX alloys - 2.80 g cm^{-3}

TABLE 2

COMMERCIALLY AVAILABLE ALUMINIUM-LITHIUM ALLOYS AS OF MID 1998

Product Form	End Use Condition	GWHL Temper Designation	Property Category	Substitute for
Sheet	Solution heat treated, quenched, controlled stretched and precipitation heat treated to an underaged condition.	T81	'Damage tolerant' i.e. low strength but enhanced toughness and impact resistance.	AA6082-T6 (BS L113) AA2024-T3 (BS L109) AA2024-T4 (BS L110)
Sheet	Re-solution heat treated, quenched and precipitation heat treated to an underaged condition (same ageing parameters as for T81 temper)	T621	Re-solution treatment by the user to promote enhanced formability in sheet/components of 'low strength'.	AA6082-T6 (BS L113) AA2024-T4 (BS L110)
Sheet	Solution heat treated, quenched, controlled stretched and precipitation heat treated to a near peak aged condition.	T8	'Medium' strength where some reduction in toughness and impact resistance compared to T81 and T621 can be tolerated to give higher strength.	AA2014A-T6 (BS L157, L159, L165, L167)
Sheet	Superplastically formed components	T6	Superplastically formed properties.	AA2024 (Assemblies) AA2007 (SPF parts)
Extruded sections and tube	Solution heat treated, quenched, controlled stretched and precipitation heat treated to a near peak aged condition	T8511	'Medium/high' strength.	AA7075-T74511 (BS L160)
Die forgings	Solution heat treated, quenched, cold compressed, and heat treated to a near peak aged condition	T852	'Medium/high' strength.	AA7010-T7451 (plate to DTD 5130A)

TABLE 3

Main Application of Alloy AA8090 on the EH101

Sheet (0.6 mm ≤ a ≤ 4mm)	Extrusions (1.0 mm ≤ a ≤ 6 mm)	Die Forgings (20 mm ≤ a ≤ 125 mm)
- Forward fuselage lower structure, cabin side, outer skins - Rear fuselage skinning and stringers - Instrument panels, consoles, avionics cabinets - Gearbox fairing substructure - Sundry sheet metal parts, including superplastically formed sheet	- Numerous standard profiles e.g. T sections, C sections, F sections, cruciform sections - Hollow seat tracks and floor beams - Square cross section tubes for instrument racking, conduits for cables and ladders - Over 40 different profiles used, mostly as 7000 mm lengths which are incorporated lengthwise in the main cabin	- All structural frames in main cabin machined from AA8090 cold compressed die forgings. These include side frames, roof frames, intercostals and sides of main undercarriage box. A total of 16 different forging configurations are made from which 38 different components are machined per aircraft.

TABLE 4

AECMA Materials Standards under Preparation for Alloy AA8090

Material Standard No.	Title
prEN 3979	Aluminium alloy AL-P8090-02. Sheet for superplastic forming. 0.8 mm ≤ a ≤ 6 mm
prEN 3980	Aluminium alloy AL-P8090-T6. Superplastic formings. 0.8 mm ≤ a ≤ 6 mm
prEN 3981	Aluminium alloy AL-P8090-T62. Sheet. 0.6 mm ≤ a ≤ 6 mm
prEN 4203	Aluminium alloy AL-P8090-T841. Sheet. 0.6 mm ≤ a ≤ 6 mm
prEN 4204	Aluminium alloy AL-P8090-T82. Sheet 0.6 mm ≤ a ≤ 4 mm
prEN 4207	Aluminium alloy AL-P8090-T8511. Extruded bar and section with peripheral coarse grain control. a or D ≤ 10 mm
prEN 4288	Aluminium alloy AL-P8090. Die Forgings a ≤ 150 mm
prEN 4291	Aluminium alloy AL-P8090. Forging Stock
prEN 4422	Aluminium alloy AL-P8090-T89. Plate 6 mm < a ≤ 150 mm
prEN 4423	Aluminium alloy AL-P8090-T8511. Extruded bar with peripheral coarse grain control. 10 mm ≤ a or D≤ 150 mm