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ALUMINIUM ALLOY TECHNOLOGIES FOR ADVANCED DEFENCE SYSTEMS

DRDO 60 YEARS OF SERVICE TO THE NATION

From the Desk of Guest Editor

Aluminium alloys have emerged as the material of choice for a variety of defence applications due to advantages like light weight, high corrosion resistance, high stress corrosion resistance, high weldability, easy fabricability and excellent recyclability. The country's defence applications require about eight to ten thousand tons of wrought, speciality aluminium alloys per annum. This figure is growing steadily as more numbers of DRDO programmes attain production status.

DMRL has emerged as a nodal point for taking up development-cum-production orders from various DRDO projects/ agencies for manufacturing speciality aluminium alloys at the industrial scale. This is the result of dedicated and continual in-house R&D studies of a variety of commercial and experimental aluminium alloys for a period spanning more than three decades.

For most engineering applications, a combination of properties is always required in a given material. To achieve these properties, it is necessary that in-depth analyses of processing-microstructure-property relationships of such materials are carried out. Also, processing parameters of commercial materials produced by major production agencies/ companies are always proprietary in nature and such technologies are established through years of dedicated in-house R&D efforts. By virtue of the aforementioned experience, DMRL has reached a position to determine such processing details, and to make use of such data while producing the materials at the industrial scale. A variety of aluminium alloys has been developed and produced under the technical guidance of DMRL in the recent past for critical defence applications that include:

- *BrahMos Supersonic Cruise Missile*
- *Submarine Launched Ballistic Missile*
- *New Generation Anti-radiation Missile*
- *Akash Missile*
- *Sarvatra Bridging System*
- *Ammunition (FSAPDS and Rocket)*
- *Futuristic Infantry Combat Vehicle*
- *Naval Warship*

All these materials are import substitutes, and the indigenous production of these materials is associated with significant cost savings. Today, it is with great happiness I can say confidently that indigenous aluminium alloys have truly arrived on the Indian defence scene.

I am glad that DESIDOC has taken the initiative of bringing out an exclusive issue of Technology Focus on aluminium alloy technologies developed by DMRL. This issue will help document the journey and provide an update on recent products, applications as well as initiatives, which will help both the users and the designers in an effective manner.

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ALUMINIUM ALLOY TECHNOLOGIES FOR ADVANCED DEFENCE SYSTEMS

Light aluminium alloys are the most preferred metallic materials (following steels) for advanced defence systems. These alloys are engineered materials offering a combination of improved properties, with the property requirement often varying from one part to another for a particular application. Thorough understanding, modifications, extension and development of the existing commercial alloys and processes are crucial in order to come up with breakthrough alloys for critical defence applications.

Until recently, a majority of the wrought aluminium alloy products required for the armed forces were being imported, resulting in issues of quality, time and cost overruns. Although, India has the fifth largest bauxite (aluminium ore) reserves in the world, the lack of technological-know-how and the dedicated, state-of-the-art infrastructure were the major factors impeding the production of speciality aluminium alloys required for strategic applications.

During the past one decade,

- Hindustan Aluminium Company (Hindalco) in collaboration with Almex, USA set up the state-of-the-art melting and casting unit for billets and slabs at Aurangabad
- Hindalco re-located a state-of-the-art rolling mill from one of its plants in UK to Hirakud
- Bharat Aluminium Co. Ltd (BALCO), using the fund received from ISRO, set up a Novelis melting and casting unit for slabs, and heat treatment facilities for plates at Korba
- Ordnance Factory Ambajhari (OFAJ) set up a 6,500 ton capacity extrusion press and a 1,500 ton capacity stretching machine at Nagpur, and
- Several small to medium scale aluminium industries located across the country were encouraged by DRDO to take up downstream processing in producing extrusion, forging, pipe, tube, rolled ring, wire, etc. using their existing infrastructure.

Defence Metallurgical Research Laboratory (DMRL), Hyderabad, one of the establishment under Defence Research & Development Organisation (DRDO), having decades of in-house research, design and development experience, and close interactions with the users and the inspection and certifying agencies, made full use of the aforementioned industrial infrastructure to develop and produce a variety of aluminium alloys in desired semi-product forms and heat treatment tempers for critical defence applications.

With this, the utilisation of different grades of indigenised aluminium alloys in different product forms and tempers has increased steadily during the past one decade as more number of DRDO programmes attained commercial production status. The requirement of various aluminium alloys has further been on the increase because of the continual modernisation of armed forces.

This special issue of *Technology Focus* highlight the major contributions and the dedicated efforts put in by DMRL for the development of indigenous technologies for the production of aluminium alloys in close collaboration with the Indian aluminium industry for critical defence applications which include missile, naval warship, military bridge, ammunition, futuristic infantry combat vehicle and indigenously produced combat aircraft.

Potential users of aluminium alloys for the defence sector

BrahMos Missile

BrahMos is a supersonic cruise missile that can be launched from multiple platforms. It is a joint venture between Russian Federation's NPO Mashinostroyeniya (NPOM) and India's DRDO. The missile reaches a maximum speed of 2.8 Mach (i.e., 2.8 times the velocity of sound). At this speed, the selection of aluminium alloys that are used in the bulk of the missile is very important.

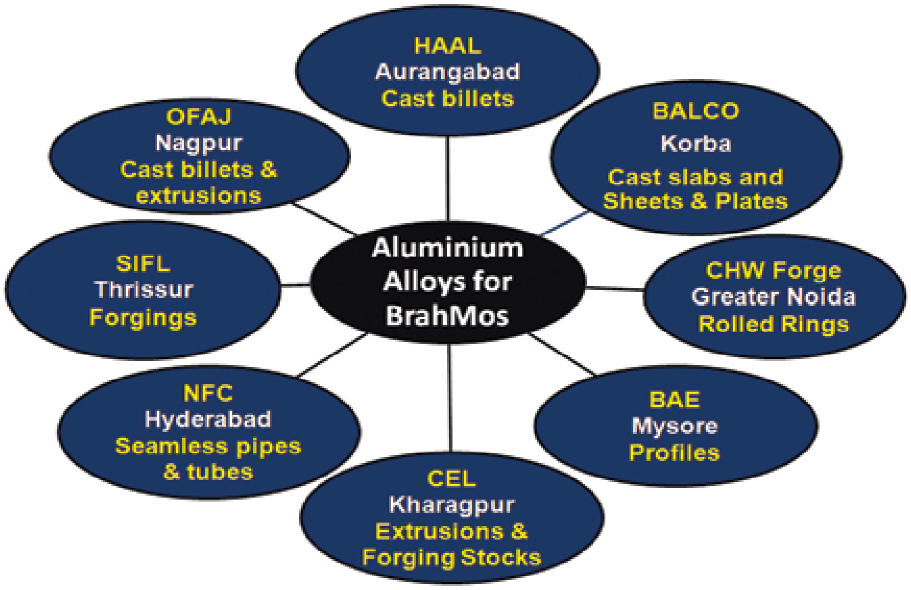
Five different Russian grades of wrought aluminium alloys, i.e., 1201, AK4-1Ч, AMГ6, AK6 & Д16Ч are utilised in different parts of the missile in eight different semi-product forms, i.e., sheet and plate (with and without cladding), forging, rod, pipe, tube, rolled ring and profile in a variety of heat treatment conditions, i.e., O, T31, T4, T6, T81, T83, T851, T852 and T87. It is noteworthy that the alloys 1201, AK4-1Ч and Д16Ч are the Aluminium Association (AA) specification equivalent of AA2219, AA2618 and AA2124 alloys, whilst, alloys AMГ6 and AK6 have no Aluminium Association specification equivalents. These two alloys are described here as BAPL5xxx and BAPL2xxx, respectively. All these five aluminium alloys had to be indigenised to match the Russian GOST specifications.

