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Innovative Forming and Fabrication Technologies: New Opportunities

Final Report

Energy Systems Division

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Final Report

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Executive Summary

The state of technology in the field of fabrication and materials forming is reviewed. The purpose of this work is to identify new fields of Research & Development (R&D) that can lead to a significant reduction in energy consumption. This report, based on an extensive literature survey, identifies sheet aluminum alloy manufacturing, forming, and applications as a core aspect, but also highlights other types of sheet metal alloys and materials.

This study found that aluminum alloy sheet manufacturing by the direct chill (DC) casting process is a mature technology where only marginal energy savings can be expected. Energy savings in this field can be accomplished mainly by individual plant wide assessments of energy consumption followed by optimization work. A possible breakthrough would come from advanced melting techniques such as plasma heating. As well, immersion heaters were recently identified as showing potential. An emerging technology in sheet manufacturing is spray rolling. The process could save $4.6x10^{12}$ kJ per year of energy for the U.S. aluminum industry. Even though the process has been proven to be technically feasible, the industrial implementation of spray rolling might need a significant effort. Improvements to the twin-roll casting process by coupling it with rheocasting could be an interesting method that would be easier to implement on the industrial scale.

Extensive research has been performed to develop processes capable of forming commercial aluminum alloys for applications in the automotive industry. The following processes are considered advanced forming technologies: superplastic forming, electromagnetic forming, age forming, warm forming, and hydroforming. They are not necessarily new but can be regarded as emerging technologies with respect to their application to aluminum alloys. Superplastic forming is already being used industrially; however, simple and inexpensive manufacturing methods for the production of superplastic aluminum sheets still require further development. Any breakthrough in the forming of sheet materials will most likely come from the development of new alloys with very high formability at low temperature or the development of processing techniques to improve formability of existing alloys that will relax the stringent requirements of the forming techniques themselves. To have significant achievements in alloy development, thermodynamic models must be developed (or improved). The recent developments in quantum physics applied to aluminum alloys could pave the way for very efficient alloy development.

Aluminum alloys are currently the material of choice to reduce weight in the automotive industry because of their commercial availability and the maturity of the aluminum industry. Opportunities still exist in the field of lightweight materials having high specific strength. Among those materials are magnesium alloys. Magnesium alloys could allow for further weight savings but high formability and high corrosion resistant alloys must be developed to overcome the limitations of the current commercial alloys. Nanomaterials are another class of materials with unique properties that could allow for the manufacturing of lightweight materials. Research is needed in this area to develop practical routes for the manufacturing of bulk nanocrystalline alloys. Furthermore, nanomaterials would benefit from the elaboration of a specific roadmap for the fabrication industry. Amorphous metallic glasses also exhibit outstanding specific properties. Research in this area should aim at developing materials with high crack propagation resistance and alloys which require lower cooling rates to achieve the amorphous state.

Fiber-reinforced composites are the principal competitors to aluminum alloys. Many advanced manufacturing processes for fiber-reinforced composites are now commercially available. The research needs in this area involve the development of environment friendly alternative resin systems for the epoxy system and new curing processes. Microwave heating is an interesting alternative for composite curing. Efficient recycling routes must also be developed to make composites environmentally sustainable. A breakthrough in composite materials would come from the development of biocomposites with natural fibers and the development of biopolymer or matrix compounds from vegetal sources.

The joining of light alloys, plastics and composites with each other or as hybrid assemblies still poses challenges. However, significant progress has been made in the development of industrial joining techniques for light alloys. Recent developments include friction stir welding, friction spot welding, and ultrasonic welding. These new technologies allow for the joining of dissimilar metals due to the absence

of fusion. The development of self-piercing rivets is the only innovation in the field of mechanical fastening. At the moment, each situation where joining is required must be evaluated on a case by case basis to determine the best joining method. Research efforts in this area should focus on developing new concepts for adhesive bonding. The target should be to develop adhesives with mechanical properties equivalent to epoxy based systems but with environmentally friendly chemistries. Methods to demonstrate the durability of new adhesive systems should be developed to facilitate acceptance by the industry.

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Introduction

The advent of light metal alloys and advanced materials (polymer, composites, etc.) have brought the possibility of achieving important energy reductions into the full life cycle of these materials, especially in transportation applications. [1] These materials have gained acceptance in the aerospace industry but use of light metal alloys needs to gain wider acceptance in other commercial transportation areas. Among the main reasons for the relatively low use of these materials are the lack of manufacturability, insufficient mechanical properties, and increased material costs due to processing inefficiencies. Considering the enormous potential energy savings associated with the use of light metal alloys and advanced materials in transportation, there is a need to identify R&D opportunities in the fields of materials fabrication and forming aimed at developing materials with high specific mechanical properties combined with energy efficient processes and good manufacturability.

This report presents a literature review of the most recent developments in the areas of fabrication and metal forming focusing principally on aluminum alloys. In the first section of the document, the different sheet manufacturing technologies including direct chill (DC) casting and rolling, spray forming, spray rolling, thin slab, and strip casting are reviewed. The second section of the document presents recent research on advanced forming processes. The various forming processes reviewed are: superplastic forming, electromagnetic forming, age forming, warm forming, hydroforming, and incremental forming. Optimization of conventional forming processes is also discussed. Potentially interesting light metal alloys for high structural efficiency including aluminum-scandium, aluminum-lithium, magnesium, titanium, and amorphous metal alloys are also reviewed. This section concludes with a discussion on alloy development for manufacturability. The third section of the document reviews the latest developments in fiber-reinforced composite materials. Emerging curing processes are presented along with a discussion on the possible developments in biocomposite materials. The fourth section presents recent developments in the fabrication of bulk nanomaterials and nanoparticles reinforced materials. Advanced joining technologies are presented in the fifth section. Future research is proposed in the last section.

Sheet Manufacturing Technologies

Direct Chill (DC) Casting and Rolling

Direct Chill Casting is one of the more significant technical innovations for aluminum manufacturing. The process was developed in the 1930s and still remains the principal process for the production of starting stock for subsequent rolling. In the DC casting process[2], molten aluminum is fed to a water cooled stationary mold that rest on a casting table. As solidification starts, the casting table is lowered and a continuous solid slab or ingot of aluminum is formed. The ingot is further cooled with water jets to continue the solidification of the molten ingot core. After casting, the ingot can be stress-relieved, scalped, cut to length and homogenized. A flowchart of typical DC-Casting/rolling mill operations is shown in Figure 1.

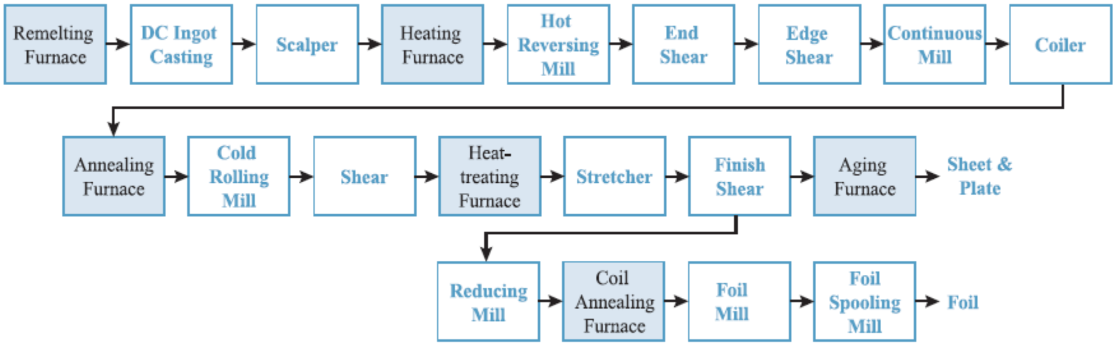

Figure 1 – Typical DC Casting/Rolling Mill Operations [2]

From Figure 1, it is obvious that the production of aluminum alloy sheets from DC cast ingots is an energy intensive process due not only to the numerous operations involved but also due to the multiple reheating steps. The combined energy[a] consumption for DC casting and cold rolling of aluminum is 1.65 (2.54^{tf}) kWh/kg. For hot rolling, the energy consumption is slightly lower at 1.63 (2.37^{tf}) kWh/kg. The complete energy profile of the aluminum industry, including sheet production by DC casting and rolling, has been reviewed in another detailed study[3].

DC casting and rolling is a mature process. No major breakthrough is expected in this technology therefore, most of the recent work done in regards to this process is optimization work and cost reduction via reduction of energy consumption. A good example of energy consumption reduction is the energy efficiency assessment that the U.S. DOE performed with one of the Pechiney Rolled Products division plants[4]. The energy efficiency assessment identified melting/casting, ingot reheating and rolling operations as the primary energy consumers in the plant. A detailed plant wide assessment (PWA) to analyze energy consumption was conducted by Pechiney to identify opportunities to improve energy efficiency and productivity. The PWA identified potential annual natural gas savings of 460,000 million Btu and 9.6 million kWh in annual electricity corresponding to an a reduction in CO_2 generation of 69 million pounds per year. On the optimization side, the work is focused around process control improvement and

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[a] "tf" superscript indicates a value that includes tacit and/or feedstock components

solidification process modeling[5, 6] in view of improving ingot quality consistency and productivity, principally by reducing ingot hot tearing and butt deformation defects.

Improvement of melting operations is also a key element in reducing the energy consumption in DC casting. The U.S. DOE recently completed a literature survey on advanced melting technologies[7]. Potential innovative melting techniques identified were electron beam melting, immersion heaters, infrared heating, microwave melting, plasma heating and solar furnaces. Even though they would allow for significant energy savings, the major implementation barriers for these techniques are high capital investment, low melting capacity and/or large space requirements. Among these techniques, immersion heaters seem to be promising and the U.S. DOE is pursuing a project in collaboration with the industry[8,9]. This technique is now made possible because of the availability of new construction materials for heaters that allow for immersion in molten aluminum.

Spray Forming

In spray forming, a liquid melt is gas atomized and the resulting spray is directed onto a substrate to form the desired shape. The best known spray forming process is the Osprey Process[10]. The process is used to manufacture semi-finished products for specialty materials. The main advantage of spray forming is the rapid solidification inherent to the process which promotes microstructural refinement and eliminates microsegregation.

