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Recent development in aluminium alloys for the automotive industry

W.S. Miller [a,]*, L. Zhuang [a], J. Bottema [a], A.J. Wittebrood [a], P. De Smet [b], A. Haszler [c], A. Vieregge [c]

[a] *Hoogovens Research & Development, P.O. Box 10.000, 1970 CA Ijmuiden, The Netherlands*
[b] *Hoogovens Aluminium NV, A. Stocletlaan 87, B-2570 Duffel, Belgium*
[c] *Hoogovens Aluminium Walzprodukte GmbH, Carl-Spaeter-Strasse 10, D-56070 Koblenz, Germany*

Abstract

The growing demand for more fuel-efficient vehicles to reduce energy consumption and air pollution is a challenge for the automotive industry. The characteristic properties of aluminium, high strength stiffness to weight ratio, good formability, good corrosion resistance, and recycling potential make it the ideal candidate to replace heavier materials (steel or copper) in the car to respond to the weight reduction demand within the automotive industry. This paper summarises the recent developments covering aluminium's use in castings, extrusions and sheet; two specific examples will be given. The first deals with hang-on parts manufactured by Hoogovens Rolled Products Duffel, for which the weight saving potential can be 50%. Currently, the highly formable 5000 alloys are used mostly for inner panel applications, whilst the heat-treatable 6000 alloys are preferred for outer panel applications. This presentation reviews recent developments in aluminium alloys to improve formability, surface quality in both 5000 and 6000 alloys, and the bake hardening response of 6000 alloys. It also indicates the trend to develop a unialloy system to improve the aluminium scrap recycling. The second area deals with brazing sheet. Over the last 10 years there has been an increasing trend to replace copper heat exchangers with ones manufactured from brazed aluminium. Hoogovens Aluminium Walzprodukte Koblenz is one of the world's leading supplier of aluminium brazing sheet and is in the forefront of developing alloys with the combination of strength, formability, brazing performance and long life required by its customers. Materials have been development for both vacuum and controlled atmosphere brazing. The current status and future trends in aluminium brazing sheet for automotive applications will be presented. Particular emphasis has been placed on the development of long life alloys with superior corrosion performance over the more conventional materials. Using these two examples the technical and commercial aspects of the manufacturing processes of aluminium automotive components and engineering design support of materials producers are illustrated. The essential feature is the close co-operation at all stages between the material's supplier and the automotive manufacture. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Alloys; Aluminium; Automotive; Performance

1. Introduction

Material competition in the automotive market has been traditionally intensive. Steel has been the dominant material used in building automobiles since the 1920s. What types of materials are likely to be winners in the 21st century?

The automotive manufacturers' decisions on material's usage are complex and are determined by a number of factors. The increasing requirement to improve fuel economy triggered by concerns about global warming and energy usage has a significant influence on the choice of materials. For example, the US government regulations [1] mandate that the automotive companies reduce vehicle exhaust emissions, improve occupant safety, and enhance fuel economy. To meet this requirement, automotive manufacturers are making efforts to improve conventional engine efficiency, to develop new power trains such as hybrid systems and to reduce vehicle weight.

Weight reduction is particularly important because average vehicle weight is expected to increase since the automobile industry will continue to market new models with increased luxury, convenience, performance,

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* Corresponding author.

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and safety as demanded by their customers. Safety features such as anti-block systems, air bags, and increasing safety body structure contribute to vehicle weight gain. Although, the car companies have responded to this by improving design and power train efficiency, these incremental improvements have not yet enabled a significant reduction in overall weight. If this is to be achieved, there will have to be a radical increase in the use of lightweight materials. A rule of thumb is that 10% weight reduction approximately equals a 5.5% improvement in fuel economy [1]. An important fact is that weight reduction has a ripple effect on fuel efficiency. For example, weight reduction enables the manufacture to develop the same vehicle performance with a smaller engine, and such a smaller engine enables the use of a smaller transmission and a smaller fuel tank. With this ripple effect, it is estimated that 10% of vehicle weight reduction results in 8–10% of fuel economy improvement [2].

In conclusion, automotive materials can have an important impact on the environment. The use of lightweight materials can help reduce vehicle weight and improve fuel economy. The pressure for weight reduction has driven a gradual decrease in the amount of steel and cast iron used in vehicles and the corresponding increase in the amount of alternative materials, especially aluminium and plastics, as shown in Fig. 1. This paper will focus on the opportunities for aluminium alloys in automotive applications.

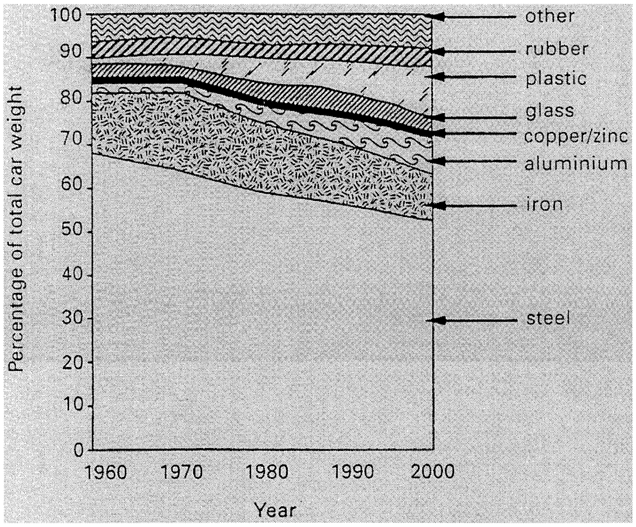

Fig. 1. The change in material consumption in average car.

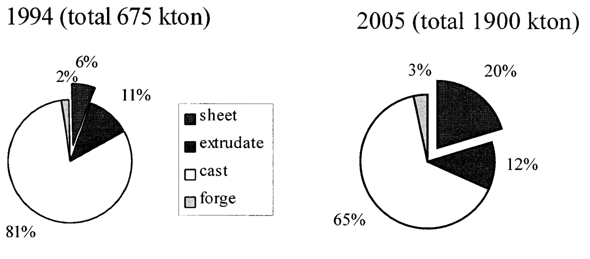

Fig. 2. Development of aluminium consumption for automotive application in Europe.

2. Aluminium for automotive application

Aluminium usage in automotive applications has grown more than 80% in the past 5 years. A total of about 110 kg of aluminium/vehicle in 1996 is predicted to rise to 250 or 340 kg, with or without taking body panel or structure applications into account, by 2015 [3]. There are strong predictions for aluminium applications in hoods, trunk lids and doors hanging on a steel frame. Fig. 2 shows the development of aluminium consumption for automotive application in Europe [4]. As shown in Fig. 2, a significant increase in sheet aluminium for automotive applications is expected, which will be discussed later with more details. Recent examples of aluminium applications in vehicles cover power trains, chassis, body structure and air conditioning.