The materials were earlier being procured from NPOM, Russia who in turn used to procure them from multiple sources resulting in issues involving quality, time and cost overruns. The cost calculations carried out in the year 2010 revealed that the total cost of imported aluminium alloys required per missile is about three times the cost of such alloys when produced by the Indian industries. This together with the fact that a significant number of BrahMos missiles was then already ordered by the Indian armed forces formed the basis for taking up the indigenisation work of these aluminium alloys.

At the time the work was taken up (in 2010), it was noted that there was hardly any industry in the country having necessary expertise for downstream processing of these aerospace grade wrought aluminium alloys. Further, although, Hindalco Almex Aerospace Limited (HAAL), Aurangabad had the expertise of producing high strength, aerospace grade aluminium alloy billets, it did not have the expertise of producing three out of the five Russian grade aluminium alloys as mentioned. BrahMos Aerospace Private Limited (BAPL), therefore, relied upon DMRL, having decades long laboratory scale R&D experience together with varying levels of industrial experience, for developing and producing the aluminium alloys at the industrial scale for BrahMos missile applications.

Under DMRL's technical guidance, a team of engineers from BAPL, Hyderabad, prepared the Quality Assurance Plans (QAPs) for production of ingots and various semi-products. Such QAPs described the process flow chart of individual alloys, ingot qualification check criteria, thermal and mechanical processing parameters, quality check details of the final products that include the targeted mechanical properties, dimensional tolerances and ultrasonic quality.

DMRL played a crucial role in the selection of the production agencies. The alloy ingots in the form of billets were produced in HAAL for all the alloys. The ingots in the form of slabs and the resultant sheets and plates were produced at BALCO, Korba for selected alloys with and without cladding. The ingots in the form of billets and the resultant extrusions (/rods) of larger sizes were produced in OFAJ, Nagpur for alloy AA2219, and the extrusions of smaller sizes together with the forging stocks were produced in Century Extrusions Limited (CEL), Kharagpur for alloys AA2219, AA2124, AA2618 and BAPL5xxx. The rolled rings were produced in CHW Forge Private Limited (CHW Forge), Greater Noida for alloys AA2219, AA2618 and BAPL5xxx. The forgings were produced at Steel and Industrial Forgings Limited (SIFL), Thrissur for alloys AA2219, AA2618, BAPL2xxx and BAPL5xxx. The seamless pipes and tubes were produced at Nuclear Fuel Complex (NFC), Hyderabad for the alloy BAPL5xxx. Later,



Production agencies responsible for indigenisation of aluminium alloys for BrahMos missile

Selected aluminium alloy semi-products produced using indigenous materials

M/s Siddhi Engineers, Ahmedabad has been established as an alternate source for the manufacture of tubes for the alloy BAPL5xxx. The profiles were produced at Bhoruka Aluminium Extrusions (BAE), Mysore for alloys AA2124 and BAPL5xxx.

These materials were produced by ingot metallurgical route for the first time in the country, thereby requiring technologies in the areas of production of sound cast billets and slabs; production of semi-products in desired shapes and sizes; and formulation of commercially viable heat treatment schedules.

DMRL made the following contributions:

(i) Provided optimum composition range for the alloying elements and restricted upper limits for the impurities for all the alloys based on the phase diagrams, mechanical property and microstructural data

(ii) Provided data, such as liquidus and solidus temperatures and thermal conductivity values for all the alloys to estimate casting parameters, and guidance on the sequence and the manners, the alloying elements should be added (i.e., in pure elemental form or in the form of master alloys) into the furnace for effective melting and obtaining desired cast microstructure for all the alloys

(iii) Formulated ingot quality check criteria for attributes such as composition, content of alkali metals like sodium, potassium, calcium, lithium, hydrogen content, grain size (core) and ultrasonic quality, each of which is to be strictly controlled for all the alloys

(iv) Provided optimum homogenisation schedules for all the alloys based on independent experiments involving thermal analysis of as-cast alloys, and microstructural characterisation of as-cast and homogenised materials

(v) Implemented the use of ring rolling (because of the unavailability of the extrusion press of large capacity) for the manufacture of large annular cylinders

(vi) Provided optimum processing conditions, for manufacturing all the eight varieties of semi-products, such as the hot rolling parameters for producing Alclad sheets and plates at BALCO, the extrusion parameters for alloy BAPL5xxx at CEL and at BAE, the extrusion parameters and introduction of intermediate annealing between the pilgering passes post extrusion for producing seamless tubes and pipes of alloy BAPL5xxx at NFC, the use of ring rolling together with saddle forging for the production of annular cylinders of alloy AA2219 with high L/D ratios at CHW forge, the thermo-mechanical process parameters for producing rolled rings of alloy BAPL5xxx at CHW Forge and the thermo-mechanical process parameters for producing BAPL5xxx tubes by multiple drawing operations at Siddhi Engineers, Ahmedabad

(vii) Provided details of thermo-mechanical processing steps for producing alloy BAPL5xxx through open die forging route at SIFL, and

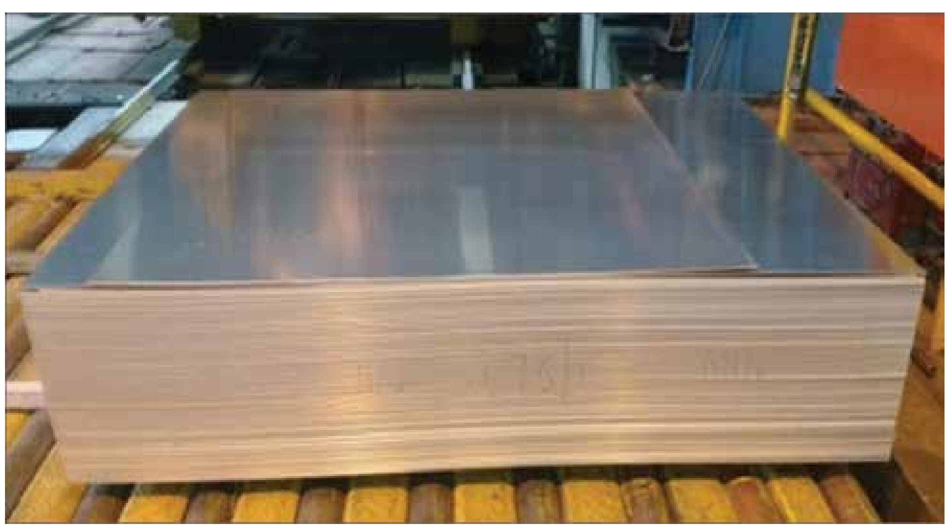
(viii) Provided rolling schedules, and alternate pre-artificial aging cold working (involving a combination of cold rolling and stretching) schedule for producing Alclad 1201 plates in T87 temper at BALCO

All the heat treated semi-products met the targeted properties, as inspected by Missile Systems Quality Assurance Agency (MSQAA), and in some cases by Directorate General of Aeronautical Quality Assurance (DGAQA) at individual production centres. The production processes and the quality control procedures of the indigenised materials were approved by NPOM, Russia, the joint venture partner, in 2016. The materials were subjected to a combination of machining, forming, aging and welding at Godrej & Boyce, Mumbai. During fabrication of the components, the indigenised materials performed at par with the imported ones. The F3 section assembly, i.e., the major load bearing part of the missile fabricated using the indigenous aluminium materials were subjected to the prescribed structural tests. The F3 section successfully qualified all the prescribed structural tests. The qualification tests of F3 section assembly also got the approval of NPOM, Russia.