Alcoa in collaboration with the U.S. Department of Energy participated in a project for the development of spray forming for manufacturing aluminum sheets[11]. The project was an extension of an earlier project for the development of spray forming for steel. Applied to sheet metal production, spray forming eliminates the reheating steps required for hot rolling in conventional DC ingot production for aluminum sheet manufacturing. The energy savings of spray forming over conventional DC casting was estimated at 15%. The spray formed material is metallurgically superior to DC cast material because the high cooling rate produces fine equiaxed grain and no macroscopic segregation of alloying elements. The inert atmosphere of the spraying chamber also allows low oxide levels.

Among various specific objectives, the project had the following two critical technical goals:

- Produce sheet free of interconnected porosity in surface layers such that no scalping or other mechanical processing would be required prior to subsequent rolling operation;
- Demonstrate interruption and restart capability.

The project evaluated two alloys: AA3003 and AA6111. Typical spray formed sheet showed significant porosity at the bottom and at the top surfaces. Surface pores could be as large as 200 μm and were often interconnected. The average grain size in the bulk of the deposit ranged from 10 to 40 μm and increased from the bottom of the deposit. The cooling rate of the atomized droplets was estimated to be between 10^3 and 10^4 °C/s. It was also determined that the cooling rate of the deposit decreased from 60 to 0.6 °C/s with distance from the bottom.

AA3003 alloy samples from trial spray forming runs were hot rolled, annealed and cold rolled to various work hardening conditions. The tensile properties of the spray formed aluminum alloys compared well with the properties of sheet produced from DC cast aluminum. AA6111 alloy samples were heat treated to T4, T6 and T8 conditions and their mechanical properties were within or above the range of typical DC cast produced alloys.

Spray Rolling

A variant of spray forming of aluminum[12] called spray rolling evaluated in a U.S. Department of Energy project in collaboration with the University of California-Davis, Colorado School of Mines, Alcoa, Pechiney Rolled Products, Inductotherm Corp., and Metals Technology Inc. In this process, liquid aluminum melt is atomized by inert gas injection. The resulting atomized spray is directed between two consolidation rolls, similar to a twin-roll caster. When the atomized spray reaches the roll surface, 30% of it remains in a liquid state. Thus, the metal is consolidated into strip (sheet) while still in a semi solid and highly formable state. The resulting sheet is continuously coiled. The benefits of spray rolling are:

- Increased metal surface area by a factor 10^{10} thereby allowing significant heat extraction rate which in turn reduces the need for cooling equipments and increased production rates;
- A cooling rate of one to three orders of magnitude higher, compared to twin-rolled casting resulting in fine grained material and absence of segregation;
- Elimination of intermediate DC ingot casting and hot rolling processes which corresponds to an estimated 4.6×10^{12} kJ/year of energy savings for the U.S. aluminum industry.

When compared to twin-roll casting, the advantages of spray rolling appear to be the high quality and production rate combined with the ability to process alloys with high freezing ranges.

Aluminum alloys AA3003, 5083, 2124, 6111 and 7050 were processed successfully in a laboratory-scale spray forming strip caster with the capacity to produce strips up to 200 mm wide and 1.6-6.4 mm thick[13]. Preliminary results indicated that the tensile properties of the strip materials met or exceeded those of strip processed by conventional DC casting route.

Thin Slab and Strip Casting

The development of continuous casters for aluminum products has been well documented over the past 50 years. Processes are classified according to the thickness that can be produced using either thin slab or strip casting. Thin slab and thin strip casting bypasses the semi-finished product stage, reducing reheating and eliminating a number of rolling steps, thus providing for considerable energy savings and significant improvements in productivity.

Thin slab casting is a continuous casting process that was developed in the 1950’s. One of the first commercial thin slab caster was the Hazelett[14,15] process. A typical slab caster incorporates two moving belts cooled by high velocity water jets[16]. Molten metal is fed into the caster through a nozzle or tundish placed between the casting belts. Metal block side dams move along with the bottom belt to contain the molten metal between the belts transversely. The side dam and the belts can be adjusted to cast slabs of different widths and thicknesses. Slab thickness can range between 15 and 150 mm, but typically corresponds to continuous hot rolling mill entry gauges, however, caster can reach widths upwards of 2500 mm. Continuous casting of aluminum alloys has been achieved on belt casters at rates of approximately 20 to 25 feet per minute at about ¾ inch gauge thickness reaching a productivity level of about 1400 lbs/h/in.

One problem with belt casters is that the belt is prone to distortion due to heating cycles. Block casters[17] avoid this problem by using a set of chilling blocks mounted adjacent to each other on a pair of opposing tracks. Metal is fed between the moving blocks and solidification is usually completed at a distance of about 12 to 15 inches from the nip. However, strict dimensional control of the block is required to avoid surface defects on the cast slab.

Strip casting was commercialized in the early 1950s[18]. Aluminum alloy sheets are mainly produced in a twin roll caster. In this process, the molten metal is introduced between a pair of counter rotating horizontal casting rolls wherein solidification is initiated when the molten metal contacts the rolls. The solid metal shell formed on the roll surface advances toward the point of minimum clearance between the rolls, referred to as the nip. When the metal passes through the nip, solidification is fully completed and the material undergoes deformation as it exits the rolls. Low alloyed aluminum alloys have successfully been strip cast at thicknesses of ¼ inch at rolling speeds of 4 to 6 feet/min (50 to 70 lbs/hr/in). The casting speed is restricted by the fact that an increase in casting speed will increase centerline segregation in the sheet. In particular, the central zone of the sheet will become enriched with eutectic forming elements (Fe, Si, Ni, Zn) and depleted in peritectic forming elements (Ti, Cr, V, Zr). Therefore, more highly alloyed materials (e.g. AA5XXX and 6XXX) are more difficult to produce by the strip casting process. Another aspect of the process is that the high separation force required to achieve the desired sheet thickness further limits the casting speed. This is because the aluminum strip is solid when it enters the nip, resulting in a required force of several tons per inch width. Difficulty in achieving uniform heat transfer as rolling speed increases also represents another impediment to increasing process speed. Commercial strip casters can produce strips with thicknesses ranging from 1 to 15 mm. Production rates can be as high as 3.2t/hr/m width[19].

Alcoa patented a process to overcome the speed limitations of strip casting[20]. Their process involves an apparatus similar to a conventional twin-roll strip caster with rolls having textured surface with surface irregularities of 30 to 50 µm. The surface irregularities in the form of grooves (or other shapes) increase heat transfer from the molten metal to the roll. The strip caster is operated in such a manner as to avoid complete solidification of the strip before it reaches the nip. This provides a significant benefit in reducing the roll separating force to about 25 to 300 lbs/inch of width. As a result, the grains in the strip retain their initial equiaxial structure formed during solidification. The patent claims that a thin gauge strip of 0.07 to 0.25 inch can be produced at rates of 2000 lb/h per inch of cast strip width.

A technique called melt drag twin roll casting (MDTRC)[21] that claims to improve the rolling speed is also reported in literature. In this process, only one of the rolls is immersed in the melt. Rolls are horizontal and the liquid metal level is maintained to correspond to the lowest part of the upper roll. Solidification occurs mainly on the lower roll which accounts for 80% of the solidified strip thickness. The low separation force of the caster enables copper rolls to be used. High conductivity of copper rolls allows increased rolling speed and eliminates the need for lubrication. AA5182 alloy sheets with thicknesses ranging from about 1 to 3 mm were cast at a speed of 60 m/min in a 100 mm wide laboratory roll caster. Successful production of high magnesium (10 wt %) aluminum strip was reported for the MDTRC process[22]. A variant of the MDTRC process with the two rolls being immerged in two different alloys were used to fabricate clad material[23]. Another technique called melt ejection twin roll casting (METRC)[24] was also proposed as a possible variant of twin-roll casting. METRC is a vertical strip caster in which the liquid metal is fed directly on one or two of the rolls. In the single ejector configuration, the melt is ejected from a slit nozzle by gas pressure onto the roll where most of the solidification occurs. The other roll contacts the meniscus of the melt pool. It is reported that AA5182 alloy was cast at rates of 120 m/min using this process.

Strip casting from a semisolid melt (a type of rheocasting) was also performed with the MDTRC process[25]. Molten A356 aluminum alloy was poured on a cooling slope to allow the formation of a slurry containing about 5-10% solid. The cooling slope was made from mild steel and coated with boron nitride. The slurry was then fed to the rolls of the MDTRC. The strip produced had grain size smaller than 50 µm and fine eutectic silicon smaller than 5 µm. Similar semisolid strip casting using a vertical twin roll caster is also reported[26,27]. Alloy AA5182 was successfully cast by vertical semisolid twin roll casting. Strips thinner than 3 mm were produced at speeds up to 150 m/min. Semisolid strip casting improved rolling speed, surface finish and reduced the tendency of the strip to stick to the roll even in the absence of lubricant. Semisolid strip casting was also performed with an unequal diameter twin roll caster with increased solidification length[28]. In this process, the upper roll has a smaller diameter size than the lower roll. The upper roll is positioned with an offset from the vertical axis of the lower roll such that rolling is performed at an angle. A back dam plate allows for a molten metal pool to be maintained in the bite of the two rolls and on the upper surface of the lower roll. Some metal solidification occurs on the surface of the lower roll that is immersed in the liquid metal. A twin-screw extruder has been proposed for the preparation of semi-solid slurry used in the twin roll casting[29]. This rheocasting technology was developed by BCAST (Brunel University) [30].

Sheet Metal Forming Technologies for Aluminum Alloys

Optimization of Conventional Processes

Descriptions of conventional aluminum forming technologies can be found in various textbooks[31]. Modeling of forming processes is used to predict whether a particular sheet metal part can be formed. Various computational methods have been used for the modeling of forming processes such as finite elements, neural networks etc. The literature for most of the methods can be found in specialized journals[32]. For conventional forming processes, the springback (elastic recovery) prediction for aluminum alloys is more difficult than for steel. The reason is that aluminum sheet materials may experience many reverse yields, and the Bauschinger effect[b] is more pronounced for these materials. Different models are being developed to predict springback but, to date, no generalized approach has been developed[33].