Aluminium castings have been applied to various automobile parts for a long period. As a key trend, the material for engine blocks, which is one of the heavier parts, is being switched from cast iron to aluminium resulting in significant weight reduction. Aluminium engine blocks are expected to increase by the year 2000 to about 50% of all cars [1]. As indicated in Fig. 2, aluminium castings find the most widespread use in automobile. In automotive power train, aluminium castings have been used for almost 100% of pistons, about 75% of cylinder heads, 85% of intake manifolds and transmission (other parts-rear axle, differential housings and drive shafts etc.) For chassis applications, aluminium castings are used for about 40% of wheels, and for brackets, brake components, suspension (control arms, supports), steering components (air bag supports, steering shafts, knuckles, housings, wheels) and instrument panels.

Recently, development effort to apply wrought aluminium is becoming more active than applying aluminium castings. Forged wheels have been used where the loading conditions are more extreme and where higher mechanical properties are required. Wrought aluminium is also finding applications in heat shields, bumper reinforcements, air bag housings, pneumatic systems, sumps, seat frames, sideimpact panels, to mention but a few.

Aluminium alloys have also found extensive application in heat exchangers. Until 1970, automotive radiators and heaters were constructed from copper and brass using soldered joints. The oil crisis in 1974 triggered are-design to lighter-weight structures and heralded the use of aluminium. The market share of

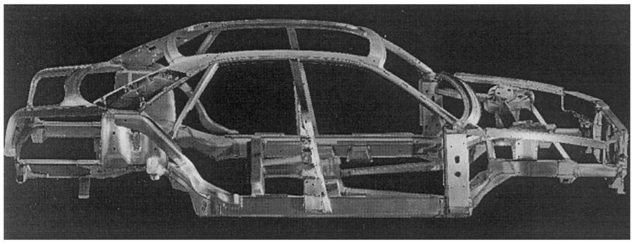

Fig. 3. Aluminium extruded space frame BIW architecture, Alcoa-Audi A8.

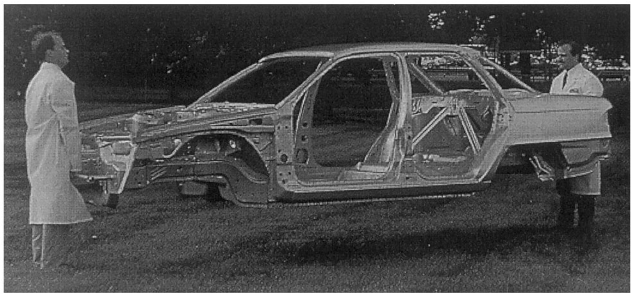

Fig. 4. Alcan-Ford AIV sheet monocoque architecture.

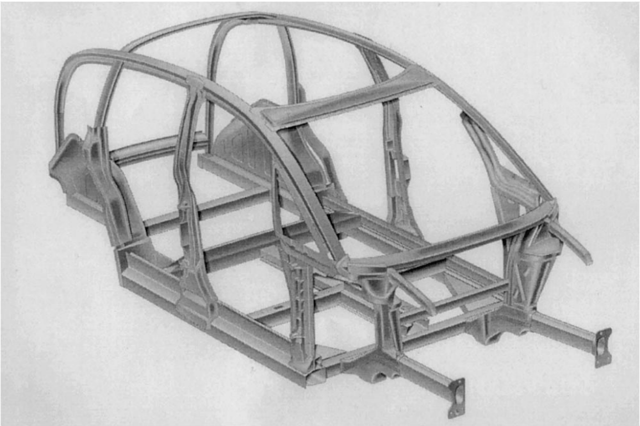

Fig. 5. Audi AL2 with an all aluminium body structure.

aluminium has grown steadily over the last 25 years and is now the material of choice for use in the automotive heat exchanger industry. Modern, high performance automobiles have many individual heat exchangers, e.g. engine and transmission cooling, charge air coolers (CACs), climate control.

Hoogovens Aluminium Walzprodukte GmbH in Koblenz (Germany) is a subsidiary of Koninklijke Hoogovens NV. The focal point of the activities at the Koblenz plant is the production of high quality niche products.

Brazing sheet is main centre point within those niche products. More than 25 years experience in the manufacturing of clad products is a firm base to supply over 50 heat exchanger manufacturers world-wide.

3. Aluminium alloys for body-in-white applications

Up to now the growth of aluminium in the automotive industry has been in the use of castings for engine, transmission and wheel applications, and in heat exchangers. The cost of aluminium and price stability remain its biggest impediment for its use in large-scale sheet applications. Aluminium industry has targeted the automotive industry for future growth and has devoted significant resources to support this effort.

The body-in-white (BIW) offers the greatest scope for weight reduction with using large amount of aluminium. Recent developments have shown that up to 50% weight saving for the BIW can be achieved by the substitution of steel by aluminium [5]. This can result in a 20–30% total vehicle weight reduction when added to other reduction opportunities.

There are two types of design each of which has a different form philosophy in the use of aluminium. One is the extruded space frame exemplified by the Alcoa-Audi A8 (see Fig. 3), and the other is the conventional sheet monocoque architecture as used in most steel structures as by the Alcan-Ford aluminium intensive vehicle (AIV) (see Fig. 4). Each type has its merits: the space frame offers lower tooling costs by eliminating some stampings, whereas the conventional sheet monocoque offers established processes and low piece costs. The updated examples of these two types are Ford P2000 and Audi AL2. Both of them could reduce weight about 40% on the BIW basis. The extruded space frame developed for Audi A8 is believed most appropriate for low volume production. The structure of Audi AL2 is a modified space frame with aluminium extrusions already developed for A8. Fig. 5 shows the Audi AL2 model with an all aluminium body structure. In the AL2, there are fewer aluminium cast joints, which were extensively used in A8 since they are replaced with direct bonds. Aluminium extrusions in the AL2 are also made into as straight shape as possible. A comparison between A8 and AL2 models is made in Table 1, showing the efforts being made to reduce production costs and to up-scale the production volumes. It is also clear that, as the automotive companies work more and more with aluminium, simplification of design results in lower overall cost.

Following are several examples of aluminium intensive vehicles with employing aluminium body components:

1. Audi A8 is an aluminium intensive space frame vehicle that reduces the body weight by 40%. The 385 kg aluminium components comprise 125 kg sheet products, 70 kg extrusions, 150 kg castings, and 40 kg other aluminium forms.
2. Ford AIV has a stamped aluminium body structure. The body and exterior panels are 200 kg lighter than the conventional steel model with 145 kg in body

structure and 53 kg in closure panels. The total usage of aluminium is 270 kg and the total weight reduction is 320 kg.

