Weight reduction through thixocasting associated with shot peening

G. Grillon, A. Leclere, M. Garat

The subject of this paper is a study of weight reduction applied to an automobile wheel disc. After assessing the potential of the main existing and emerging material-process solutions, it turns out that thixocasting of aluminium alloys is a very attractive solution in terms of changing the asymptote "Weight Reduction-Freedom of Style-Cost". The performance levels of thixocast parts are compared with the specifications of automobile manufacturers in the fields of metallurgy, surface finish, fatigue and impact resistance and ambience tests resistance of the protective coating. These performance levels are also compared with those of identical reference parts produced by low-pressure casting or forging. The fatigue resistance observed on our prototypes, which is lower than expected from the thixocast discs (Lf = 120 MPa at $6x10^6$ cycles) due to insufficient control of the surface finish, did not enable the required weight reduction to be achieved. In economic terms, for this disc, originally designed to be forged, thixocasting is less competitive than low-pressure permanent mould casting. In order to get closer to the required weight reduction (20% compared with the best reference solution), surface prestressing by shot peening was implemented with an Almen intensity F23-F30A, compatible in terms of surface roughness with the protective and decorative coatings certified by vehicle manufacturers. When treated in this way, thixocast discs show high endurance limits, leading to potential weight reduction which may exceed 40% but for many of them, no improvement is recorded. This phenomenon can be explained by non-compliant surface finishes before shot peening. It is demonstrated that the residual compressive stresses show the appropriate stability required to resist the thermomechanical stresses to which wheel discs are subjected. It is also verified that shot peening does not alter the coating's properties to provide efficient environmental resistance. These initial results point to several certifiable and industrializable solutions using such prestressing treatments which are well-positioned in terms of "Cost-Weight Reduction-freedom of style". Thixocasting and, even more, rheocasting show the best potential, as long as the surface quality of the parts is under control and complies with specifications.

Parole chiave: alluminio e leghe, tixoformatura

INTRODUCTION

As cars have become safer and more comfortable, they have become heavier, which has increased their fuel consumption. At the same time, regulations on the emission of CO_2 and other pollutants are getting severe and consumers are becoming increasingly concerned with reducing the amount they pay for fuel; apart from the classic progress ways (motorisation, catalytic exhausts aerodynamics …), weight reduction is becoming a major issue for car manufacturers. The weight of vehicles could only be reduced to any significant extent, without increasing the price, by revolutionary materials and car architecture. In this respect, weight-reduction constitutes a veritable challenge in terms of research and industrialisation.
It is estimated [1, 2] that a reduction of 100 kg in a vehicle's weight results in a gain of 30 kg on mechanical parts (suitable sizing) and also that a gain of 100 kg reduces consumption by an average of around 0.5 liter per 100 km on the open road and 0.7 liter per 100 km in built-up areas.
For wheels, a gain of 1 kg has as much impact on consumption as reducing 1.5 kg elsewhere on the vehicle. Another advantage, linked to reducing the weight of wheels, as for any other unsprung part, is the improvement in the dynamic handling of the vehicle when subjected to vibrations generated by uneven road surfaces. There is a positive impact on two aspects:
- holding wheel-road contact
- ride comfort.

So, research has intensified in order to identify new material/process solutions that would enable a change of asymptote to be made in the search for a better "Weight-reduction/Freedom of Style/Cost" compromise.
This is the framework for this study in which the demonstrator test piece is a car wheel disc.

G. Grillon, A. Leclere
Michelin Technology Centre- France

M. Garat
Aluminium Pechiney – France

Paper presented at the International Conference " Aluminium 2000",
Roma 18-22 March 2003

STUDY FRAMEWORK

The specifications for all the solutions assessed were identical and the prototypes made were subjected to the same validation tests.
The routes explored were as follows:
- Sheet metal (HSLA steel, aluminium alloys).
- Forging (aluminium alloys).
- Casting (aluminium alloys: Low Pressure permanent mold casting and sand gravity).
- Thixocasting (aluminium alloys).