Advanced Forming Processes

Superplastic Forming

Typical aluminum alloy sheets can elongate 10-30% during forming. A class of materials, referred to as superplastic materials, can achieve elongation of more than ten times the level of conventional aluminum alloys. In the case of aluminum alloys, superplastic forming is generally performed at a temperature close to the alloy solution heat treatment temperature. Forming must also be done at low strain rates on the order of 10^{-3} to 10^{-4} s^{-1}. Owing to the low forming rate inherent to the required low strain rate, superplastic forming has been a niche area for the last few decades, primarily for aerospace applications.

There are several different types of superplasticity in terms of the microstructural mechanisms and deformation conditions. These are:

- Micrograin superplasticity
- Transformation superplasticity
- Internal stress superplasticity

Micrograin superplasticity is of significant importance in the fabrication of sheet metal parts. The basic requirements for micrograin superplasticity are:

- Very fine grain size of the order of 10 μm or lower
- High temperature forming of about one-half the melting temperature of the alloy
- Low strain rate between 10^{-3} and 10^{-4} s^{-1}.

Because of these requirements only a small number of commercial alloys will exhibit superplastic behavior. Moreover, theses alloys must be formed using methods and conditions that are different from conventional forming processes.

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[b] Any change in stress-strain characteristics for both single crystal and polycrystalline metals that can be ascribed to changes in the microscopic stress distribution within the metal.

The following processes have been reported for forming superplastic sheet materials:

- Blow/vacuum forming
- Thermo-forming
- Deep drawing
- Superplastic forming/diffusion bonding (SPF/DB)

Blow forming and vacuum forming are in essence the same process in that a gas pressure differential is imposed on the superplastic sheet, which acts as a diaphragm, causing the material to form into the die cavity.

The thermo-forming process is based on the well known method of forming thermoplastics. The die can be either male or female and is moveable. The moveable die aids in prestretching the sheet material before gas pressure is applied to make the sheet material form into the die cavity.

The ability to form superplastic aluminum alloys using blow/vacuum forming and thermoforming processes is the major advantage of this class of materials because those processes require only a single die as opposed to conventional deep drawing processes.

Conventional deep drawing assisted with heating can be applied to superplastic materials. However, the process does not offer significant advantages in the forming of superplastic materials as it depends on strain hardening to achieve the required formability and to prevent thinning and rupture during forming and that superplastic materials do not strain harden to any great extent.

SPF/DB is the combination of any superplastic forming (SPF) technique and diffusion bonding (DB). This process has evolved as a natural combination of the SPF and DB process because the temperature requirements for both processes are similar. Although diffusion bonding is not a sheet metal process, when combined with superplastic forming it provides such unique opportunities in fabrication methods that the two processes should be discussed together.

Aluminum alloys do not exhibit superplastic properties under conventional processing conditions. The aerospace industry first developed the AA2004 (Al-6Cu-0.5Zr) alloy, also known as Supral 100, for superplastic applications[34]. The alloy composition corresponds to a relatively large addition of zirconium which provides a dispersion of very fine Al_3Zr particles that stabilize the wrought structure developed during hot/cold rolling and prevent recrystallization until the onset of superplastic forming[35,36]. This alloy is a medium strength alloy with mechanical properties similar to AA6061 and 2219. It is usually used in lightly loaded or non-structural applications.

Aluminum-magnesium alloy AA5083 has been identified as a good candidate for SPF fabrication of automobile body parts[37]. This alloy is relatively inexpensive and it has good weldability, good corrosion resistance and moderate strength. Superplastic sheets of AA5083 can be manufactured by the addition of grain refiner elements such as Cu or Zr followed by hot cross rolling. Compared to other superplastic aluminum alloys AA5083 has a limited elongation limit of 600% under optimum conditions. Superplastic forming of AA5083 alloy was investigated in the temperature range of 480-530^{o}C at a strain rate of the order of 10^{-3} s^{-1}. The main issue associated with the use of AA5083 is the need to apply backpressure to suppress the formation of internal voids (cavitations) at high deformation. Minimum backpressure for inhibition of void formation is dependent of deformation, typically 2.5 MPa at 300% deformation. AA5083-H18 (Al-4.7%Mg-0.7%Mn-0.15%Cr) alloy SPF formed parts are currently produced and used in aircraft produced by Israel Aircraft Industries. AA5083 alloy has also attracted interest in the aerospace[38] industry for application in non structural parts due to its relatively low cost. Parts produced by superplastic forming of AA5083 are used by commercial aircraft manufacturers such as Boeing and Airbus[39]. Superplastic alloy AA5083 ALNOVI-1 has been approved by Airbus[40]. In a research project by Pacific Northwest National Laboratory, a lower cost version of superplastic AA5083 alloy was developed[41]. Superplastic elongation of 600% was achieved.

New production methods of superplastic aluminum alloy sheet with improved superplastic properties have been investigated. Severe plastic deformation (SPD) is a method that achieves remarkably small grain size of the order of submicrometer or even nanometer range. The fact that ultrafine grain size could be obtained by submitting metals to severe plastic deformation was recognized more than a decade ago[42]. One of the more convenient techniques for SPD processing is the Equal-Channel Angular Pressing (ECAP) method. In the ECAP method, the material is pressed through a die constrained within a channel that is bent abruptly through a sharp angle very close to 90^o. The process needs to be repeated many times to achieve substantial grain size reduction. In practice, the batch nature of the ECAP process, the high number of cycles required for developing a fine grained microstructure, and the force required to deform large billet limits the commercial viability of this process. A further limitation is that the ECAP process cannot be used directly to produce sheet metal[43].

A few SPD processing techniques for sheet metal have been studied. Accumulative roll bonding (ARB) is an alternative SPD technique to produce sheet metal. The process involves stacking two sheets of material of equal thickness, which are then rolled to exactly 50% reduction. The resulting sheet is then cut, stacked and the rolling process is repeated indefinitely with no reduction in sheet thickness. Laboratory accumulative roll forming was performed on 1mm thick AA6061 alloy sheet at strain rate of $18s^{-1}$, temperatures above 523K and 5 passes rolling[44]. Final grain size after ARB was on the order of 0.4 µm compared to 40 µm in the initial sheet material. The main limitation of ARB is that it is a batch process. The process is also sensitive to surface preparation to achieve proper bonding between the sheets. Furthermore, the textures developed during ARB are different from those obtained by conventional rolling which could impart deformation behavior and sheet formability[43].

Another proposed technique for the production of superplastic aluminum sheet is constrained groove pressing (CGP). In this process, the sheet material is subjected to repetitive shear deformation under plastic strain deformation condition by alternate pressing with asymmetrically grooved dies and flat dies[45]. During the first pressing performed with the corrugated die (i.e. grooved die), the gap between the mating dies is kept equal to the initial sheet thickness. The material in the inclined region of the dies is subjected to pure shear deformation under plain strain deformation. However, no deformation is induced in the flat region. Then, by subjecting the resulting corrugated sheet to a flat pressing under constrained conditions, the previously deformed region is subjected to reverse shear deformation while the previously undeformed region remains undeformed. After the second pressing, the sheet is rotated 180^o to allow the undeformed region to be deformed. By repeating the CGP process, a large amount of plastic strain can be accumulated in the sheet without any dimensional change. Commercially pure aluminum sheet having an initial grain size of 38 µm was CGP processed to give a 1 µm grain size[46]. A variant of the CGP process, continuous repetitive corrugation and straightening (RCS) was also proposed. In this process, the sheet material is continuously passed through two rotating corrugated cylinders (dies) and subsequently straightened by rolling in a standard two rolls rolling mill. This process has only been applied to pure copper for the production of sheet having grain size of the range of 20 to 100 μm[47].

Asymmetric rolling is another SPD processing technique. It involves rolling with an imposed shear deformation which changes the strain path and increases the total effective strain level for a given rolling reduction. This can be achieved by using a rolling mill with different upper and lower roll diameters or conventional mills having equal diameters rolls but with the two rolls operating at different speeds. Grain sizes of the order of 1 μm for AA6061 alloy have been reported[48]. Asymmetric rolling of AA6111 alloy and AA1100 pure aluminum sheets has been reported[49,50]. Asymmetric rolling is one of the more promising SPD processing technique for commercial implementation because it requires only minimal modification to existing rolling technologies and it can be operated continuously.

A new technique related to friction stir welding (FSW) called friction stir processing (FSP) was developed[51]. In this technique, a cylindrical rotating tool shaped as a pin with a shoulder, similar to FSW, is plugged into the material to be processed and moved along the direction to be processed. During FSP, the severe plastic deformation and friction between the rotating tool shoulder and the top surface of the base material both produce localized heating. It was found that the thermo-mechanical effect of friction stir processing enabled the grain refining of aluminum alloys. FSP of AA7075 alloy has been studied extensively[52,53,54,55,56,57]. Grain sizes on the order of 0.5 to 0.8 μm have been achieved using FSP leading to elongation as high as 1000% and strain rate of the order of 10^{-2} s^{-1}. Combination of FSP with controlled cooling has been shown to produce grain size as small as 100 nm[52].

General Motors Corporation patented[58,59] a process that forms superplastic aluminum alloy sheet, preferably AA5083, at elevated temperature. The process is referred to as Quick Plastic Forming. In this process, a sheet of AA5083 aluminum alloy having grain size of approximately 5 to 30 um is heated at a temperature of around 400 to 500°C. The sheet is stretched under the pressure of a working gas into conformance with the surface of a forming tool. The sheet forming pressure is increased gradually up to a final pressure of about 250 to 500 psi. Strain rates of the order of 10^{-3} s^{-1} can be achieved and forming can be performed within 12 minutes. The process is being used for production vehicles[60].

Electromagnetic Forming

Electromagnetic forming is a process that has been commercially used for the last 30 years primarily for the joining and assembly of concentric parts[61]. Electromagnetic forming (EMF) which uses electromagnetic forces to form the part is a high velocity forming technique. In the EMF process, a current pulse from a capacitor is passed through a coil that is located in proximity to the workpiece. The current pulse generates a strong magnetic field around the coil which, in turn, induces an eddy current in the workpiece. The eddy current itself generates a secondary magnetic field. The two magnetic fields are repulsive and cause the deformation of the work piece. The force is sufficient to stress the work piece beyond its yield strength, resulting in a permanent deformation. By nature, EMF is limited to conductive materials.