3. Honda NSX has also a stamped body structure and exterior panels with a weight of 210 kg of aluminium, about 100 kg of aluminium chassis components and 130 kg of other power train and drive train components.
4. Several other companies have also built aluminium intensive prototypes and/or concept cars. Chrysler together with Reynolds Metals has built the Neon Lite to be 270 kg lighter than the conventional Neon. Renault and Lotus have designed and built a Spider that is 30-50% lower in weight than a comparable steel car. Other examples are Jaguar XJ 220, GM-EV1 etc.

Table 1
Comparison in space frame design A8 vs. AL2

	A8 (249 kg)	AL2 (153 kg)
Sheet	71%	71%
Castings	15%	8%
Profiles	14%	21%
Straight	49%	84%
2D	34%	8%
3D	17%	8%
Spot-welding	500	None
Clinching	178	None
SPR	1100	1500
MIG	70 m	20 m
Laser	None	55 m

Table 2
Alloy choice: Europe vs. North America

	Europe	North America
Outer panels		
Alloy	6016-T4	6111-T4
Surface texture	EDT or EBT	MF
Pre-treatment	pickling+Zr/Ti conversion	none
Lubrication	oil or dry-lubricant	Oil
Inner panels		
Alloy	5051/5182/6181A	6111/2008/5182
Surface texture	MF or EDT	MF
Pre-treatment	pickling+Zr/Ti conversion	none
Lubrication	oil or dry-lubricant	Oil
Structure/sheet		
Alloy	6xxx-T4	5754-O
Surface texture	EDT	MF
Pre-treatment	pickling+Zr/Ti conversion	conversion
Lubrication	oil or dry-lubricant	oil
Structure/extrusion		
Alloy	6xxx	6xxx

Table 3
Product range-automotive aluminium sheet from HANV

	HANV
Outer panels	HANV6016-T4 HANV6016-T4P (super-lite)
Inner panels	HANV5051 A-O HANV5182-O (inner-lite) HANV6016A-T4
Structural sheet	HANV5754-O HANV5454-O HANV6016A-T4

Much of the activities at Hoogovens Rolled Products Duffel have been directed towards the opportunity for aluminium sheet in automotive applications, and therefore a more detailed discussion will be devoted to reviewing the materials and design technology for this important market sector.

Determining the right alloy for the body structure and hang-on panels has been the subject of considerable development effort [6] and most of the activity is now concentrated on a relatively small number of alloys. For skin sheet material the emphasis is on achieving a good balance of formability, strength after the paint-bake, and a high surface quality after pressing and paint finish. Consequently, the bake hardening 6xxx alloys are the primary choice for these applications. For structural sheet materials, strength may be a limiting factor in certain areas, impact energy absorption and good deep drawing behaviour are often the most important. To meet these requirements, 5xxx alloys are mostly used in North America. In Europe, 6xxx-T4 materials are still widely used.

One obvious and significant difference between aluminium and steel is the outstanding bare metal corrosion of the 5xxx and 6xxx aluminium materials. Increasingly large amounts of steel are supplied zinc-coated to achieve acceptable paint durability, this is not necessary for aluminium. However, the aluminium coil or sheet can be supplied with a range of pre-treatment and primer layers which can improve formability, surface quality and may eliminate the need for E-coating.

There is a wide range of aluminium materials and surface qualities, which can be chosen, and the growing design and process experience is enabling the aluminium industry to help the customer specifying the right material for the application.

There is a clear difference [7] in the alloy choice and treatments for these applications between Europe and North America, as shown in Table 2. Hoogovens Aluminium NV Duffel (HANV) has developed a wide range of aluminium materials for automotive applications, mainly conform to the European system. Table 3 shows the product range for automotive from HANV.

The development of aluminium alloys for BIW applications within Hoogovens has been focused on:

1. Outer panels: developing 6xxx alloys with excellent balance between formability and roping perfor-

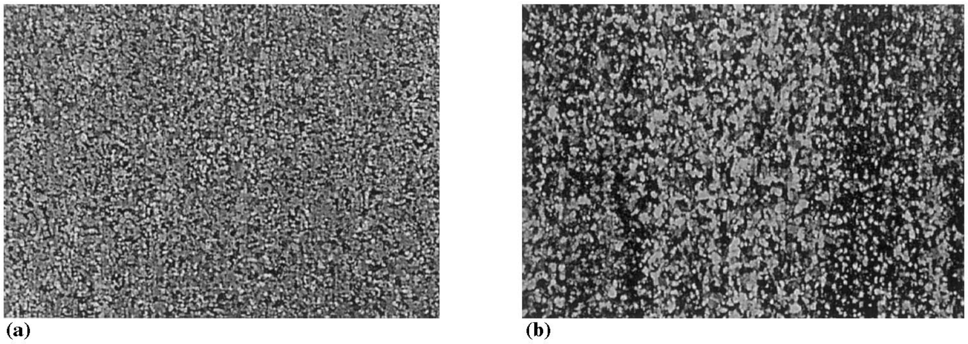

Fig. 6. Surface appearance related to roping performance in 6xxx alloy for outer panel application: (a) roping free, and (b) severe roping.

mance; developing the T4P (pre-bake treated) 6xxx alloys which provides a substantial increase in strength after the panels have gone through the paint bake line; developing new surface texture to improve the forming and surface appearance.

2. Inner panels: developing 5xxx alloys with excellent deep drawing performance and best formability; developing 6xxx alloys for inner panel applications in response to the unialloy concept.
3. Pre-treatment for outer and inner panels: developing Zr/Ti conversion and dry-lubricant.
4. Structural applications: developing 5xxx alloys with Mg < 3.0 wt.% to eliminate the potential to intergranular corrosion degradation; developing 6xxx alloy for unialloy concept body structure.

3.1. Development of aluminium alloys for outer panels

For outer panel applications, both the surface quality and formability are important issues. One of the surface defects is roping. The roping performance of 6xxx sheets is controlled by the size of the band-structure in the end product. The bands, consisting of parallel sets of similarly oriented crystals (textured structure) aligned along the rolling direction, result from the shear deformation during hot rolling up to a certain depth from the surface. Two factors are important to evaluate the roping performance of a sheet material during pressing or stretching: one is the surface roughening level which can be determined by surface roughness of a deformed sheet; the other is the roping line appearance-as continuous lines or discontinuous lines (cigar shaped broken lines). Therefore, from the metallurgical point of view, the key factors to control the roping are the size (diameter and length) of bands and the depth of the shear deformation layer. Fig. 6 shows microstructures in 6xxx alloys, which correspond, to roping free and severe roping situations.

In order to have a good, overall formability, the materials should have an isotropic mechanical property. In this case, a random texture is required. However, in sheet product of 6xxx alloys it is always the case that the end material has a relatively strong recrystallization texture. Therefore, in order to achieve an isotropic mechanical property, a balance between the recrystallized and retained deformation textures should be developed by proper process design.