Selected components fabricated (and subsequently integrated) using indigenous aluminium alloys

Combat ready F3 section manufactured using indigenous materials

AA2219 slab produced at HAAL, Aurangabad

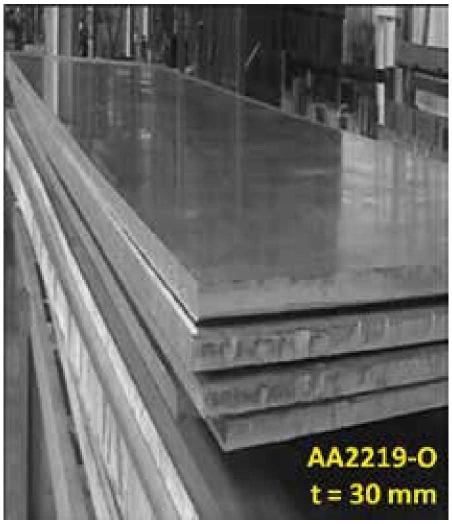


Indigenised AA2219-O sheets produced at Hindalco, Hirakud

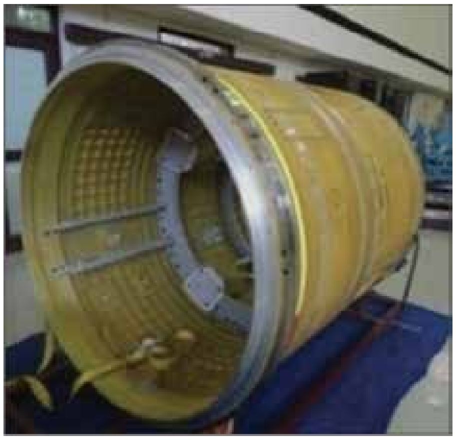
The first combat ready F3 section manufactured using indigenous aluminium alloys was handed over by Godrej & Boyce to BAPL in 2017. This is a major milestone in DRDO's indigenisation program for aluminium materials.

At DMRL's earnest request, HAAL initiated the process of slab casting in the year 2015. The slabs for alloys AA2219 and AA6061 have already been successfully produced at HAAL. The AA2219 slabs were subsequently processed at Hindalco, Hirakud to sheets of desired thicknesses in the annealed (O) temper for fabrication of components for the launcher for BrahMos missile. The AA6061 slabs are currently being processed to produce sheets at Hindalco, Hirakud for BrahMos applications. The successful indigenisation of the aluminium alloys for BrahMos supersonic cruise missile applications has several major advantages as follows:

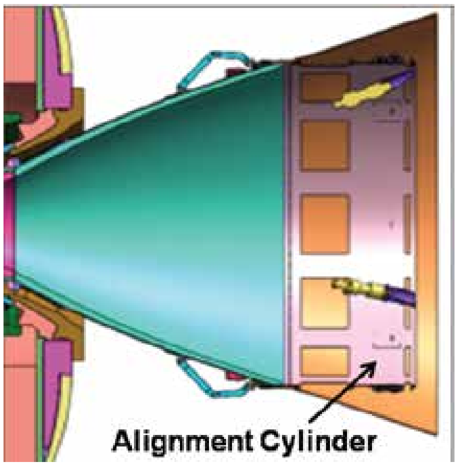
- Present work has created self-reliance in this specific field in the country. Henceforth issues such as cost escalation, quality, and time for delivery of these materials could be overcome
- Cost savings associated with the indigenisation of the subject aluminium alloys are high
- Present technologies, already established at the commercial scale, shall be utilised to produce the same grades of aluminium alloys being currently imported by certain Ordnance Factories (OF) for the manufacture of ammunitions using Russian technologies
- Present technologies, already established at the commercial scale, shall further be utilised to produce a few of the same grades of aluminium alloys being currently imported by certain HAL factories for the manufacture of aircraft components using Russian technologies



Indigenised AA2219-O plates



Nose cap shell



Alignment cylinder, fabricated from Indigenised AA2219-T87 plate

Indigenised AA2219-T87 plates

Submarine Launched Ballistic Missile-K4

Aluminium alloy, AA2219 plates having thicknesses of 30 mm and 20 mm, width of 1400 mm and lengths varying from 4000 mm to 6000 mm were produced in annealed (O) and T87 tempers at BALCO, Korba for the manufacture of nose cap dome and nose cap shell and alignment cylinder components, respectively of the SLBM-K4 missile. DMRL provided all necessary process parameters for the production of these plates. Production of Class A1 ultrasonic quality plates was ensured for these applications.

The nose cap shell components were made using 20 mm thick AA2219-T87 plates and the process of joining by friction stir welding. One such component was first successfully

Nose cap dome, fabricated from indigenised AA2219-O plate utilised in SLBM-K4 flight trial held in 2014. Several of these indigenised components were further successfully utilised in successive flight trials.

The nose cap dome components were made from 30 mm thick AA2219-O (annealed) plates, and later heat treated to the precipitation hardening temper. One such component was successfully utilised in SLBM-K4 flight trial held in 2017. These nose cap domes will continually be used in all future SLBM-K4 flight trials.

Yet another component, i.e., alignment cylinder, made from 20 mm thick AA2219-T87 plates, shall be used in the future flight trials of SLBM-K4 missile.

The temper T87 implies the provision of a minimum of seven per cent (and not exceeding 8 %) cold work by stretching prior to artificial aging. However, the capacity of the stretching machine at BALCO, Korba was not sufficient to impart seven per cent stretching to these wide and thick plates.

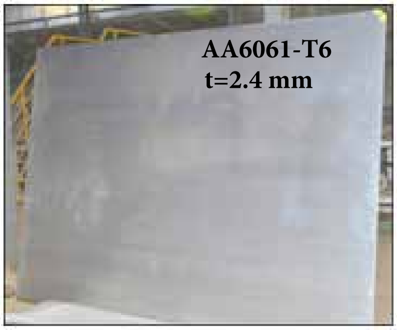
Using the rolling mill and 250 T stretching machine available at DMRL, it was formulated that a combination of pre-aging cold work involving five per cent cold rolling followed by two per cent stretching (i.e., a total of a minimum of 7 % cold work) imparts desired strength properties in T87 temper. In fact, the same cold working schedule was earlier utilised to produce Alclad AA2219-T87 plates at BALCO for BrahMos missile applications.