Electromagnetic forming has many advantages. First, the method has a high repeatability. This is because in an electrical process the energy output is nearly infinitely adjustable. Pressure accuracy of the order of one-half of one percent of the output setting can be obtained. Once the equipment has been setup for a given application, the only forming variable remaining is the material itself. In EMF, there is no contact between a tool and the work piece. The magnetic field that applies the pressure to the work piece requires no lubrication (except in some special cases), leaves no tool marks, and therefore requires no cleaning of the part after forming. Because EMF is a non-contact process, materials with surface finish can be processed without damaging the coating. The springback associated with forming using mechanical process is greatly reduced when using EMF due to the high velocity of the process[62]. Achievement of high forming rates is also an inherent advantage of EMF. In fact, the forming rate is only limited by the time required to load and unload the work piece. In a typical EMF process, the material can achieve a velocity of 100 m/s in less than 0.1 ms[63]. EMF is also known to increase the formability of some materials because of the absence of mechanical stress and friction encountered with mechanical forming processes. However, the basis for the increased formability in EMF is still a matter of discussion[64,65].

EMF processes have some limitations. Because the forming takes place in a very short period of time, the material does not have time to stretch. Thus, the process is not suited for deep drawing. Also, the maximum forming pressure that can be applied using conventional compression coils is about 350 MPa which limits EMF forming to relatively thin sheet material.

Ford, GM, and Daimler Chrysler in partnership with Pacific Northwest National Laboratory started in 2002 an intensive research program to develop EMF technology that will enable the economical manufacturing of automotive parts[62,66]. The project demonstrated the feasibility of EMF for aluminum sheet in automotive applications. The durability of coil systems and methods for the economical design, construction, and implementation still need to be demonstrated. Other recent university research has confirmed that EMF is a viable process for aluminum sheet forming[67].

A hybrid process integrating pulsed electromagnetic forming with conventional forming has been proposed[68]. In this process, the EMF is applied only locally to the difficult to form geometry of the part. Integration of EMF with the conventional forming method in this manner resolves the conflict between enhanced forming performance of EMF and the design issues of scaling up the process[69].

Age Forming

Age forming has been used primarily to form aircraft wing panels[70,71]. In age forming, a solution heat-treated, quenched, and cold-stretched material sheet is heated to a temperature sufficient for it to age, creep and allow stress relaxation to occur. Age forming can be performed on any heat treatable alloy in the AA2XXX, 6XXX and 7XXX series. In practice, the forming pressure is applied using common vacuum bagging and autoclave techniques similar to those which are used in the composite industry. During the autoclave process, the vacuum forces the material into the mold and at the same time, precipitation of intermetallic compounds occurs. Time and temperature cycles typically correspond to standard industrial aging practices[72]. Springback occurs following age forming because the limited aging time which is required to achieve optimum mechanical properties is not sufficient to convert elastic strain into permanent deformation. Some recent work has focused on the prediction of springback for age forming[73,74]. Age formed parts have lower residual stress compared to parts formed by conventional forming processes[75].

Age forming cannot generally be used on alloys in the damage tolerant condition (e.g. AA2024-T351)[76]. Therefore, one challenge for age forming is to obtain the best balance between operating creep and resulting part damage tolerance characteristics such as fatigue crack growth. To overcome this challenge, there is a need to introduce new alloys that can be used in artificially aged tempers. AA6056 and AA7475 have been shown to be less sensitive to the age forming process compared to the AA2XXX series alloy[77].

Warm Forming

Research has shown that increasing the temperature of aluminum alloys as part of the forming process allows for substantially greater elongation without fracture and without the use of excessive force. When forming aluminum alloys at an intermediate temperature below the recrystallization temperature, a significant increase in formability is achieved. This process is referred to as warm forming. Warm forming is a technology that shows some promise for improvement of aluminum alloys at high production volumes corresponding to strain rates of approximately 1 to 10 s^{-1}. Li et al.[78] have performed a detailed review of phenomenological observation related to the warm forming of aluminum alloys. The warm ductility of aluminum sheet alloys for automotive applications has been studied extensively[79]. Research focused mainly on the AA5XXX alloy series. Tensile ductility of these alloys was increased by a factor of 2 to 3 as temperature was raised from room temperature to 300°C. Commercial grade alloys AA5083 and AA5182 have been identified as candidates for warm forming. As a general rule, alloys with high magnesium content exhibit higher ductility.

Oak Ridge National Laboratory reports research on warm forming of aluminum alloys for automoitve body structures [80]. An AA5182-O aluminum alloy was used. Heating of the aluminum sheet was performed by infrared heating in an oven into which the sheet was continuously advancing on a conveyor belt. However, significant lamp overheating was necessary to achieve production-feasible heat-up time due to the high emissivity of aluminum. The overheating has the potential to melt the sheet if the conveyor is stopped. For these reasons, a conductive heating system was designed to replace the IR heating. Forming trials were performed in the temperature range of 200-350°C at strain rates of 0.015 to 1.33 s^{-1}. A wax based lubricant was used to provide sufficient lubricity. However, staining of the part due to the lubricant curing on the aluminum was a problem. Cleaning options and methodologies remain to be defined. Thermal modeling of the die and blank for determining optimal heater specifications for future tooling and process design was undertaken.

Novotny and Geiger proposed warm hydroforming of aluminum [81]. CANMET Materials Technology Laboratory is working on gas pressure warm forming of tubular aluminum alloy components and is planning to perform research in the area of sheet alloy forming using a similar process[82]. The process uses a modified hydroforming press in which the working fluid is nitrogen gas. The use of a gas instead of a liquid fluid eliminates the contamination of the workpiece and subsequent cleaning operations.

Hydroforming

Hydroforming is a well-known technique applied to tubular products in which a fluid medium such as water is confined inside the tube to apply an internal pressure that results in forming of the tube to the shape of a surrounding die. Sheet metal hydroforming is comparable to a stamping process. In sheet metal hydroforming, the punch or the die is replaced by a fluid through which pressure is applied to the work piece. There are various classes [83] of processes: hydroforming with a membrane diaphragm, hydromechanical deep drawing, hydraulic stretch forming, combined deep drawing and stretch forming and double-blank hydroforming.

The advantages of sheet metal hydroforming are:

- Higher and more uniform strain distribution over the entire sheet surface;
- Greater depth of draw (up to 1.5 X) when compared to conventional draw-die operations;
- Improved surface finish, lower springback, shorter tool development time and lower tooling cost.

However, due to long cycle time, sheet metal hydroforming is more suited for low-volume production.

General Motors Corp. used sheet metal hydroforming for the production of steel body panels on the 2006 Pontiac Solstice[84]; the first use of this technology for a production vehicle. Hydroforming achieved a uniform panel thickness and precise dimensional accuracy - particularly important due to the complex shape of the part.

Recent studies have indicated that 5754-CC alloy is a promising candidate for hydroforming applications[85]. Volvo[86] is reported to be using Schuler Hydroforming technology[87] to produce a hydroformed AA6XXX aluminum alloy chassis part.

Hydroforming of aluminum alloy sheet using a viscous pressure medium, such as a high viscosity polymer has also been proposed[88]. The process claims improved formability of aluminum alloys even though the benefits of the use of a viscous fluid remain unclear. One reported advantage of the process over conventional hydroforming with water is the improved sealing[89]. Some research work on viscous pressure forming has been carried out in China[90].

Incremental Forming

In incremental forming, a metallic blank is held at its periphery by a blank holder and a ball rolls on the blank to develop the desired shape[91]. Incremental forming was developed for small-batch production of sheet metal components and prototyping. The process enables a high degree of deformation to be achieved because deformation occurs incrementally. The Fraunhofer Institute patented a process in which a hammering tool (100 punches/s) and a robot are used to form sheet metal parts[92]. Demonstration of the process has been achieved on low complexity shapes.

Laser forming is also an incremental forming technique. In laser forming, the forming mechanism is the temperature gradient during which the sheet metal is formed by internal stress induced by the laser. Laser forming can be used only for the forming (bending) of simple shapes; mainly curved surfaces[93,94,95]. The process has been shown to be feasible for the forming of fiber metal laminates[96].

Shot peen forming is another incremental forming process used by the aerospace industry. In this process, shot peening is performed on the sheet metal part to induce an internal stress which in turn cause a deformation of the sheet. Shot peen forming of aluminum alloys is more effective in developing curvature than roll or stretch forming[97].

Light Metals Alloys

A brief summary of research and development of light metal alloys relative to manufacturability is provided below.

Aluminum-Scandium Alloys

Although a number of improvements in aluminum alloys achieved by scandium addition have been demonstrated, the current uses of such alloys are limited due to the high price of scandium[98]. The current price of aluminum-scandium (Al-Sc) is around US$ 2000 per kg of scandium; this means that for an aluminum alloy containing 0.2 wt% of scandium the corresponding cost increase is around US$ 4 per kg of alloy. Availability of scandium is another issue. Most of the scandium is produced in Russia from the reduction of Sc_2O_3. As the stockpiles of Sc_2O_3 will be exhausted within a few years, new production routes for scandium are being investigated. One possible route is the extraction of scandium from the Red Mud generated by the Bayer process.

The thermodynamics of Al-Sc systems in combination with other alloying elements have been studied extensively[98]. Initially, Al-Sc alloy development started in the Soviet Union. The main effect of scandium additions to aluminum is that they cause a very strong work hardening that increases yield strength on the order of 1000 Mpa per weight percent Sc, which is much higher than any other commonly used alloying element[99]. The strengthening effect of scandium is due to the formation of the intermetallic compound Al_3Sc in the aluminum matrix. This intermetallic compound has the same cubic face centered crystalline lattice as the aluminum with their lattice parameters differing only by about 1%. After aging, Al_3Sc precipitate size is in the order of 10 nanometers. Scandium is also a very effective grain refiner[100,101]. Fine grain size is stabilized by the fact that scandium inhibits recrystallization. As an example, Al-0.26Sc alloy has a recrystallization temperature of 540°C compared to around 150°C for pure aluminum. Increases in the alloying element content further increase the recrystallization temperature to the point that some alloys do not exhibit recrystallization when heated up to the their melting point. The small grain size contributes to the good formability of Al-Sc alloys. Al-Mg-Sc alloys have been proposed as good candidates for superplastic forming[102]. For example, the addition of 0.22 wt% Sc into an Al-6Mg followed by conventional superplastic conditioning treatment has produced a maximum elongation of 1200%, which corresponds to a four times elongation increase compared to the original alloy.