Hoogovens has developed 6xxx alloys for outer panels within the EN6016 specification which have an excellent balance between roping performance and formability. As compared with typical properties achieved in AA6111 alloy, the HANV6016 alloy shows a lower strength, thus less spring back, and a higher ductility, as shown in Fig. 7.

The dent resistance of the panel is an important material's property. The HANV6016 alloy after paint bake provides sufficient strength that leads to a much higher dent resistance than that of steel (1 mm gauge of HANV6016-T6 versus 0.8 mm FePO5 steel). In order to further enhance the dent resistance, a high and fast bake hardening response during the paint bake cycle is desired. The recently developed HANV6016-T4P material, registered as super-lite, gives a much higher strength after paint bake treatment as compared with the HANV6016-T4 variant, as shown in Fig. 8. The yield strength of HANV6016-T4P material after 180°C/30 min ageing, is close to that of the 6111-T4, which largely compensates its initial low strength in the as supplied condition. However, the bake hardening re-

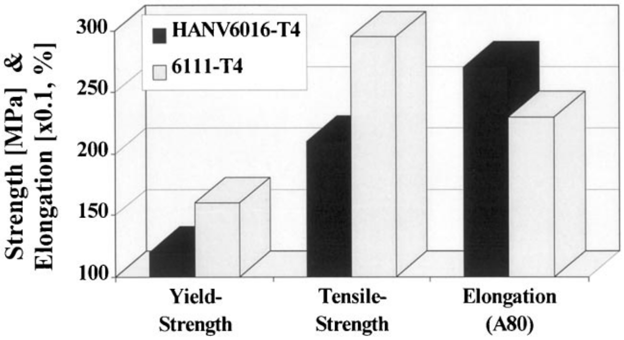

Fig. 7. Tensile properties of HANV6016 alloy in comparison with typical properties in AA6111 alloy.

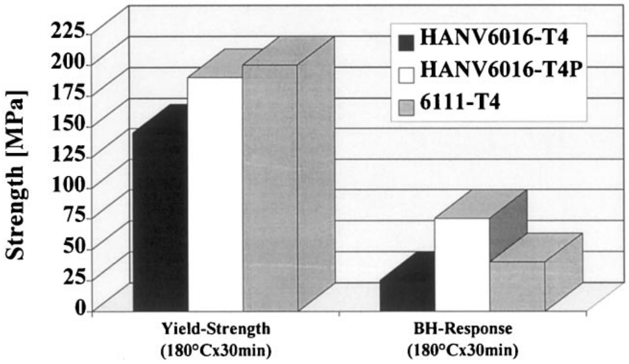

Fig. 8. The HANV6016-T4P (super-lite) material shows a better bake hardening response than that of the 6111-T4 material.

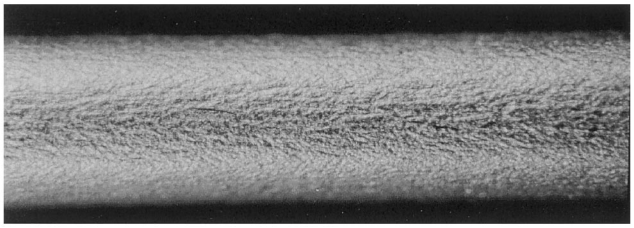

Fig. 9. The HANV6016 alloy shows a good flat hem capability (after 10% pre-strain).

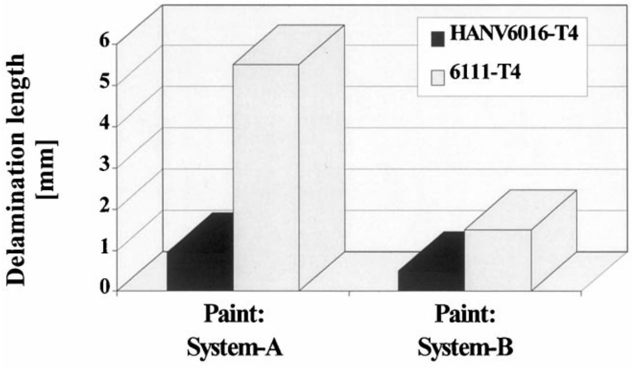

Fig. 10. The HANV6016 alloy shows a much better FFC resistance as compared with that of AA6111 alloy (tested following the ASTM G85-A2).

sponse of the HANV660-T4P is much faster and greater. It is also important to note that the T4P material has comparable mechanical properties with the T4 material in the as-delivered condition. The bake hardening response can be further enhanced by proper modification of alloy composition.

The HANV6016 alloy shows also a much better flat hem capability [8], as shown in Fig. 9. After 10% pre-strain, the HANV6016 alloy shows a mild surface roughening, while the AA6111 shows continuous surface cracking. Furthermore, the HANV6016 alloy is less susceptible to filiform corrosion as compared with the AA6111 alloy, as shown in Fig. 10.

Normally the aluminium surface is not textured but has a mill finish (MF). In the 1980s the introduction of electron discharge texturing (EDT) for aluminium improved the forming behaviour due to better lubrication and avoided the occasional appearance of directional lines through the paint, as seen on the MF surface. A recent development is the introduction of electron beam texturing (EBT) for aluminium [9]. Fig. 11 demonstrates clearly the difference between the EBT, which has a fully deterministic texture, and EDT, which has a stochastic texture. The EBT textured aluminium sheet has a structure showing a regular pattern of isolated pockets, which have identical morphology, and high roughness as often observed in EBT textured steel sheet. This is beneficial for forming behaviour and paint appearance. The isolated pockets serve as a reservoir for lubrication-EBT has a higher closed void volume compared to EDT and MF resulting in less sensitivity to galling without effecting the friction behaviour. The regular pattern of EBT improves the homogeneous distribution of paint represented by the tension measured with a wavescan, see Fig. 12, which can result in less orange peel defect.

3.2. Development of aluminium alloys for inner panels

For inner panel applications, good deep drawing and stretch behaviour is the most important. Hoogovens has developed a highly formable 5xxx alloy, registered as inner-lite, for inner panels within the EN5182 specification. The mechanical properties, especially the formability of this alloy, are much better than the competitor's materials resulting from a combination of composition design and process modification. As shown in Fig. 13, the 5xxx alloys (data from HANV5182 alloy) show a much better deep drawing behaviour than that of 6xxx alloys (data from HANV6016 alloy), demonstrated by a wider working range and a higher total product height. The HANV5182 alloy shows the best properties as compared with other 5xxx alloys for this application, as shown in Fig. 14.

In response to the unialloy concept to increase the recycling potential, Hoogovens is developing 6xxx alloys for inner panel application. Table 4 shows typical properties achieved in the HANV6016A alloy.