Akash Missile

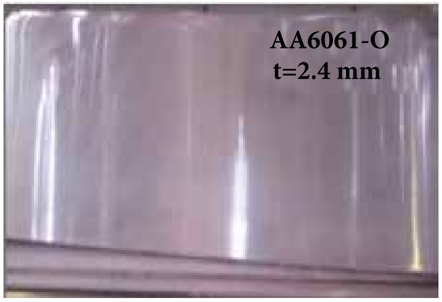
Akash, a medium-range surface-to-air missile, currently being produced for Air Force and Army is a ramjet propelled missile with air intakes manufactured from aluminium alloy AA6082 seamless tube. This tube is imported from various sources abroad as a straight tube of 114 mm OD, wall thickness of two mm and length as 1500 mm. The tube is then bent as per the design requirement and heat treated to the peak aged temper for the actual application.

Indigenised AA6082-O straight tubes

M/s Siddhi Engineers, Ahmedabad (who successfully produced the thin walled tubes of alloy BAPL5xxx for BrahMos missile earlier using billets from HAAL and mother hollow tubes from OFAJ) produced the AA6082 straight tubes for Akash. DMRL provided crucial metallurgical inputs in terms of optimum alloy composition, ingot quality check procedures and billet acceptance criteria to the firm to procure billets and the resultant mother hollow tubes of 122 mm OD and wall thickness varying from 5 mm to 8 mm. Further inputs, in terms of formulation of process schedules for the manufacture

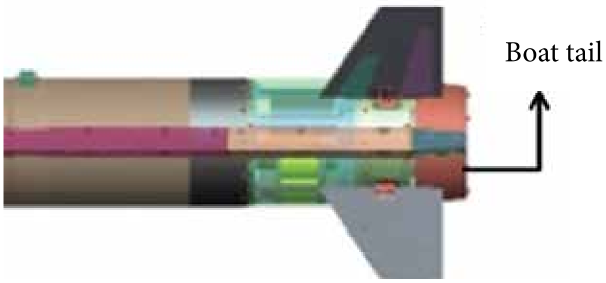


Indigenised AA6061-T6 sheet



Indigenised AA6061-O sheet

Indigenised tube, bent as per the design



Boat tail component (arrowed) in NGARM, fabricated from indigenous AA6061-O sheets of the tubes by restricting the process to three-step drawing operations without the need of an intermediate annealing treatment, and a suitable annealing cycle for the resultant straight tubes to be heat treated subsequently to the O temper. The resultant annealed straight tubes were then subjected to chemical, dimensional, tensile and hundred per cent non-destructive tests.

The straight tubes were subjected to the required bending operation (as per the design) at M/s Autoforms, Mumbai. The bent tubes were then heat treated to the peak aged temper at M/s L&T, Coimbatore. The mechanical properties, dimensional tolerances, shape, etc. have been verified and the process has been fully established.

New Generation Anti-Radiation Missile (NGARM)

Aluminium alloy AA6061 sheets having thickness of 2.4 mm and heat treated to annealed (O) and peak aged (T6) tempers were produced at BALCO, Korba for the manufacture of air frame components of NGARM. DMRL provided all the necessary metallurgical inputs in terms of process parameters and quality control procedures for the production of slabs and heat treated sheets of the alloy having the desired dimensions and mechanical properties.

Naval Warship

Aluminium-magnesium based alloys are widely used for the manufacture of superstructure of naval warship. DMRL provided crucial metallurgical inputs to reduce, the loss of magnesium during melting and casting, hydrogen content in the molten metal prior to casting, and rejections at various stages of production processes through control on rolling and heat treatment parameters for the production of sheets and plates of various thicknesses (up to 30 mm) and desired tempers (H24 and M) at BALCO, Korba.

The resultant materials met all the targeted properties, as inspected by Quality Assurance Establishment (Naval), [QAE(N)], Kolkata. Other properties such as corrosion resistance (i.e., exfoliation corrosion resistance and stress corrosion cracking resistance) and weldability were evaluated in Central Electro Chemical Research Institute (CECRI), Karaikudi and Welding Research Institute (WRI), Trichy, respectively. The

3.0 mm thick DMR291A-H24 sheet produced at Hindalco, Hirakud

0.9 mm thick DMR291A-H24 sheet produced at Hindalco, Hirakud

production processes and the quality control procedures of the indigenised materials (named DMR291A) were approved by QAE(N), Kolkata and Directorate of Naval Architecture (DNA), New Delhi.

The competent authority in Indian Navy approved the indigenised DMR291A sheets and plates for their use in superstructures in naval warships in February, 2014. The Naval Construction Document (NCD) for these materials was issued by

Indigenised Al-Mg alloy DMR291A in the form of (a) as-cast ingots, (b) M plate (t = 25 mm), and (c) H24 sheets (t=2 mm) produced at BALCO, Korba

Directorate of Naval Architecture (DNA), Integrated Headquarters, MoD (Navy) in September, 2014. Indian Navy, in February, 2016, placed bulk order on BALCO for the procurement of the aforementioned materials. However, in early 2016, M/s BALCO took an internal decision to close the downstream facilities for the production of hard alloys. As a result, it became necessary to establish an alternate source for the production of alloy DMR291A sheets at Hindalco, Hirakud, wherein, a four-high rolling mill is available to produce these materials.

As a first step, Hindalco carried out trial production of DMR291A sheets of thicknesses 0.9 mm and 3.5 mm in H24 temper. The sheets were made using the same process schedules established earlier by DMRL at M/s BALCO, Korba. The production trials at Hindalco, Hirakud occurred under the supervision of DMRL. The sheets were acceptable in terms of Dye Penetrant (DP) tests and dimensional, thickness and flatness checks carried out at the site by a team of representatives from DNA, DQA(N), QAE(N) and DMRL. Other tests, i.e., corrosion and weldability, as a part of the acceptance tests were also carried out at CECRI and WRI, respectively. Based on these results, the Indian Navy has decided to place bulk orders on Hindalco for the procurement of the DMR291A sheets.

Fin Stabilised Armour Piercing Discarding Sabot (FSAPDS): An Anti-tank Ammunition

DTD5124 is an aluminium-zinc-magnesium-copper based 7xxx series aluminium alloy, the class of highest strength aluminium alloy produced by the ingot metallurgical route. The chemical composition of DTD 5124 alloy (introduced in UK) is similar to that of alloy AA7075 of Aluminium Company of America (ALCOA), USA.

Aluminium-zinc-magnesium-copper based Directorate of Technical Development (DTD) UK, 5124 alloy is utilised for the manufacture of tail fin and sabot components of FSAPDS, an anti-tank ammunition, used by Indian army. Typically, these components are machined from heat treated (T651) DTD5124 round bar extrusions of suitable diameters and hard anodised prior to its use. Hard anodising provides thermal barriers to the components during exposure to high temperatures for a few milliseconds during firing, and also protects the material against general corrosion during long term storage.