Scandium addition has a favorable impact on weldability, believed to be due to the presence of fine grained microstructure in the weld and in the heat affected zone[103]. As a result, the tendency for hot cracking during welding is lowered. Filler metal containing scandium has also resulted in improved weldability of aluminum alloys[104].

Good stress corrosion cracking and exfoliation resistance were reported for Al-Mg alloys containing trace amounts of scandium[105]. In some other studies, the corrosion behavior of Al-Mg-Sc is reported to be better than Al 5456 and Al 6061 alloys, which are well known for their performance in seawater service[106,107,108].

To date, the use of Al-Sc alloys is limited to some niche markets such as sporting goods such as baseball bats, bicycle frames and welding wires. Easton has developed a 7XXX series alloy, termed Sc7000, containing scandium. The alloy is reported to have yield strength as high as 68 ksi[103]. The main commercial alloys available are produced in Russia[109].

Interest in scandium modified aluminum alloys has been renewed in the aerospace industry. Major aluminum rolled product manufacturer Corus is co-developing an Al-Mg-Sc-Zr in the 5XXX series alloy sheet in collaboration with Airbus[110]. This alloy has excellent fatigue crack growth resistance, low density (2.65 g/cm^3), good weldability and creep forming capabilities. Recently, it was reported that Al-Mg-Sc sheet alloys for fuselage applications were developed by EADS Deutschland GmbH[111]. Significant research work is currently ongoing[112] on the development and characteristics of Al-Sc alloys.

Aluminum-Lithium Alloys

Aluminum-lithium alloys have been attractive for aerospace applications because they have a lower density and higher modulus than conventional aerospace alloys. Each percent of lithium lowers the density of aluminum by approximately 3% and increases the modulus by approximately 6%. However, Al-Li alloys have not yet received widespread usage. The cost of Al-Li alloys which is typically three to five times that of conventional aluminum alloys and the difficulty of processing these alloys have limited their use. Applications include some specific uses in military aircraft and in the U.S. Space Shuttle[113]. Weldable Al-Li alloys have been developed.

Magnesium Alloys

Although magnesium alloys offer a signifcant potential for weight reduction in automotive applications, at the present time only an average of 12 lbs of magnesium is used per vehicle, principally as nonstructural die-casting[114]. The advantages of magnesium are its lightweight (density of Mg is 1.8 g/cm^3 which is about two third that of aluminum alloys), high specific strength and stiffness, good damping characteristics and acceptable weldability. The high specific strength, notably the high specific flow stress of magnesium, could enable weight savings up to 30% compared to aluminum[116].

The disadvantage of magnesium alloy sheet is its poor formability at room temperature which is the result of the hexagonal lattice structure of magnesium. Formability of magnesium alloys can be improved by warm forming at higher temperature[115]. As an example, formability of AZ31 alloy, measured in a deep-drawing test[116], reaches its limit drawing ratio at a temperature of 275°C. AZ31 alloy sheet is currently the only sheet material available[128,117,118]. The mechanical properties of AZ31 are comparable to those of conventional aluminum sheet material used for car body applications with a yield strength around 200 MPa and rupture elongation of 20 %.

A detailed evaluation of current wrought magnesium alloys was performed by Bettles and Gibson[119]. In their work, the minimization of asymmetric yield behaviour due to strong texture generated by rolling processes was identified as a factor limiting broader use of wrought magnesium alloys. Mg-Li alloys,with a density in the range of 1.45-1.56 g/cm^3 have been investigated for automotive sheet applications[120]. Russian researchers have developed two commercial Mg-Li alloys (MA21 and MA18). Recent developments in the U.S. include alloys based on the Mg-Li-Al-Rare Earth which shows a decrease in yield asymmetry and an increase in ductility. It is reported in a patent that increasing lithium content above 6% in a Mg-Li alloy initiates the formation of a body-centered cubic structure that increases ductility[121]. Improved formability of Mg-5Li alloy over AZ31 has also been reported[122].

Twin-roll strip casting of magnesium alloy AZ31 was achieved by Commonwealth Scientific and Industrial Research Organization (CSIRO) for the production of thin strip in an industrial scale pilot plant. The technology was developed in 2000 and is described in a patent and various papers[123,124,125]. The caster is similar to that used for strip casting of aluminum except that the melt delivery system is modified to account for the reactivity of magnesium. For this purpose, a mixture of SF_6, 1,1,1,2-tetrafluoroethane and air is used as a cover gas during casting. One of the challenges of casting magnesium alloys is their wider freezing range compared to aluminum alloys. It is reported that the cooling rate is in the order of 500 to several thousand of degrees per second which leads to a high homogeneity of the microstructure (especially minimizing the size of manganese-rich particles) and refined grain size. As a result, mechanical properties of the sheet material are improved compared to the conventional process. The pilot plant operation has produced 2.5 mm thick and 600 mm wide strip in commercial quantity. The research focus is now on lowering the construction and operation costs of the metal delivery system. ThyssenKrupp Stahl AG also developed a strip casting process for the production of magnesium sheet[126]. Semisolid strip casting of magnesium alloys has also been reported[127].

A limitation of magnesium wrought alloys is their relatively low corrosion resistance. A goal for magnesium alloys would be to produce high purity wrought products with a corrosion resistance comparable to magnesium die casting alloys[128]. Magnesium alloys require corrosion protection in the form of passivation or anodic oxidation. Commercial corrosion protection methods are available. Cladding of Mg-Li alloys was proposed as a corrosion protection treatment[129].

Magnesium alloys are weldable by a variety of process. Laser welding[130], gas tungsten arc welding and gas metal arc welding are effective techniques for welding magnesium alloys. Friction stir welding has been applied to weld magnesium alloys to themselves and to aluminum alloys. However, it appears that further development is needed to obtain joints as strong as the base metal[131].

Titanium Alloys

Titanium alloys have been used in the aerospace industries mainly for structural applications. Titanium alloys have very high specific strength. As an example, Ti-6%Al-4%V (4.43 g/cm^3) in aged condition has a specific yield strength of 1100 MPa compared to 462 MPa for 7075-T6 structural aluminum alloy (2.81 g/cm^3) . Superplastic forming of titanium alloys at elevated temperatures (750^{o}C) has been used to fabricate production parts[132]. The formability of commercially pure titanium at low temperatures (200^{o}C) has also been demonstrated[133]. Recently, Gamma-TiAl has been proposed as a sheet material for the fabrication of high temperature engine components using superplastic forming [134] . The main disadvantages of titanium alloys are their high forming temperature and their high cost. The high cost of titanium alloys is due to the current production method of titanium that is extremely energy, labor and capital intensive.

Amorphous Metals

Amorphous metals (or metallic glass) are a relatively new class of materials which possess exceptional hardness, strength, damage tolerance, and corrosion resistance. Most metallic glasses require very rapid quenching from the liquid state to retain their amorphous structure. Two recent advances are reported in the literature[135]. One advance is the discovery of a family of multicomponent alloys involving Zr, Fe and Mg based systems that can achieve the amorphous state in bulk volume at slow cooling rates or during intense deformation of a layered component assembly. The second advance is the discovery of Al and Fe based alloys that can be produced by rapid quenching. The Al alloys are of interest due to their low density and hence high specific properties. Metallic glasses typically have a fracture stress that is about 2% of the elastic modulus, so that metallic glasses have roughly double the strength of crystalline alloys of the same alloy base element. Thus, strengths of up to 1500 MPa have been measured for amorphous Al alloys[99]. Amorphous aluminum alloys are generally based on the Al-RE-TM[c] system[136].

Boeing is conducting some research work for the development of metallic glasses for aerospace application[137]. Oak Ridge National Laboratory has conducted research to develop techniques for rapid solid or liquid state sintering of difficult-to-process materials in sheet form and in mildly complex shapes. The technology is based on a high density radiant infrared (IR) source. The ORNL IR technology produces extremely high power densities up to 3.5 kW/cm^2, radiant energy in the 0.2 to 1.4 micron range, and power delivery widths of up to 35 cm. This capability provides a means for selective directional energy sintering or melting to allow for large buildups of controlled cooled metals. In other research, the feasibility of manufacturing bulk Zr and Cu based bulk amorphous alloys by the twin-roll strip casting process was demonstrated[138].

Alloy Development for Forming Processes

The lack of predictive capabilities for the development of alloys and forming methods is a limitation that was highlighted in previous roadmap for the aluminum industry[139]. That is, the capability to use the formed part requirements (mechanical properties and shape) and to then directly relate those requirements to alloy formulation and process design is limited. Predictive capabilties can be developed empirically by developing a materials properties database linked to process parameters[140]. Limited work has been conducted in this area and development of empirical data is relatively expensive intially. Quantum analysis has been used for the prediction of thermodynamic properties of alloys[141] and their integration into mechanical and thermal properties simulation software[142, 143]. The method has been shown to reduce the development time for new high strength ferrous materials. However, this technology has not been applied to aluminum alloys or other light metal alloys and does not generally relate to forming processes. Conventional thermodynamic modeling packages are also useful for the prediction of phase equilibrium[144]. In forming, the final properties of the part are closely related to the initial properties of the sheet that in turn are determined by the microstructure of the part. Various approaches have been taken for modeling of microstructure evolution during rolling of aluminum. Mathematical models of this nature attempt to describe the complex interactions between deformation, heat flow, and microstructural evolution that occur during the rolling process[145]. Fraunhofer IWM Institute has developed a simulation package that is reported to be applicable to steel, magnesium and aluminum[146].

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[c] RE : Rare Earth, TM: Transition Metals

Fiber-Reinforced Composite Materials

Overview of Manufacturing Processes

Composite materials[147] use began with the aircraft industries in the 1960s. Initially, composites were limited to non-structural applications, but with the advent of carbon fiber, composite materials were used in structural applications. Composite materials are now being used increasingly for structural parts in the aerospace industries and the auto industry has started to consider the use of composites for series production of structural parts.