3.3. Pre-treatment for outer and inner panels

Suitable surface modification allows the realisation of additional customer advantages ensuring easier and cheaper processing of the materials. Fig. 15 shows the general trend in the development of pre-treatment technology. Hoogovens is developing new pre treatment technologies to improve the material's performance and reduce the total cost of the manufacturing of aluminium panels. The conversion treated aluminium

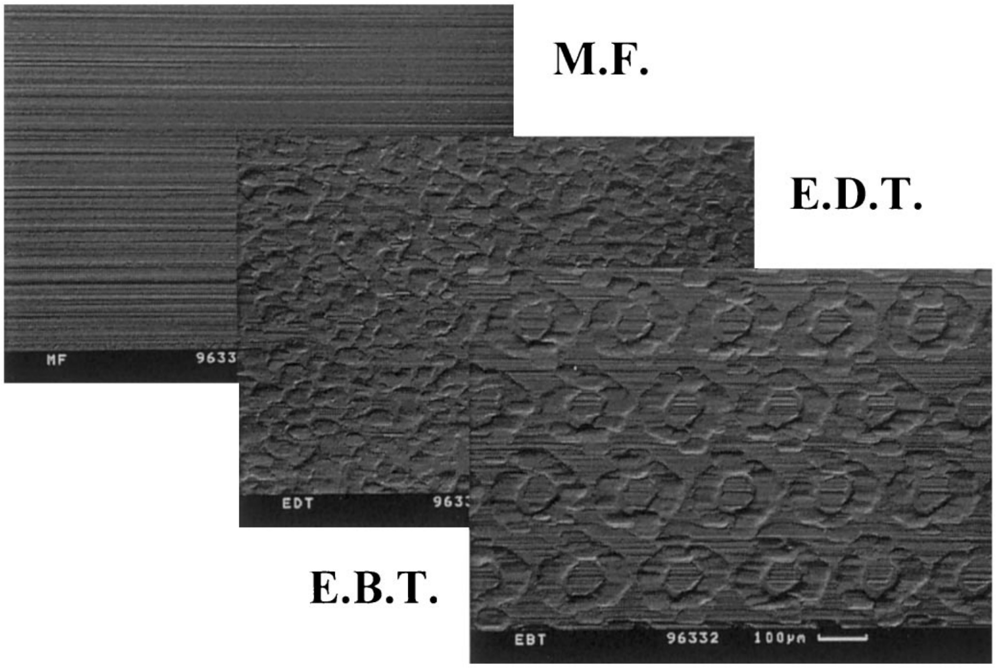

Fig. 11. Difference in surface morphology of different types of textures on aluminium.

products allow the car producers to skip the passivation treatment in-house. The combination of conversion treatment and dry lubricant provides several benefits: (a) paper interleaves can be left out which allows mass production; (b) it diminishes oxide growth and improves galling behaviour during processing, and (c) it improves formability.

3.4. Development of aluminium alloys for structural applications

For structural applications, most of the prototype structures produced from sheet materials so far have been with the AA5754 (AlMg3) alloy. The use of stronger materials (both 5xxx and 6xxx alloys) can be considered in certain circumstances, but care has to be taken over certain structural performance issues. The higher Mg alloys can be susceptible to intergranular corrosion degradation, especially in conjunction with severe environments, elevated temperatures and stress. The use of bake hardening alloys for structural parts might be desired in some areas for strength reasons, but care should be exercised in the crumple zones, which are designed to absorb impact energy. Therefore, the car producers should consult the material supplier for evaluation of specific applications related to material's choice. Hoogovens has developed 5xxx alloys within the EN5754 and EN5454 specifications that have a good formability and intergranular corrosion resistance. In response to the market demand on the unialloy concept to increase the recycling potential, Hoogovens has also developed a 6xxx alloy within the EN6016A specification. The HANV6016A alloy shows the improved crash performance which has typical properties comparable to that in AA6009 alloy: T4–

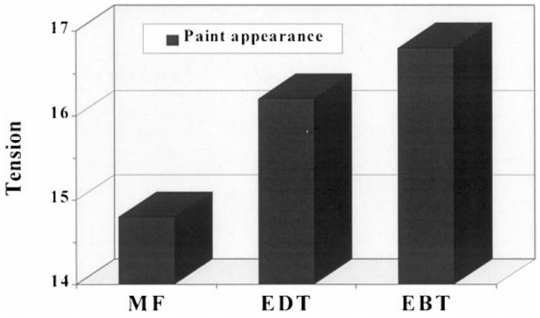

Fig. 12. Paint appearance for vertically coated panels with different substrate texture (tension = 0 showing the orange peel, tension = 24 showing the mirror-like appearance).

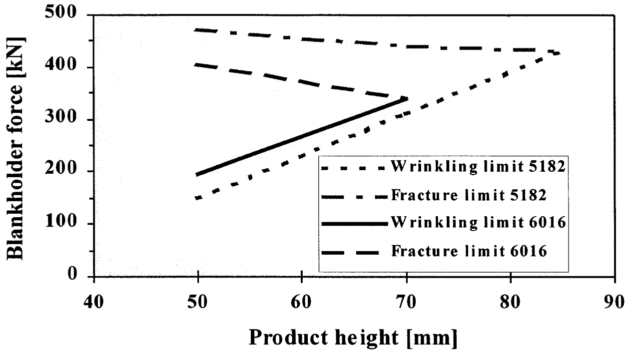

Fig. 13. Comparison of deep drawing behaviour between 5xxx alloys and 6xxx alloys.

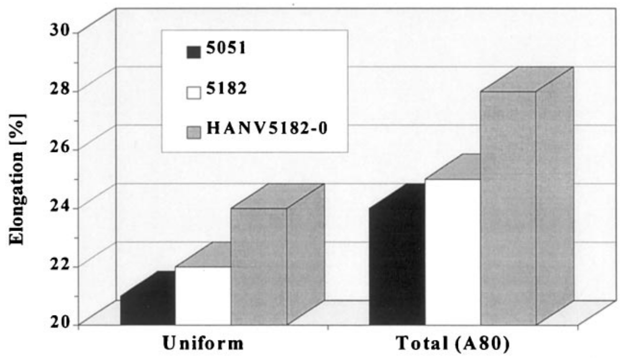

Fig. 14. The HANV5182 (inner-lite) alloy shows superior formability as compared with other 5xxx alloys.

Table 4
Properties of HANV6016A alloy for inner panels

Property	T4 (as supplied)		T6 (205°C/30 min)	
	Specification[a]	Typical	Specification[a]	Typical
PS (MPa)	≤140	120	≥210	245
UTS (MPa)	≤240	230	≥280	285
A_u (%)	≥19	21	–	–
A_{80} (%)	≥23	26	≥10	12
n (10–20)	≈0.23	0.26	–	–
r (20)	≈0.6	0.7	–	–

[a] Specification from Audi.