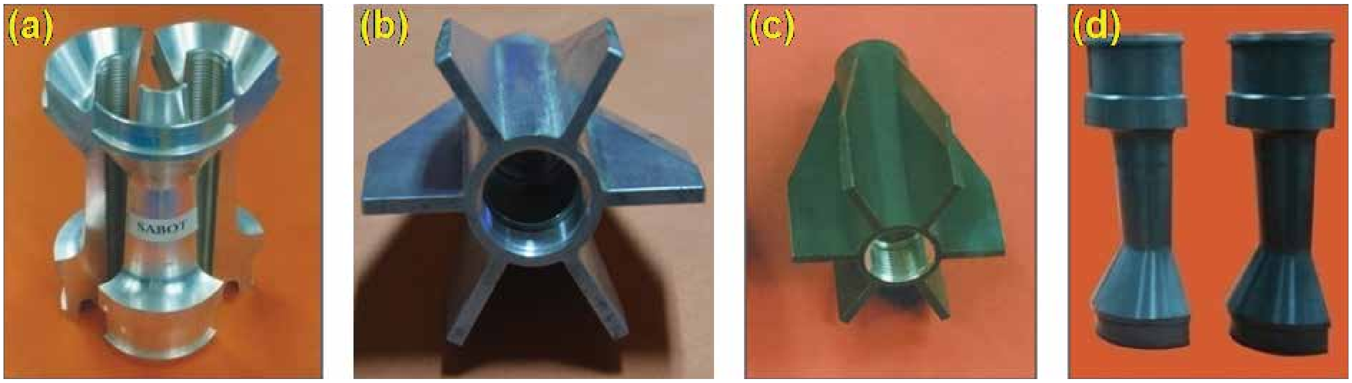
While both, tail fin and sabot are made of DTD5124 for Mk-I FSAPDS ammunition, only the sabot component is made of this alloy for Mk-II FSAPDS ammunition. For Mk-II FSAPDS ammunition, the tail fin is made out of steel.

During the course of technology development, some technical problems faced were:

(i) An unacceptable percentage of rejection of the fully heat treated extrusions due to the formation of an increased width of the peripheral recrystallised layer (i.e., as high as 21 mm for the 116 mm diameter extrusions)

(ii) Inadequate strength properties of the DTD5124-T651 extrusions for the present application. The typical T651 strength properties of this alloy, i.e., 0.2 per cent, PS of 500 MPa, UTS of 570 MPa were lower than the minimum required strength properties of 0.2 per cent, PS of 520 MPa and UTS of 580 MPa for the 81 mm diameter extrusions from which the tail fin component used to be machined

(iii) Rapid voltage rise with time during hard anodising of the tail fin and sabot components made from the indigenised DTD 5124-T651 extrusions. As a result, the process had to be interrupted to avoid burning of the components



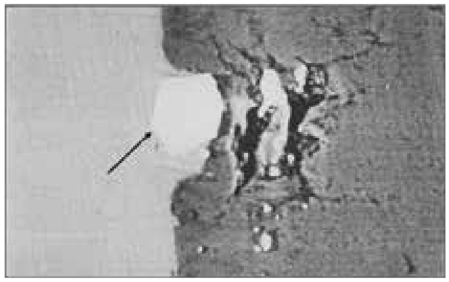
(a) Sabot and (b) Tail fin, both machined from indigenised DTD5124-T651 extrusions, and (c) hard anodised tail fin, and (d) a couple of hard anodised sabot petals

The use of zirconium additions together with reductions in the initial billet temperature and the ram speed restricted the width of the peripheral recrystallised layer to ≤1.5 mm on peak aged extrusions of all the three sizes (i.e., 81 mm 116 mm and 135 mm). The conventional single step artificial aging was replaced by a suitable two-step artificial aging treatment. This aging practice improved the peak aged tensile properties of all the three sizes of the extrusions. The two-step aging treatment is based on the concept that the formation of strengthening phases during artificial aging treatment (at relatively higher temperature) could be aided by prior formation of solute clusters/Guinier-Preston zones by the use of a suitable low temperature artificial aging (i.e., this temperature being lower than the second step artificial aging temperature).

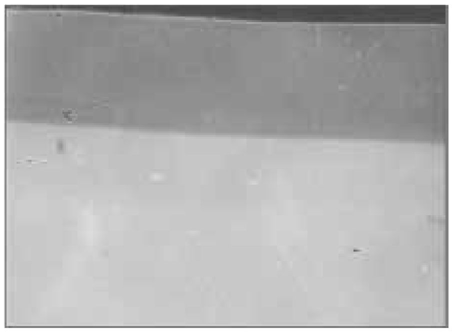
Detailed studies carried out at DMRL showed that the constituent particles based on $Al_{12}(FeMn)_3Si$ do not dissolve during the hard anodising treatment, and they inhibit nucleation and growth of oxide coatings in local regions, thereby disrupting the continuity of the anodic coatings. Further, such particles add resistance to the electrical path, causing a rapid rise in the bath voltage with time, often causing burning of the components.

It was established that in the absence of the $Al_{12}(FeMn)_3Si$ phase, the other types of the Fe-bearing phases formed in the alloy do not survive the hard anodising treatment. This results in a steady rise in bath voltage with time and a uniform growth of the anodic oxide film. Reductions in Fe, Si and Mn impurities below certain levels in the alloy inhibited the formation of the $Al_{12}(FeMn)_3Si$ phase in the alloy, and provided a solution to the hard anodising problem.

The FSAPDS ammunitions of different calibres fitted with tail fin and sabot, fabricated from the indigenised DTD5124-T651 extrusions, were successfully test fired.



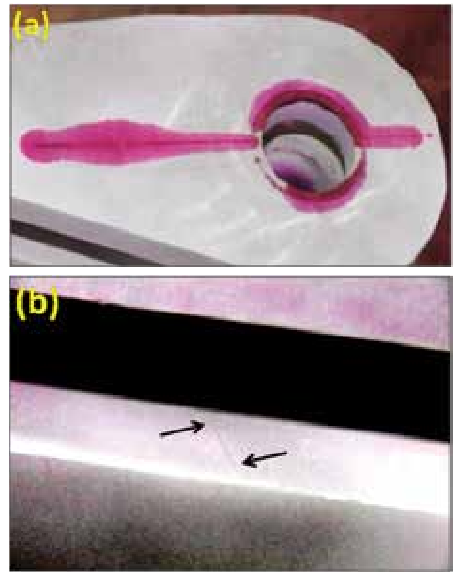
Inhibition of growth of the anodic oxide coating by $Al_{12}(FeMn)_3Si$ particles



A uniform growth of the anodic oxide coating in the absence of the $Al_{12}(FeMn)_3Si$ particles

Other Ammunitions

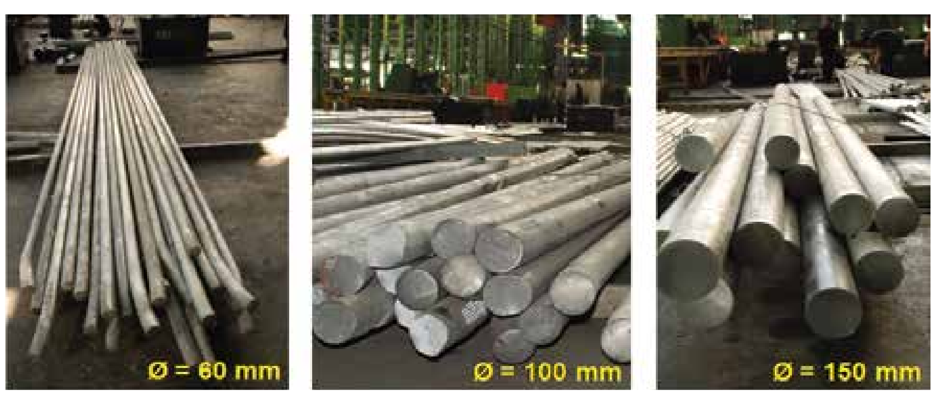
Aluminium–magnesium–silicon based alloy AA6082 was produced in the form of extruded rods (having three different diameters, i.e., 60 mm, 100 mm and 150 mm) and heat treated to T651 temper at OFAJ, Nagpur, under a DRDO project. This alloy has a combination of good strength and corrosion resistance. These materials have been used for rocket nozzles, mandrels for propellant casting, electronic housings and several other components for a variety of ammunitions.