Polymer composite materials can be divided into two classes[148]: thermoset and thermoplastic matrix. Traditionally, thermoset resins have been used as a matrix material for fiber-reinforced composites. Thermoplastic resins have several advantages over thermoset resins. Among these are: unlimited shelf life at room temperature, shorter fabrication time due to the absence of cure, possibility of thermoforming, ease of welding, and ease of recycling. In spite of these advantages, the development of thermoplastic resins has been slower because of high melt viscosity that leads to some difficulties of incorporation of continuous fibers as required by the aerospace industry. Also, the common commercial thermoplastics resins did not possess sufficient creep resistance and thermal stability. However, recent thermoplastic resins such as polyether-ether-ketone (PEEK) and resins from the polyimide family have high heat resistance and could be used in high performance composite materials.

Thermoset or thermoplastic resins are available in the form of prepreg which consist of a mat of the fiber reinforcement impregnated with resin. Prepregs are used to manufacture parts by hand-lay up, a process in which prepreg sheets are stacked in a mold, enclosed in a vacuum bag, and cured at high pressure in an autoclave. The bag molding process is used mainly in the aerospace industry where high fiber content is required along with very high mechanical properties. Sprayable vacuum bags have been proposed recently to increase productivity of the process[149].

The recent developments[150] in manufacturing processes for continuous fiber composites have focused principally on reducing process cycle time by using a liquid molding technique as opposed to hand lay-up of prepregs. These advanced manufacturing processes are: resin transfer molding (RTM), vacuum assisted resin transfer molding (VARTM), structural reaction injection molding (SRIM), resin film infusion (RFI), and their variant.

The aerospace industry has recently announced its use of filament winding for the production of a composite fuselage. Boeing will build the fuselage of the 787 Dreamliner from filament-wound sections of carbon reinforced composites[151,152]. Advantages of a composite fuselage are the reduced weight of the structure and better dent resistance of composite materials compared to aluminum alloys. Similar projects have been conducted in Europe[153].

Curing Processes

One of the limitations of composite manufacturing is the long cycle time due to the curing of thermoset resins. Additionally, the curing temperature is relatively high, which in turn requires the use of expensive metallic molds. Recent advances in this area involve using modified resins along with different heat sources to reduce cure time. Among the proposed curing processes are ultraviolet (UV), electron beam and microwave assisted curing. Endruweit, *et. al.*[154] have performed a detailed review of UV curing of fiber reinforced polymer composites. Curing of polymer matrices with UV radiation can be applied to a variety of conventional composite manufacturing processes as long as the part can be directly irradiated. Process film that is used in vacuum bagging of parts can still be used as long as they are transparent to UV radiation. Masking of the laminate with an opaque film allows selective local irradiation and local curing of the part. After the removal of the opaque film, a second laminate can be overlapped onto the uncured area of the part. The curing of the assembly results in a primary bond between the part and the second laminate. An example of this technique is the bonding of stiffeners onto shell structures. Cure cycles are minimized when the material is completely transparent to UV radiation. This is the case for epoxy resin/glass fiber composites. Expected cure cycles are on the order of minutes. However, carbon or aramid fibers are not transparent to UV radiation and laminates can only be cured to the B-stage. Filler pigments can also interfere with UV curing. This problem is overcome by the use of a dual curing resin formulation with a photoinitiator and thermal initiator. The resin is first cured by UV radiation and the balance of the resin that was shadowed by the fibers is cured by conventional thermal curing. However, the cycle time is increased with the dual cure. A major advantage of UV curable resin over conventional prepreg material is that they do not require storage at low temperatures. It is also reported that UV curing can reduce volatile organic compounds (VOC) emissions by 60 to 90% compared to conventional resin systems[155].

Electron beam curing (EB)[156] of composites was investigated between 1994 and 1997 as part of a US DOE Cooperative Research and Development Agreement (CRADA). The project led to the development of several toughened and non-toughened EB-curable epoxy resins. Prepreg, filament winding and vacuum assisted resin transfer molding (VARTM) technologies using EB-curable epoxy resins were all demonstrated with success. The cost reduction associated with electron beam curing has been estimated to be between 10 to 50% for the aerospace industry[157]. Another advantage of EB-curing is its ability to combine several different resin systems in the same curing cycle. Because EB-curing can be programmed to expose a given area of a part to a specific amount of radiation, materials that would normally require different curing temperatures can be processed in the same curing cycle. Among the reported advantages of this method is the reduction of the residual internal stress in composite parts[158].

Microwave curing has also been investigated as an alternative to conventional thermal curing. In recent work[159, 160], it was demonstrated that the mechanical properties of microwave cured glass/epoxy composite were similar to those of the same thermally cured material. The epoxy resin used in this work was a commercial grade resin. Identical glass transition temperatures were determined for both the microwave and the thermally cured composite. The microwave cure was 30 times faster than the thermal cure and the microwave cure was 20 times more energy-efficient. Investigation of curing composite materials with microwaves has been constrained due to the lack of a sufficient homogeneous electromagnetic heating field or reasonable cost for suitable source and components providing industrial scale up. A novel industrial microwave system HEPHAISTOS-CA2 (High Electromagnetic Power Heating Automated Injected Structure Oven System)[161] for curing carbon fiber reinforced composites is being developed at Forschungszentrum Karlsruhe (FZK) in Germany. The system has been operational since the end of 2005 and integrates the basic processing steps of a liquid resin infusion (LRI) process which are: tooling, tempering of the resin and lay up, the impregnation of the fibers, pre-forming techniques and the curing of the composite. Among reduction in cycle time and energy savings due to the selective heating of the composite part (i.e. the oven and other components are not heated), one of the other advantages of this technology is the possibility to effect rapid control of the process due to the absence of thermal inertia. This is particularly important in controlling the temperature in the presence of overheating due to exothermal reactions in the material. One of the key features to apply this process to carbon reinforced composite is the use of a highly homogenous electromagnetic field distribution. This is essential for carbon fiber composites because the fibers have high microwave reflectivity and the tendency for arcing and breakdown at loose ends. Demonstration parts were successfully manufactured using RTM and LRI process with the HEPHAISTOS-CA1 unit. Compression strength was measured and found to be 20% higher than for conventional autoclave cured composite and the parts were substantially free of voids. The "CA1" unit was evaluated by EADS Corporate Research Centre[162] and the "CA2" unit was developed based on it.

Biocomposites

An area of great interest is the development of biopolymer composites (biocomposites). Natural fibers such as wood fibers have been used to reinforce both thermoplastic and thermoset plastics in the automotive industry. The University of Michigan has conducted a number of research projects on the development of composites including natural fiber composites[163]. Recently, a patent application was filed for a sheet molding compound using a natural fiber as reinforcement[164]. The sheet molding compound is in the form of a prepreg.

A breakthrough technology would be the development of a natural polymer matrix that would be combined with natural fibers to produce a composite material of appropriate mechanical and physical properties. This system would be totally based on renewable sources. Until recently, biopolymer research has focused mainly on the development of biodegradable polymer like Polylactic Acid based polymer (PLA)[165]. Even though they are biodegradable, these polymers can achieve interesting mechanical properties. For example, pure PLA has a tensile modulus of 3 GPA, tensile strength 60 MPa and elongation at break 4% which is comparable to molding grade polypropylene[166].

Recent development in Composites

Fiber-metal laminates

Fiber-metal laminates have found applications in the aerospace industry. This material is a hybrid made up of aluminum sheet with a layer of fiber composite in between. These materials have high fatigue resistance and are resistant to burn through. Commercial[113] materials include ARALL (aramid-fiber-reinforced) and GLARE (glass-fiber-reinforced). The main problem with fiber-metal laminates is the lack of formability when used in combination with thermoset resins. Research in the development of formable metal/polymer composite laminates is currently ongoing at the Australian National University[167].

Metal Matrix Composites

Metal matrix composites have mostly been used for structural components. Metal prepreg is an technology that allows the extension of metal matrix composite to the fabrication of sheet. Metal prepreg is similar to polymer prepreg except that the fiber binder is a metal. Aluminum alloy prepregs are now available commercially[168]. The same manufacturing techniques that apply to conventional composite manufacturing can be used for metal prepreg. Development work of metallic prepreg focused on the combination of an aluminum alloy matrix and Al_2O_3 fibers although any combination of aluminum and fibers is possible. Metal prepreg can also be use for selective reinforcement to provide additional strength or stiffness in specific areas[169] of a part.

Another process, employing thixoforming, was proposed for the fabrication of composite sheets[170]. In this process, a carbon fiber cloth and alternating aluminum foil (AA5182) are laminated to form a prepreg. Alternatively, the prepreg can be fabricated by thermal spraying the surface of the cloth with the appropriate aluminum alloy. The material is then thixoformed to the desired shape. An advantage of the thixoforming process is a reduced fiber damage due to the chemical reaction.

Nanomaterials

Metallic

Nanotechnology comprises technological developments on the nanometer scale, usually 0.1 to 100 nm. Figure 2, shows the impact of reducing grain size (D), strengthening precipitates or dispersoids size (δ) and increasing volume fraction (d) on strengthening in metallic alloys.

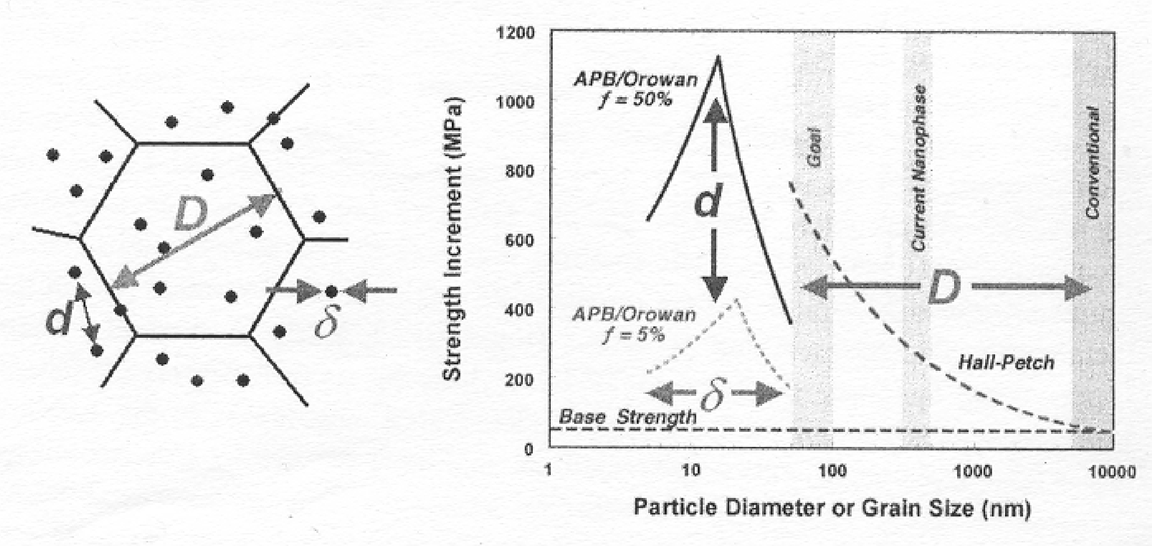

Figure 2 – Influence of length scale on strengthening mechanisms in nanoscale metals

From Figure 2, it is clear that nanoscale structures can have a significant impact on the strength of metals.