$A_{80} > 25\%$ and PS < 140 MPa and T6 (205°C/30 min)-$A_{80} > 13\%$ and PS > 230 MPa.

3.5. Joint development with car producers

Hoogovens is working together with car producers for specifying the proper materials and treatments for applications. This area is gaining more and more attention recently and will be an important issues for coming years. Examples here are: the joint study on the influence of the application of dry-lubricant on the production route for aluminium hang-on part at Volvo [10], joint development on laser welded blanks at Volvo, joint development at Volvo on the forming operation demonstrating the HANV5182 alloy (inner-lite) as the best choice for inner panel applications [11] and development of an aluminium bonnet for SAAB 9-3 [12] using: inner panel -HANV5182-O; outer panel-HANV6016-T4; surface texture-EBT; pre-treatment-pickling + Zr/Ti conversion.

4. Aluminium alloys for brazing sheet applications

As mentioned earlier brazed aluminium components are used extensively in modern vehicles for engine and transmission cooling, charge air coolers and climate control. Fig. 16 shows the typical structure of brazing sheet. It consist of a core alloy which provides the strength and life cycle requirements of the heat exchanger and a clad layer which is of a low melting point aluminium silicon alloy. During the brazing process the Al–Si alloy melts and seals joints in the heat exchanger between the different sheet components. The brazing sheet can be clad on one or both sides with the Al–Si alloy and in some cases one side is clad with a different alloy to provide corrosion protection on the inner (water-side) of the a radiator.

During 1970 vacuum brazing [13] was developed to solve the problems associated with old techniques of dip brazing. It was an environmental friendly approach but requires significant capital investment. It became the main method for manufacturing heat exchangers in the 1980s and still remains the preferred brazing

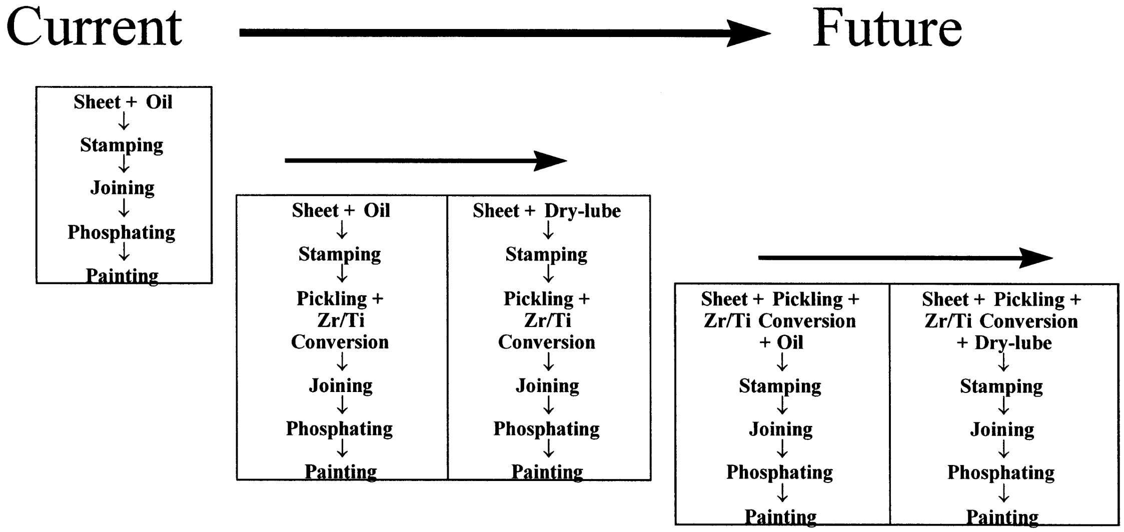

Fig. 15. Trend of development in pre-treatment technology for aluminium auto body sheet products.

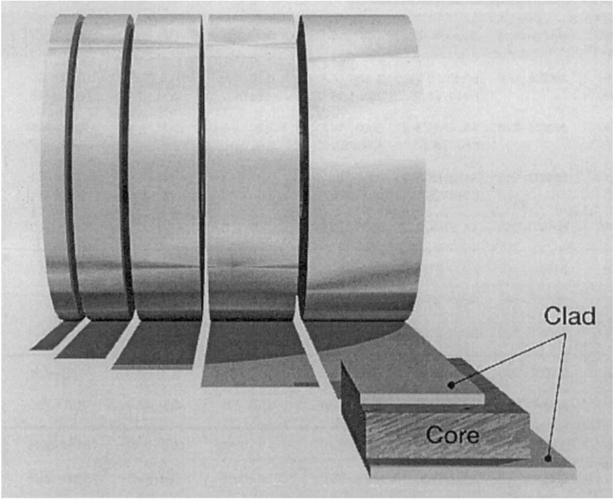

Fig. 16. Schematic illustration of a typical brazing sheet.

method for evaporators and charge air coolers. It is gradually being superseded by controlled atmosphere brazing. A main advantage of vacuum brazing above controlled atmosphere brazing is that high (> 0.3%) magnesium containing alloys can be used. Although, now in use for several decades the complete mechanisms behind the technique are still not fully understood. Since the introduction of Nocolok process by Alcan in 1978 [14], this process has become the workhorse in the brazing industry. It is a very attractive process since it can be operated continuously at low costs [15]. Although the CAB process is very popular it has some constraints like, the flux can not tolerate high magnesium alloys [16] and the uniform application of the flux on the heat exchanger to be brazed can be very difficult to control.

The material requirements of brazing sheet are diverse and depend on the brazing method and the final application. Some of the key requirements are listed below.

4.1. Formability

High formability is required since the space under the hood for head exchanger is minimised. This results that heat-exchanger designer have to come up with drastic solution to find a way to optimise the heat exchanger capacity for a limited space. This puts a large demand on the forming characteristics of brazing sheet. A simple tensile test is no longer a guarantee to predict the forming behaviour of the material.

4.2. Brazeability

The term brazeability has not been well-defined in scientific terms. However, it is generally considered [17] to be a measure of how well the clad layer flows during brazing to manufacture a joint, without causing erosion of the underlying core material. The main factors influencing brazeability are the surface condition of the aluminium alloy (oxide thickness and type and the presence of residual rolling oil), the atmosphere within the brazing furnace, temper of the brazing sheet, alloying elements in clad and core material.

4.3. Vacuum brazing

For the vacuum brazing process (which is carried out at a pressure of 5×10^{-5} MPa) the brazing clad alloy contains magnesium (0.2–1.5%). During the vacuum brazing cycle the magnesium diffuses to the surface and evaporates through the oxide surface and fractures the film allowing the cladding to flow [18]. The magnesium vapour generated purges the atmosphere of residual oxygen and water vapour [19].