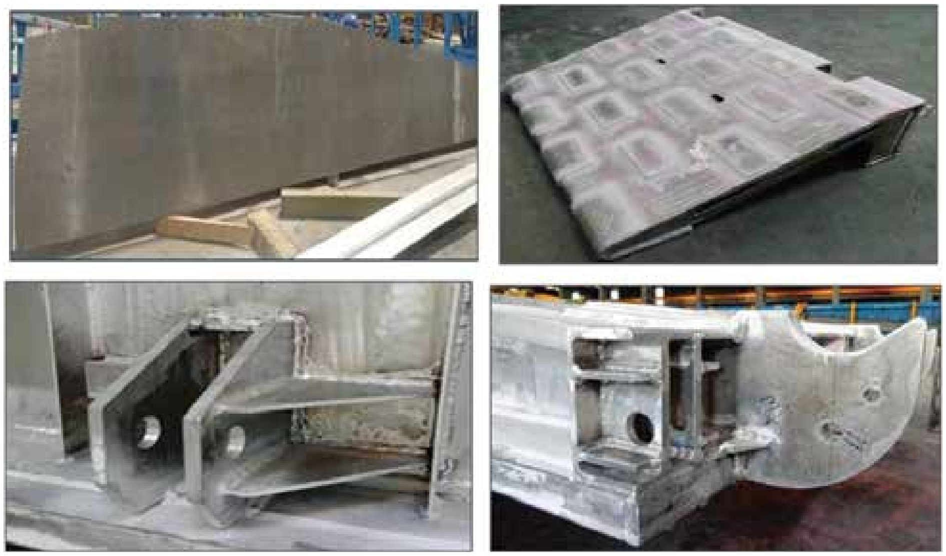
(a) DP test carried out on a hinge component of alloy RDE40 revealing presence of cracks, and (b) Presence of cracks in regions away from hinge locations, as detected by DP tests

Sarvatra Bridging System

7xxx series aluminium alloys are based on aluminium-zinc–magnesium and aluminium–zinc–magnesium–copper systems. The copper-bearing aluminium–zinc–magnesium system represents the class of highest strength



Indigenised AA6082-T651 extrusions produced at OFAJ, Nagpur



Different parts of the Sarvatra bridge such as (a) Web plate, (b) Ramp assembly, (c) Lifting hook, and (d) Pier bracket as fabricated from the indigenised RDE40M-T 7x51 sheets and plates having different thicknesses

(a) Manufacture of Sarvatra bridges by utilising indigenised RDE40M-T 7x51 sheets & plates, and (b) Load testing of Sarvatra bridge

aluminium alloys, and such alloys could be made immune to Stress Corrosion Cracking (SCC) by suitable heat treatments. However, such alloys are non-weldable.

On the other hand, the copper-free aluminium-zinc-magnesium alloys are weldable and could be utilised for application such as light military bridges where joining by welding is an essential step. However, such alloys suffer from poor SCC resistance.

Suitable changes in compositions (such as maintaining specific zinc: magnesium ratios and zinc+ magnesium contents, and additions of suitable recrystallisation inhibiting elements (such as manganese, zirconium, etc. and heat treatments (involving over aging treatments) are known to improve the SCC resistance of the copper-free aluminium–zinc–magnesium alloys.

Accordingly, a suitable composition and an overaging treatment were designed for a copper-free aluminium–zinc–magnesium–manganese–zirconium alloy for this application. The resultant alloy was designated RDE40M, i.e., a modified form of the previous alloy RDE40.

The alloy RDE40 developed about two decades ago has now been discontinued because in 2012, in as many as twenty (20) Sarvatra bridges, cracks were observed. Such cracks were initially detected in hinge (forged product) locations, but later on such cracks were also detected in regions away from hinge locations involving components fabricated out of plates.

The analysis carried out by DMRL showed that the cracks are of stress corrosion cracking origin. Specimens made out of RDE40 materials from forged and plate components were subjected to SCC tests at CECRI, Karaikudi. These specimens could not qualify the ASTM G47-98 SCC tests implying that the materials were indeed susceptible to stress corrosion cracking. This alloy was successfully produced in the form of sheets and plates, in various thicknesses (t = 4 mm to 20 mm) at BALCO.

The resultant materials have electrical conductivity values of ≥ 40 per cent IACS and 0.2 per cent PS values of ≥ 300 MPa.

RDE40M-T7x51 sheets of thickness (a) 6 mm and plates of thickness (b) 20 mm produced at BALCO, Korba

These materials survive forty (40) days of SCC tests (when loaded against 90 % of the 0.2 % proof stress value in LT direction) as per ASTM G 47-98. Under DMRL's technical guidance, twenty one (21) tons of these materials were produced at BALCO within a record six (6) months time during 2014-2015. Inspection and certification of these materials were carried out by Controllerate of Quality Assurance (Establishment) [CQA(E)], Pune.

L&T fabricated one set, i.e., five (5) numbers of Sarvatra bridges and delivered to BEML in 2015. The bridges qualified the structural tests at L&T, Talegaon prior to their dispatch to Bharat Earth Movers Limited (BEML). Following this, the bridges underwent successful trials at various locations of the country. Extrusions of the alloy RDE40M, produced by Hindalco using a modified aging heat treatment, prescribed by DMRL, are now ready for the manufacture of components for Sarvatra bridging system.

Futuristic Infantry Combat Vehicle (FICV)

Aluminium alloy AA2519 is used in the state-of-the-art Advanced Amphibious Assault Vehicle (AAAV). The AAAV is an amphibious armoured personnel carrier wherein

Indigenised AA2519-T87 plate (t = 10 mm) produced at BALCO, Korba

this aluminium alloy has been utilised to reduce the weight of the vehicle. No information is available regarding the processing details of this material in the literature.

The alloy AA2519 contains high copper (slightly less than what the alloy AA2219 contains) and also small amounts of magnesium. Because of the presence of magnesium, the procedure of melting and casting of the alloy considerably differs from those of the alloy AA2219. The presence of magnesium makes the alloy prone to hot cracking during solidification.

DMRL provided optimum alloy composition, melting and casting procedure as well as thermal and mechanical processing parameters for the production of this alloy at BALCO, Korba.