In the area of metal forming and fabrication, nanomaterials must be available in the form of a bulk nanostructured material which can further be defined by a bulk solid with nanoscale microstructure. Presently, the most common process to manufacture nanomaterials is high intensity ball milling and therefore material must be processed through powder manufacturing techniques in order to obtain a bulk solid. Bulk nanocrystalline aluminum alloy AA5083 was produced in a laboratory from mechanically milled powder of the same alloy under liquid nitrogen atmosphere (cryomilling) followed by hot isostatic pressing and extrusion at 250°C. The resulting material had a thermally stable grain size of 25-35 nm at the processing temperature. The material was found to have about a 30% increase in yield strength and ultimate strength compared to commercial 5083-H343 alloy and no decrease in elongation was observed. Friction stir welding has also been explored as a technique for the processing of nanoscale grain bulk aluminum alloys. In a laboratory work, nanocrystalline 7075 aluminum alloy with an average grain size of 100 nm was prepared by friction stirred processing[171].

The incorporation of magnetic and electrically conducting nanopowders to composite materials could allow for new design approaches for composite applications. It was reported that nano-scale ferrite powder was added to an epoxy resin and submitted to microwave curing[161]. The ferrite powder has a magnetic permeability of $\mu_y > 1$, that significantly increases the strength and the density of the electric field pattern within the resin sample. This causes a stronger heating for the same microwave radiation applied.

The US DOE is involved in the development of nanotechnology through Vision 2020 Chemical Industry of The Future[172]. This program is more oriented toward the chemical industry and not toward the manufacturing industry. As a result, the production of bulk nanocrystalline material is absent from the program. However, research needs for nanotechnology commercialization[173] have been established and could serve in a program oriented toward the manufacturing of bulk nanocrystalline materials. The only aspect that relates to the fabrication industry is the use of nanocrystalline hard coating to improve tool life in manufacturing processes[174].

The European Commission has elaborated a roadmap for the use of nanomaterials in the automotive sector[175]. However, the guidelines of the roadmap are somewhat vague probably due to the fact that nanotechnology is a relatively new field and challenges are not very well defined at the moment.

Composites

Composite materials can also benefit from nanotechnology. It was shown that addition of nanoparticles of SiO_2 and $BaSO_4$ to an epoxy resin improved the properties of the final composite without reducing the fluidity of the resin[176]. Low viscosity is very important in injection manufacturing techniques of composites. A nanoclay-reinforced polypropylene polymer composite has been proposed as a substitute for steel or aluminum in light-duty vehicle body panels[177]. The addition of nanoclay in polypropylene improves the mechanical properties, principally Young's modulus, of the polymer. The use of carbon nanotubes to manufacture carbon fiber has also been investigated[178]. Yarns of limited size (30 cm) have been produced in a laboratory environment but yarn properties remain to be optimized.

Joining

The use of light metals and composite materials in combination with conventional materials like steel brings some new challenges in the joining of materials.

The ability to develop automated welding processes to assemble body parts is of critical importance for the automotive industry and any other mass production environment. Most of the welding performed on the body and frame in the automotive industry is made by resistance spot welding (RSW) of steel. The RSW process has also been developed for aluminum alloys with patents dating back to the 1930s. The process is similar to the RSW of steel alloy except that aluminum alloys require higher welding currents and very uniform pressure due to their high electrical conductivity. Recent work in this area has focused on extending electrode life and improving weld quality. However, weld consistency still remains to be proven[179]. Another process for spot welding of aluminum alloys is friction stir spot welding (FSSW). FSSW is a patented[180] process that uses a technology similar to friction stir welding to make overlap joints. A tool similar to that used for friction welding is brought into contact with the surface of the two aluminum sheets to be joined while applying a pressure[181]. The pin of the tool penetrates into the material and continues to travel past to fray the surface between the upper and lower sheet. The displaced and plasticized material forms a fully consolidated weld. The FSSW process is a viable method for production spot welding of aluminum alloys and the process is at the optimization stage. It is reported that FSSW of aluminum and steel was achieved by Mazda Motor Corp. by optimizing existing FSSW process parameters and using galvanized steel instead of bare steel.

Self-pierce riveting is another process that has been identified as a potential technique for automotive body part assembly. In this joining process, a tubular (hollow) steel rivet with a flat head is pushed through the stack of aluminum sheets to be joined without the need to drill a hole. Self-pierce riveting combines the ability to join multi-layer multi-material stacks with good shear and peel strengths. Briskham[179] *et. al*. have performed a comparison study of self-pierce riveting, resistance spot welding and friction stir spot welding. The main features of the three joining method are summarized in Table 1.

Table 1 : Comparison of Automotive Body Welding Processes [179]

Self-Pierce Riveting + Best mechanical properties + Possibility of mixed material joints when used with adequate corrosion protection - Ongoing cost of rivets - Gun flexibility is required due to the different size of rivets required to join different sheet thicknesses
Resistance Spot Welding + Low cost of equipment + Gun flexibility and automation - Consistency remains to be proven - Electrode maintenance needed
Friction Stir Spot Welding + Ability to join thin materials + Low operating costs - Long process times for thick materials - Gun flexibility is low due to the specific tool geometry needed for different type of joints

Plasma arc spot welding of aluminum and magnesium alloys has also been investigated as a potential technique for welding automotive bodies. The process itself is not new[182] but its application to light metals alloys is. The US Department of Energy is supporting research to demonstrate this process[183]. Feasibility of the process was demonstrated but use of filler rod was necessary to eliminate microcracking in the spot weld.

One area where joining of dissimilar material is obvious is the fabrication of tailor welded blanks (TWB). A tailor-welded blank is one part made up of different materials and/or the same material with different thicknesses welded together. The blank is then formed into the desired shape. The main advantage of a tailor-welded blank is that it allows the placement of the optimum material or thickness where the part requires specific properties. The process allows weight reduction because no reinforcement is required. Tailor welded blanks have been used for the manufacturing of steel automotive body parts where laser beam welding has been adopted for joining[184]. The same benefits also apply to welded blanks made of aluminum alloys. Laser beam welding has been used successfully to manufacture welded blanks of 1 mm and 2 mm AA5182-H00 aluminum alloy[185]. However, lower formability was reported. Although laser beam welding is used in industry, it is still not a mature process. Areas of improvement in laser beam welding of aluminum alloys include: control of alloying element loss, control of porosity formation, control of weld pool geometry, from the point of view of understanding the physics of the process[186]. Friction stir welding (FSW) is a promising process for the manufacturing of tailor-welded blanks. FSW can be applied for the manufacturing of tailor-welded blank of aluminum alloys. FSW was used to manufacture hybrid TWB of AA5182 aluminum alloy and SAE 1006 steel[187]. The hybrid TWB was submitted to deep drawing and its maximum drawing ratio was identical to the maximum drawing ratio of the 5182 alloy. Other studies[188] on the formability of friction stir welds in the automotive stamping environment have shown that FSW had significant advantages over fusion welding process. Airbus[189] announced that it plans to begin using FSW (instead of traditional riveted joints) to weld together longitudinal fuselage skin joints of production aircraft.

Composite-to-metal joining has usually been performed in the aerospace industry by using mechanical fasteners (bolts, rivets, etc.) or by adhesive bonding. Adhesive bonding is seldom used alone but rather in combination with mechanical fasteners for load transfer purposes. The benefit of adhesives has been demonstrated by a number of car manufacturers mainly in concept cars and low volume products[190]. Adhesive bonding has many advantages:

- Improved joint stiffness compared to spot welding
- Energy absorption leading to good noise and vibration damping properties
- Ability to prevent moisture ingress in the structure by sealing the joints
- Good fatigue resistance due to smoothness of joint
- Dissimilar metals assembly is possible since the joint isolates the materials

However, the process of adhesive bonding has some limitations. Most of the structural adhesive systems are epoxy or solvent-based. This is an important environmental concern as well as health and safety issue in the work environment. Curing is required for adhesive bonding which is also a limitation of the process. However, Lotus has demonstrated that the curing of the adhesive can be achieved during the paint-baking process[191]. Limited shelf-life and an increase in viscosity of the adhesive is another issue in production. Also, adhesive joints are inherently weak in peel which needs to be taken into consideration when designing with that type of joint.

Thermoplastics can be more easily bonded to themselves and to metals than thermoset materials because of their ability to be melted. The most promising bonding techniques for thermoplastic matrix composites are ultrasonic, induction, and resistance welding[192]. Ultrasonic welding of metal-composite joints has been investigated but the problem of fiber damage was highlighted [193]. The use of thermoplastics as a hot melt adhesive for bonding dissimilar materials has been investigated. The process requires surface preparation similar to bonding with a conventional solvent based adhesive. Joint properties can be similar to conventional epoxy based resin. The main advantage of hot melt adhesives is that they do not contain solvents.

Recently a new process for the bonding of composite to metal surfaces was patented by TWI under the trademark of COMELD[194]. The process uses co-curing of the composite material with a metallic insert to allow the composite part to be welded to a metallic structure. The COMELD process includes a special surface preparation step of the metal insert before curing. This pre-treatment is called the Scurfi-Sculpt[195,196] and uses an electron beam to reshape the material precisely in order to create protrusions on the surface of the material. These protrusions allow increased bond strength between the composite and the metallic part. Bond strength improvement on the order of 40% has been achieved when compared with co-curing untreated metallic parts. The process is very flexible as it allows finished metallic parts to be prepared for bonding as required anywhere on there surface.