4.4. Controlled atmosphere brazing

In CAB a flux ($KAlF_4$) [20] is used to dissolve and break-up the oxide film before the clad layer melts. The flux is non corrosive and insoluble in water. The furnace atmosphere must be controlled with high purity nitrogen containing less that 40 ppm O_2 and a dew point below -40°C. The performance of the flux is reduced in the presence of Mg above 0.3%. The formation of MgO [21] reduces the performance of the flux by raising the melting point of the flux.

4.5. Strength

A minimal strength is necessary to maintain the integrity of the heat exchanger during its life cycle. Different parts of the heat exchanger like the header, plate and tube material from a car radiator require different strengths. During selection of the alloys or temper for the different parts an optimum in gauge and strength has to be the goal. Higher strength is demanded to reduce the gauge of the used materials and to tolerate higher operating pressures. In this way, the weight of the heat exchanger is reduced and its performance is improved. This means that existing materials have to be improved or new solutions have to be found to fulfil this demand.

4.6. Corrosion

The standard test for corrosion is saltwater acetic acid test (SWAAT) which is aimed at reproducing lifetime performance. The different automotive heat exchangers, radiator, charge air cooler, evaporator, oil cooler, are subjected to different corrosion environments. This means that for every application the right alloy has to be selected to obtain maximum corrosion resistance. This implicates that every application has to be specifically tested under condition that simulated real life exposure.

4.7. Fatigue/pressure cycle testing

Pressure cycle tests simulate the mechanical expansion of a heat exchanger during its lifetime. The test exposes the complete heat-exchanger to fatigue testing and not just to the alloys. This test can reveal faults in joints, material selection or in the design.

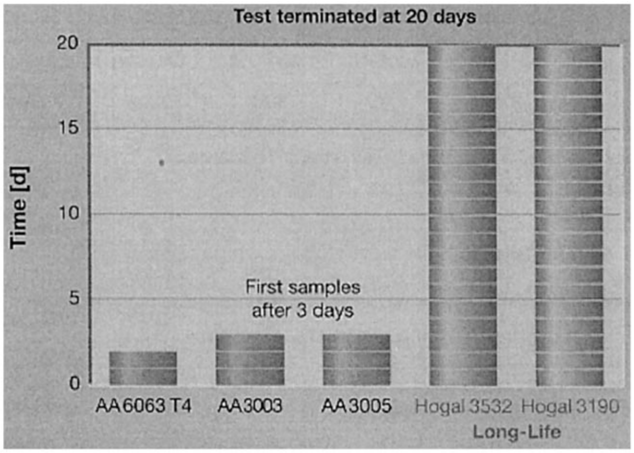

Fig. 17. The 'long-life' alloys show five times higher corrosion resistance over those alloys such as 3003, 3005 and 6063.

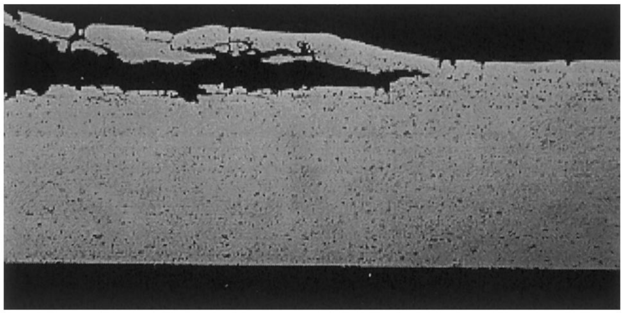

Fig. 18. Optical micrograph showing typical morphology of samples after corrosion tests observed in 'long-life' alloys.

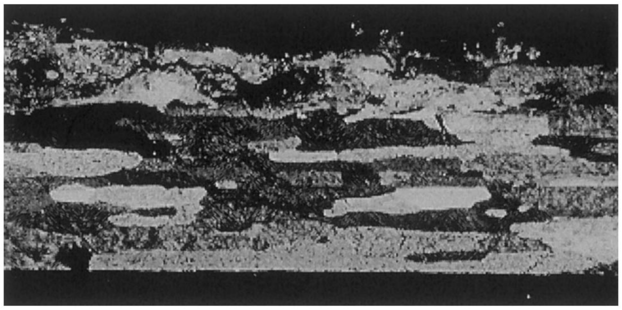

Fig. 19. Optical micrograph showing the elongated grain structure observed in 'long-life' alloys.

Hoogovens Aluminium Walzprodukte has developed special chemistries which together with well designed thermo-mechanical processing gives significantly improved corrosion performance compared with the more conventional 3000 series alloys. These 'long-life' alloys have over five times higher corrosion resistance compared to more conventional brazing core alloys such as 3003, 3005 or 6063 (see Fig. 17).

This corrosion resistance is created by a combination of two features. Firstly during brazing Si diffused into the core. In the diffusion zone small particles of Al–Mn–Si precipitate adjacent to the core/clad interface with a width of around 20–50 μm. This band of precipitates has a lower corrosion potential compared with the core and thus acts as a sacrificial layer. In addition the alloys is supplied in the H24 temper. This controls recrystallization during brazing to be controlled to produce a final product with coarse elongated grains. Since grain boundaries are the path through which corrosion proceeds the pancake shaped grains minimises grain boundary area and further enhance the materials long life performance. Fig. 18 shows the typical corrosion for long life alloys and Fig. 19 shows the elongated grain structure of the long life alloys.

The development of brazing sheet is an on-going research programme within Hoogovens Aluminium Walzprodukte. Customers are putting high demands on material properties. The demands are not longer confined to strength and corrosion resistance but properties like formabilty, and brazeabilty after forming are becoming ever more important.

Recently Hoogovens has presented several papers [22–25] on the development of new materials for brazing. The general trend in the development is to achieve higher strength. Heat treatable alloys are a way to achieve those strengths. A constraint however is that strength development after heat treatment should not be too sensitive to the quench rate applied after the brazing process. A second constraint with these alloys will be their possible change in properties when exposed to service conditions. Table 5 show the alloy chemistries of Hoogovens Walzprodukte's existing long life alloy together with those of the new alloys under development. It is important to note that these new alloys are in the development stage, particularly Hogal-3536, for which only laboratory data are presented.

Table 6 shows typical post brazing properties obtained using H24 tube stock. The tests were carried out on material naturally aged 1 month after brazing. The brazing cycle had a cooling rate of 60°C min^{-1}, which is typical of conventional production lines.

Fig. 20 shows how the 0.2% PS in the naturally aged T4 condition is influenced by the cooling rate after brazing. The data shows that the cooling has limited effect on the final 0.2% PS. Even at relative low cooling rates, a higher strength can be reached when compared to conventional alloys.