The alloy was processed in the form of plates having thicknesses of 10 mm and 15 mm and heat treated to T87 temper. The 15 mm thick plates of the alloy were subjected to ballistic tests against 7.62 mm x 54 mm AP (I) ammunition at DMRL. The test requirement is 7.62 mm x 54 mm AP(I) at average proof velocity of 509 m/s. The tests showed six (6) per cent superior results with reference to MIL-STD-46192C (MR).

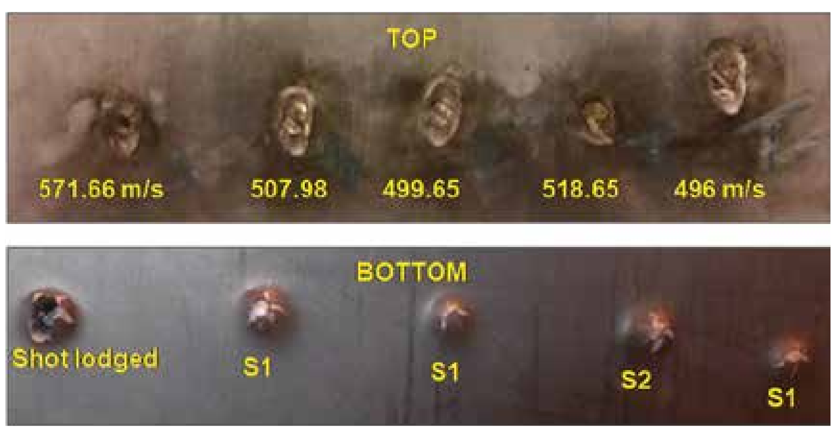
These materials were tested for weldability, stress corrosion cracking resistance, sub-zero temperature tensile strength, fracture toughness, etc. for product qualification purposes. All essential properties were achieved for these materials.

Indigenously Built Combat Aircraft

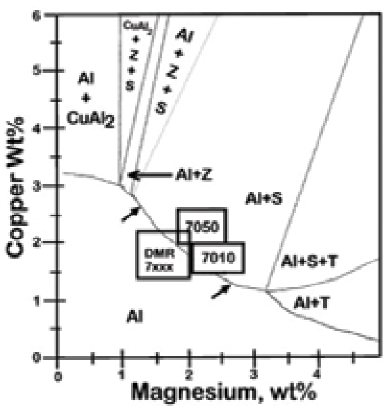
Aluminium–zinc–magnesium–copper base 7xxx series represents the class of highest strength aluminium alloys that is produced using the ingot metallurgical route. These alloys are non-weldable and utilised for structural components where strength is the primary requirement.

An additional advantage of copper-bearing aluminium-zinc-magnesium alloys is that they could be heat treated to suitable T7x51/ T7x52 tempers to significantly improve the exfoliation and stress corrosion cracking resistance. An important

Indigenised AA2519 (a) Slab, and (b) T87 Plates (t = 15 mm) produced at BALCO



Top and bottom sides of the 15 mm thick AA2519-T87 plate subjected to the ballistic test against 7.62 x 54 mm AP (I) ammunition



Al-Cu-Mg-Zn Phase diagram at 460 °C and 6 wt % Zn

property required by the designers for thick sections of these materials is low quench sensitivity. Reduced quench sensitivity greatly improves the through-thickness properties. Although, the quench sensitivity, in general, increases with total solute content in the alloy, the element copper has been identified to greatly accelerate the precipitation reactions, thus greatly influencing the quench sensitivity of this alloy. Taking into account these aspects, ALCOA (USA) in 2002 came up with an aluminium alloy AA7085 having the composition (wt %) of aluminium-(7-8) zinc-(1.2-1.8) magnesium-(1.3-2.0) copper-(0.08-0.15) zirconium. It is noteworthy that this alloy has substantially lower copper and magnesium compared to the other existing high strength 7xxx series aluminium alloys. An obvious consequence of this is the attainment of low strength values in the alloy in the desired tempers. These strength values obviously decrease further in LT and ST directions.

(a) DMR7xxx ingots of 580 mm diameter, (b)-(d) extruded sections of thicknesses 20 mm, 70 mm and 100 mm, respectively, and (e) 240 mm diameter extrusions as forging stock.

With this background, DMRL has come up with an alloy DMR7xxx having higher strength than the existing alloy AA7085 [Indian Patent No. 268056 (2015)]. The related Patent Cooperation Treaty (PCT) application got the approval of the European patent authority, got the grant of a patent from China [CN 101835915 B (2013)], and awaiting grant of patents from Germany, France and South Korea. In DMR7xxx alloy, the zinc content varies between 8 wt % to 10 wt %, while the copper and magnesium contents are in the composition ranges of (1.4-2.2) wt % and (1.2-2.0) wt %, respectively. Like AA7085 and all other high strength 7xxx series alloys, zirconium is present in this alloy in trace amounts.

Also, in DMR7xxx alloy, high purity primary aluminium (i.e., 99.9 wt % plus) are utilised for the preparation of this alloy in order to compensate the loss in ductility, fracture toughness and other mechanical properties because of the increase in the zinc content.

Further, in the actual DMR7xxx alloy composition, the copper and magnesium contents are so chosen that the alloy lies in the α-aluminium phase field of the aluminium-copper-magnesium-zinc phase diagram at 460 °C, for the purpose of homogenisation. This would not allow the anodic S (Al_2CuMg) phase to be present at the solution treatment temperature of 460 °C. Accordingly, the DMRL patented DMR7xxx alloy, containing a suitable amount of zinc, would possess a combination of high strength, high SCC resistance together with the reduced level of quench insensitivity.

As-cast round ingots of DMR7xxx (580 mm diameter) have been successfully produced at HAAL, Aurangabad. The resultant sound billets following homogenisation, scalping and ultrasonic testing have been extruded at OFAJ, Nagpur to produce extruded sections of suitable thicknesses, i.e., t of 20 mm through 100 mm, and forging stocks of diameter 240 mm.

The extruded sections/flats have been heat treated to T7651 temper. Desired through-thickness properties have been obtained in 100 mm thick extruded sections at the laboratory scale. These materials are currently being heat treated at OFAJ to realise the desired mechanical properties at the industrial scale.

The forging stocks shall be utilised to produce selected forged components in T7452 temper for indigenously built combat aircraft applications. The 20 mm and 30 mm thick plates are being utilised for ballistic tests against 7.62 mm AP(I) ammunition for vehicle armour applications.

Table 1 summarises the details of the past and ongoing indigenisation activities of aluminium alloys with DMRL as the nodal agency. Table 2 further describes the details of the heat treatment conditions (/tempers) to which the indigenised aluminium alloys were subjected to.

Although, DMRL had success with the production of aluminium alloys for a variety of critical defence applications, as discussed, the existing industrial infrastructure requires augmentation and/or upgradation (wherever necessary) for the production of a majority of the components required for indigenously built combat aircrafts. This is because the dimensions and the surface quality requirements of the semi-products for such applications are considerably greater than those required for missiles, armaments and armour applications.

Further, following the recent closure of the heat treatment facilities for sheets and plates of the age hardening aluminium alloys at BALCO, Korba, there exists currently no such facility in any of the aluminium industries in the country. The processing of the maximum thickness of the plates at BALCO was, however, limited to about forty (40) mm because of the limitations of the capacity of the plate stretcher.