Ultrasonic welding of aluminum foils has been used for various applications in the industry. The US DOE has a research program on ultrasonic welding for advanced transport systems[197,198,199]. In this process, an electromechanical converter (e.g. piezoelectric transducer) converts high-frequency electric current to mechanical vibrations. The vibrations are then modulated and amplified when applied to the work piece through a sonotrode. Moderate force is applied to the work piece and the sonotrode to ensure that the mechanical vibrations are transferred to the sheets interface. Typical pressures of 70 psi have been used successfully. The process parameters for the sonotrode are 20/40 kHz and amplitude of 5 to 50 μm. The feasibility of welding various aluminum, magnesium, and steel alloys to themselves and in combination has been demonstrated. The welding time for ultrasonic welding is comparable to the production rate of conventional resistance spot welding of steel.

Future Direction of Research

Sheet Manufacturing Technologies

From this literature review, it appears that the DC casting process is a mature process that only requires optimization toward improving ingot quality, consistency and productivity, principally by reducing ingot hot tearing and butt deformation defects.

The production of aluminum sheets by spray forming and spray rolling has been the subject of extensive research in the past years. The research has been devoted exclusively to continuous manufacturing of sheet by spray rolling. High capital cost might also be a major road block to the commercialization of the spray rolling process. The area of conventional semi-solid forming (rheoforming) of aluminum sheet has been somewhat neglected. Rheoforming could possibly allow for the processing of alloys having large solidification range and produce high homogeneity, fine grained material. Rheoforming of aluminum sheet can be achieved on equipment similar to conventional twin roll caster and therefore retrofitting might be relatively simple compared to spray rolling.

Several advanced melting techniques were reviewed: electron beam melting, immersion heaters, infrared heating, microwave melting, plasma heating and solar furnaces. The two more promising technologies are immersion heaters and plasma heating. A new torch configuration/technology should be developed to be able to operate in the immersed mode which is the optimum configuration to minimize radiation heat loss. Innovative nanotechnology based materials should be evaluated for the fabrication of immersion heater. The use of nanomaterials could possibly increase significantly the corrosion and wear resistance of immersion heater protecting elements in aluminum melts.

Sheet Forming Technologies

A significant effort has been put into the development of advanced forming processes such as superplastic forming, electromagnetic forming, age forming, warm forming, and hydroforming. These forming techniques were identified in previous aluminum industry roadmaps[200]. Until now, the research strategy in this area has been to try to develop enabling technologies for the production of aluminum parts from commercial alloys. All of these technologies have the potential to form aluminum parts and some are already used commercially[60]. Any breakthrough in the forming of sheet materials will likely come from the development of new alloys with very high formability at low temperature and/or the development of processing techniques to improve the formability of existing alloys. There is still a need to develop low cost manufacturing techniques for the production of superplastic aluminum sheets.

To enable the development of new alloys with very high formability at low temperatures, research will be needed to develop integrated models that relate structural properties to manufacturing processes and the material itself. This predictive capability will be achieved by developing empirical models from materials properties and process parameter databases in combination with thermodynamic models derived from first principles. Quantum models have been used to some extent in the field of ferrous alloys development. Aluminum alloy development would strongly benefit from quantum and thermodynamic modeling.

Light Metals Alloys

As recycling of materials is a key aspect for the sustainability of materials development, there is a clear need to develop aluminum alloys that are tolerant to high impurities level (i.e. scrap-tolerant alloys). Innovative impurity removal methods with low environmental impact should be examined.

Among the aluminum based alloys to be used for sheet metal forming and fabrication, priority should be placed on aluminum-scandium alloys. The Al-Sc family of alloys is a class of material that needs to be studied for application in wrought sheet aluminum alloys. Al-Sc alloys have high yield strength, stable fine microstructures, show good potential for joining and weldability, show improved corrosion resistance and are very good candidate for superplastic forming. The strengthening mechanism of Al-Sc alloys should be investigated to identify low cost substitutes for scandium.

Magnesium alloys also have the potential to be used as a lightweighting structural material. Further reduction in weight is possible with Mg-Li alloys (1.45-1.56 g/cm^3). Development of magnesium alloys having high formability and improved corrosion resistance without the need of chemical conversion or anodic oxidation treatment is needed.

Titanium alloys also have high specific properties but their use in the near term is unlikely due to the very high manufacturing cost of titanium. Development of low cost/low energy titanium production techniques is required.

Amorphous metals are attractive due to their high specific properties. However, their low resistance to crack propagation makes them undergo catastrophic failure upon crack initiation. Research in this area should focus on improving fracture toughness of amorphous aluminum alloys. Amorphous alloy reinforcement with nanoparticles could be investigated as a mean of increasing crack propagation resistance.

Fiber-Reinforced Composite Materials

A lot of development has happened in the last decades regarding the manufacturing of fiber-reinforced composites. Advanced techniques are now available for the fabrication of composite parts. No major breakthrough is expected in the field of composite manufacturing except in the development of new materials and curing technologies. One interesting area of research would be the development of biocomposites with natural fibers and biopolymer or matrix compound elaborated extensively from vegetal sources. Developments in this field have the potential for reducing the CO_2 load to the environment through photosynthesis. Biopolymers with mechanical properties similar to those of conventional thermoplastics have already been developed. However, the focus for the development of biocomposites has been directed toward biodegradable composites until now. Those biodegradable biocomposites are not suited for application as structural materials where durability is required. Therefore, research is required to develop high durability (i.e. improved weatherability) biocomposites.

Curing of composites is also an energy intensive process for the composite industry. The US Department of Energy has been active in various research programs for electron beam curing. However, few efforts have been devoted to the development of microwave assisted curing which has demonstrated some good potential from research work in Germany. This area of research should be investigated in a more detailed way.

Nanomaterials

Nanomaterials show the potential to achieve unique mechanical properties. Among other, these materials include nanocrystalline alloys, carbon nanotube based materials, and nanoparticle filled materials. There is a huge need to develop practical processing techniques for the manufacturing of bulk nanomaterials in the grain size range of 10 nm, where the mechanical properties are optimum. During this review, no roadmaps for the development of nanomaterials technologies in the fabrication sector were found. Therefore, a specific roadmap for the fabrication sector would be an essential tool to structure the research in this field.

Joining

Proper joining technologies are essential to allow the efficient use of lightweight/high structural efficiency materials. Many automotive body welding techniques are in the evaluation stage. Those welding techniques are: self-pierce riveting, resistance spot welding and friction stir spot welding. Innovative sheet joining techniques such as laser welding and friction stir welding have also been used commercially and have allowed the welding of dissimilar materials due to their low heat input characteristic.

From this literature review, it seems that welding processes are applied to a specific welding problem (e.g. welding of two dissimilar metals) using a trial and error approach. The research in the field of fusion welding should focus on identify global strategy for the welding of dissimilar metals. The identification of versatile filler alloy that would allow fusion welds of dissimilar materials by conventional techniques without signification reduction in joint properties should be investigated.

For the bonding of plastic or composites and metals, co-curing of metallic inserts is a viable solution but it does not allow for a lot of flexibility in design. Research efforts should focus on developing new concepts for adhesive bonding. The target in this area should be to develop adhesive with mechanical properties equivalent to epoxy based system but with environmentally friendly chemistry.

Benefits from Future R&D Work

It was mentioned previously that the development of new forming processes aims at allowing the use of new lightweight materials, which often have some forming limitations, in transportation applications. Development of these enabling technologies will lead to significant energy savings as a consequence of weight reduction of structural materials. However, many research opportunities still exist in the area of innovative lightweight/high structural efficiency materials development. This is the area where the most significant energy savings can be made. As an example, Alcan claims that 113 kg of aluminum can replace 226 kg of steel in a typical North American sedan car. This translates into 1000 liters of fuel saving over a 12 year life cycle. A quick estimate[d,201] using 120 million as the fleet[202] of cars in the U.S. and the data from Alcan gives an annual energy saving of more than 300 000 trillion Joules. This value exceeds by many orders of magnitude the expected energy saving from some advanced melting techniques such as immersion heaters[e,203]. From these figures, it becomes obvious that investing in R&D projects that would allow developing lightweight materials, with high formability and high strength will have a very high payback. Furthermore, developing materials with higher specific mechanical properties than aluminum enhances the potential to further increase energy savings. Investing in the development of light weight materials is of major importance for the production of high performance electric or hybrid vehicles as the vehicles of the future*.*

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[d] Gasoline properties : Density = 0.75 kg/L, Heating Value = 44 MJ/Kg

[e] Expected energy saving of 2.7 to 4.2 trillion Btu/year if 25% of the industry converts to this technology

Conclusions

This literature review indicates that most of the recent research work in the area of aluminum sheet manufacturing focused mainly on the development of spray rolling. This was done somewhat at the expense of twin-roll casting, which is difficult to apply to large solidification range alloys. However, some research effort should be applied in trying to adapt twin-roll casting to difficult to cast alloys using technologies such as semi-solid casting. Also, the optimization of conventional DC casting process can still bring significant energy savings.

It was also observed that, in the last decade, intensive research was performed on the development of advanced forming processes for aluminum alloys. The research was oriented at developing processes that would enable the use of commercial aluminum alloys. However, any breakthrough in the forming of sheet materials is more likely to come from the development of new alloys with very high formability at low temperature or the development of processing techniques to improve formability of existing alloys that will relax the stringent requirements on the forming techniques themselves.

Another important observation is that there are many research opportunities for alloy development that remain unexploited. Alloy development programs making use of advanced thermodynamics and quantum modeling should be established with the objective of developing materials with high structural efficiency and high manufacturability. New classes of materials such as nanomaterials and metallic glasses are among the promising high structural efficiency materials but significant research is needed to allow for the manufacturing of these materials in bulk quantities. The development of materials having a higher specific strength than conventional aluminum alloys can lead to even higher energy savings for the transportation industry, where an extra reduction of only 1 kg in weight can generate energy savings in the order of several trillions of Joules across the complete vehicle fleet of the U.S. Furthermore, the development of materials with very high specific strength will become increasingly important for the development of high performance electric or hybrid vehicles.

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