Table 5
Typical chemical compositions (wt.%) of existing and new high strength brazing alloys

Alloy	Brazing process	Si	Mn	Mg	Cu	Fe
Hogal-3532	CAB	≤0.3	0.7–1.00	0.1–0.3	0.5–0.7	≤0.40
Hogal-3190	Vacuum	≤0.30	1.0–1.5	0.4–0.7	0.2–0.5	≤0.40
Hogal-3571	Vacuum	0.30–0.70	1.00–1.40	0.30–0.70	0.60–0.90	≤0.40
Hogal-3572	CAB	0.30–0.70	1.00–1.40	0.10–0.35	0.60–0.90	≤0.40
Hogal-3536	Vac/CAB	0.2	0.7–1.0	0.7–1.2	0.1–0.35	≤0.40

Table 6
Typical post brazing properties

Alloy	Brazing Process	0.2% PS (MPa)	UTS (MPa)	Elongation (%)	SWAAT
Hogal-3532	CAB	50	150	18	>20 days
Hogal-3190	Vacuum	58	160	18	>20 days
Hogal-3571	Vacuum	99	220	15	>20 days
Hogal-3572	CAB	94	214	10	>20 days
Hogal-3536	Vac/CAB	100	214	13	>20 days

A key issue is whether these alloys can maintain their properties during their lifetime. Fig. 21 shows Hogal 3572 that the mechanical properties increase during its lifetime.

An ageing time of 60 days in the 'life cycle' test is roughly comparable to a real life time service of approximately 3 years for a car that makes 25 000–30 000 km year^{-1} (10 h a week).

Corrosion protection of the new alloys is comparable with existing long life alloys. For the standard long life alloys the protection mechanism is fairly well understood.

A sacrificial layer is obtained by Si diffusion from the clad layer into the core. The diffusion stimulates the precipitation of α-AlMnSi particles. This leads to a high density of these precipitates just beneath the clad/core interface, usually called the band of dense precipitates (BDP). This BDP is taking Mn out of solid solution and by this way lowering the corrosion potential of the matrix. Due to the lower corrosion potential of the sacrificial compared to the matrix, corrosion will preferential take place in this layer. This will deflect any corrosion from a pitting mode into a lateral corrosion attack and thus preventing or delaying leakage.

A constraint for the use of this type of corrosion protection is that the core alloy contains low (< 0.3%) of silicon. The new alloys like Hogal 3571 and 3572 have however higher Si contents so the above described mechanism can not work.

A possible protection can come from the copper diffusion. Copper diffuses during brazing from the core to the clad alloy and just below the clad/core interface a depletion of copper will occur. Copper being a more noble alloying element will, because of its locally absence, lower the potential of the depleted zone. The copper depleted zone can now act as a sacrificial layer. The study of the protective mechanism of high copper alloys is part of an ongoing research. An alloy like Hogal 3536 is probably protected with both mechanisms.

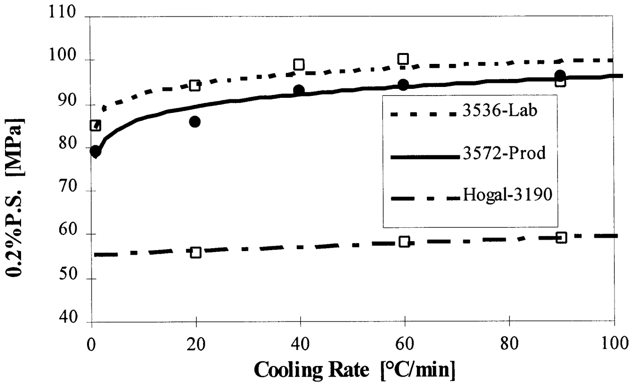

Fig. 20. The influence of cooling rate during brazing process on the post brazing strength.

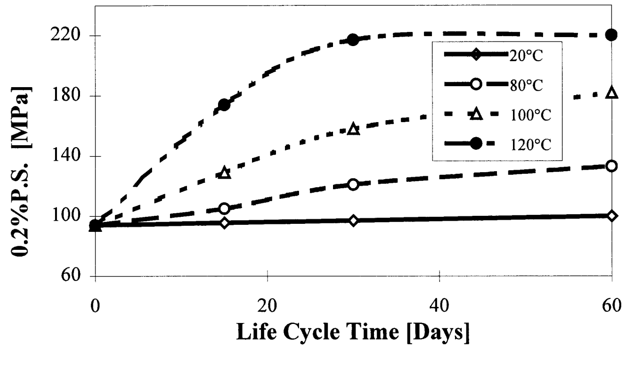

Fig. 21. Mechanical properties of Hogal-3572 alloy after a life cycle treatment at elevated temperatures.

The first mentioned protection mechanism is only valid when the material is non-homogenised and is in H24 temper before brazing. The copper depleted zone is able to protect O temper material giving it >20 days of SWAAT resistance. This fact opens new applications for long life alloys where formability is an issue.

Another benefit from the new heat treatable alloys and specially the ones developed for CAB is that the Mg content of the alloy is relative lower compared to typical AA6XXX alloys used for applications where high strength is an issue. The low Mg levels of the new alloys need only standard amounts of flux application.

It is important to understand that these alloys have been developed in response to specific customer demands for particular application in which the higher strength can be translated into lighter weight or increase efficiency (higher pressure). For many applications the standard long life alloy Hogal 3532 and Hogal 3190 will remain the material of choice.

5. The future trend of light weight materials in automotive industry/concluding remarks

The following remarks can be made over the future trend of light weight materials:

1. Alternative materials will gain more market share in automotive industry.
2. Aluminium is the greatest long-term threat to sheet steel.
3. Magnesium application will grow, but will still be limited mainly to castings.

Particularly, some remarks can be made over the future trend of aluminium sheet for car body applications:

1. Steel will continue to be the principal material of choice for car body for the next decade.
2. Aluminium penetration has been limited up to now due to factors: raw material cost; manufacturing cost; industrial structure; recycling; regulations.
3. With joint development on manufacture technology for high volume production, aluminium has a realistic chance to capture a greater share in car body applications.

To summarise the recent development in aluminium alloys for automotive industry within Hoogovens, following conclusions can be made:

1. Hoogovens Aluminium has developed several alloys for auto body sheet applications: the highly formable HANV5182 (inner-lite) for inner panels; the roping-free HANV6016-T4 combined with good hemming and formability as well as, the HANV6016-T4P (super-lite) for outer panels; and uni-alloy (6xxx series) system to improve the aluminium scrap recycling.
2. Hoogovens Aluminium is continuously optimising existing brazing alloys and developing new generations of high strength alloys to meet the market demands for down gauging and light weight structure. With this aim Hoogovens Aluminium has developed two new high strength/long-life alloys for CAB brazing-the Hogal-3572 and the Hogal-3536 alloys.
3. Hoogovens is working closely with the automotive manufacture at all stages to promote the widespread application of aluminium in automotive industry.

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