On the other hand, plates having the maximum thickness of about one hundred eighty (180) mm are required for combat aircraft applications.

Stretching machines of appropriate capacities to stretch rolled products ranging from thin sheets (t = 0.5 mm) to thick plates (t = 180 mm) are, therefore, required. These equipments should be associated with suitable homogenisation and solution treatment furnaces, aging ovens together with state-of-the-art handling, inspection and testing facilities for the production of aluminium alloys for all varieties of defence applications.

Also, the current practice is that many of the components are machined from thick plates and/or forgings, leading to huge wastage of materials. This necessitates the use of closed die forging of appropriate capacity (35,000 T) to produce near net shape products.

A committee on aluminium materials, with members from ISRO and DRDO, under a national material policy initiative, is currently looking into the aforementioned infrastructure requirements. Hindalco is further advocating for a similar build-up of infrastructure through a joint government-private partnership. As realised by all concerned, such infrastructure is indeed critically required for the development and indigenisation of speciality, wrought aluminium alloys in the country.

DRDO Monographs Series

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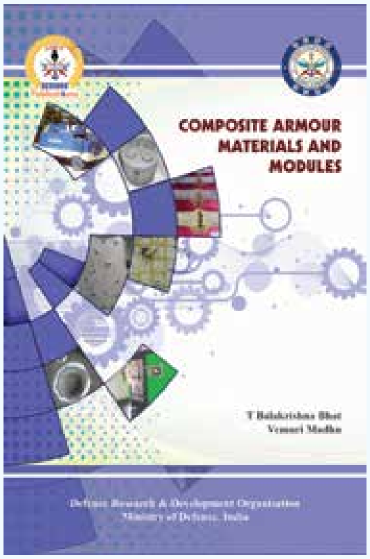

Table 1. Aluminium Alloys Produced using the Existing Infrastructure in Indian Industries

Alloy and Temper	Production Agency	Applications	User	Inspection Agency (IA), Certifying Agency (CA)
Alloy :1201 (AA2219), AK4-1Ч (AA2618); Д16Ч (AA2124), AK6 (BAPL2xxx) & AMГ6 (BAPL5xxx) Temper: O, T31, T4, T6, T652, T81, T83, T8511, T87 Semi-Product : Sheet and plate (with and without cladding), rod, seamless pipe, seamless tube, forging, rolled ring and profile	HAAL, Aurangabad (cast billet and slab) BALCO, Korba (cast slab, sheet and plate) OFAJ, Nagpur and CEL, Kharagpur (extrusion and forging stock) SIFL, Thrissur (forging) CHW Forge, Greater Noida (rolled ring) NFC, Hyderabad & Siddhi Engineers, Ahmedabad (seamless pipe & tube) BAE, Mysore (profile)	BrahMos Supersonic Cruise Missile (Airframe)	Armed Forces (Army, Navy and Air Force)	MSQAA (IA), NPOM Russia (CA)
Sheet: AA2219-O and AA6061-O	HAAL, Aurangabad and Hindalco, Hirakud	BrahMos Supersonic Cruise Missile	Armed Forces (Army, Navy and Air Force)	MSQAA (IA), CEMILAC (CA)
Plate: Unclad AA2219-O Plate: Unclad AA2219-T87	BALCO, Korba	Submarine Launched Ballistic Missile (Nose cap dome and alignment cylinder)	Navy	RDAQA, Midhani (IA), CEMILAC (CA)
Seamless Tubes: AA6082-T6	Siddhi Engineers, Ahmedabad	Akash Missile (Air intake tube)	Army Air Force	Project Akash, QC(L&T), Mumbai (IA)
Sheets: AA6061- O and AA6061-T6	BALCO, Korba	New Generation Anti-radiation Missile (NGARM) (Airframe)	Air Force	RDAQA, Midhani (IA), CEMILAC (CA)
Sheets: DMR291A-H24 and Plates: DMR291A-M	BALCO, Korba and Hindalco, Hirakud	Naval Warship (Superstructure)	Navy	QAE(N), Kolkata and DQA(N), Delhi (IA), DNA (CA)
Sheets and Plates: RDE40M- T7x51	BALCO, Korba	Sarvatra Bridging System	Army	CQA(E), Pune (IA & CA)
Plates: AA2519-T87	BALCO, Korba	Futuristic Infantry Combat Vehicle	Army	DGQA, Kolkata (IA), CQA(Metals) (CA)
Extrusions: AA6082-T651	OFAJ, Nagpur	Ammunition (Rocket, etc.)	Army	RDAQA, MIDHANI (IA), CEMILAC (CA)
Extrusions: DTD5124-T651	OFAJ, Nagpur and HAPP, Trichy	FSAPDS Ammunition (Hard anodised tail fin and sabot components)	Army	DGQA, OFAJ (IA), CQA (Metals) (CA)
Extrusions: DMR 7xxx-T7651 and Forging stock: DMR 7xxx Forging: DMR 7xxx-T7452	HAAL, Aurangabad, OFAJ, Nagpur and HAL, Bengaluru	Indigenously built combat aircraft (Forging) and vehicle armour	Air Force and Army	RDAQA, Midhani (IA), CEMILAC (CA) (ongoing project)

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Table 2. Heat Treatment Conditions (/Tempers) of the Indigenised Aluminium Alloys

Heat Treatment Nomenclature	Description	Aluminium Alloy, Semi-Product Form
F or M	As-fabricated or as-manufactured	DMR291A (a modified composition of AA5086), plate
O	Annealed	AA6082, Extrusion; AA2219, Sheet and Plate; BAPL 5xxx, rod, forging, rolled ring, plate, profile, pipe and tube; AA6082, tube
H24	Strain hardened (half hard) and partially annealed	DMR291A, Sheet
T31	Solution treated, cold worked and naturally aged	Alclad AA2219, Sheet
T4	Solution treated and naturally aged	AA2124, Profile
T451	Solution treated, stress relief by stretching and naturally aged	Alclad AA2219, Sheet
T6	Solution treated and artificially aged	AA2618 & BAPL 2xxx, Forging and Extrusion
T651	Solution treated, stress relief by stretching and artificially aged	AA6082, Extrusion; AA6061, Sheet
T7X51	Solution treated, stress relief by stretching and stabilised by overaging	RDE40M, Sheet and plate DMR7xxx, Flat and forging
T81	Solution treated, cold worked and artificially aged	Alclad AA2219, Sheet
T83	Solution treated, cold worked and artificially aged	Alclad AA2219, Sheet
T851	Solution treated, cold worked by stretching and artificially aged	AA2219, Extrusion
T852	Solution treated, cold worked by compression and artificially aged	AA2219 & AA2618 & AA2124, Rolled Ring
T87	Solution treated, cold worked (a minimum of 7 % but not exceeding 8 %) and artificially aged	Unclad AA2219 and Alclad AA2219, Plate

Note: Tx51, i.e., stress relief by stretching (1-3 %), Tx511, i.e., minor straightening after stretching and Tx52, i.e., stress relief by compression (1-5 %) are applicable for various tempers, where x = 3, 4, 6, 7 and 8, whichever is applicable. Stress relief by either stretching or compressing is provided following solution treatment. The exact details of the heat treatments utilised to obtain reproducible and improved properties in the indigenised materials are proprietary in nature.

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