The first phase was dimensioning the part by means of finite element calculations for a known material and making detailed drawings. Based on these elements and the specifications, an opportunity study allows the technical feasibility

Fig. 1 – Demonstrator disc made of aluminium alloy welded onto an aluminium series 5000 rolled rim.

Fig. 1 – Disco dimostrativo in lega di alluminio saldato su un bordo laminato di alluminio serie 5000.

and economic advantages of each solution to be assessed. The technical/economical assessment governs the decision as to whether or not the prototypes are to be made. In a second phase, the prototypes are subjected to surface prestressing treatment by impact. Fatigue resistance performance is assessed, as well as an economic approach, based on an industrial production assumption.
The reference part is a 6jx15 wheel (with a 15 inches diameter) that complies with the manufacturer's specifications. The standard production part is made of an aluminium alloy (AlSi7Mg0.3 T6), low-pressure cast and of the mass-optimised type, with a limited style. The wheel mass is 6.2 kg, and the disc mass is 3.1 kg. The demonstrator test part is the wheel disc (Fig.1).

SPECIFICATIONS

The wheel fulfils a large number of functions and, since it is a part where safety is a particular concern, it must comply with prevailing regulations and standards.
Wheel specifications are established by car manufacturers and their objective is to define the required characteristics and corresponding test methods – either standardised or proper to each one.
This dossier only covers the following functions:
- stress transmission between the tyre and wheel assembly
- environmental resistance of the protective coating.

Stress transmission

Fatigue
A wheel, while running, transmits transversal (Y), vertical (Z), horizontal (X) and rotating stress. It is therefore subjected to complex fatigue stresses, constantly varying, depending on the load, driving style, vehicle, road context, etc., and the two parts of the wheel (rim and disc) are subjected to different stresses in the same cycle; it is essentially the disc and its linkage with the rim that are primarily under stress as regards fatigue. They must be able to withstand a very high number of cycles (100,000 km = $5x10^7$ cycles).
Disc fatigue resistance is verified with two types of test.
- The disc on its own: rotating bending test under transversal stress (FY),
- Disc fitted to the wheel, i.e.fixed to a rim: rotating bending test under bi-directional stress (FY and FZ).

To receive homologation, the disc must be able to resist rotating bending, at an equivalent bending moment in relation to the wheel centre of 2000 N.m, for 2 millions cycles and 1540 N.m for 6 millions cycles, with a 50% confidence level in both cases.

Metallurgy
Mechanical properties (tensile strength, yield strength and elongation) on dissection samples and the hardness value, irrespective of the measurement point, must comply with the values specified in Table N° 1.
Dissection samples are taken from the spokes.

Internal soundness: No imperfections detectable by radioscopy or X-ray are permitted in the hub/rim connecting piece. Outside these critical zones, parts are accepted with a fault limit class of between 2 and 3, as per the ASTM E155 standard.

Presentation – Appearance: Parts must not present any casting, forging or machining defect liable to be detrimental to their use and appearance.

Welding aptitude: The alloys chosen to produce the wheel discs must have good welding capability and be compatible with “rim” materials.

Environmental resistance of the protective coating

For a protective coating, applied to wheels, to be homologated, it must comply with the manufacturer requirements. Associated with each test implemented is a test method specified by the manufacturer or a standard method.

DIMENSIONING AND PRODUCTION OF THE WHEEL DISC

The pertinent criterion for dimensioning is the fatigue limit Lf^n, where n = 2/3 under rotating bending [3].
Modelling by finite elements was carried out from a displacement imposed on the edge of the disc at the level of the spokes and openings. Figure 2 represents a breakdown of radius and circumference strain, stemming from the modelling. It enables verification that the maximum stress is located at the top and bottom of the openings when the part is subjected to a given bending moment.
The thixoformed parts were studied and produced by a company called STAMPAL of the Euralcom group. The as thixocast parts, the tooling and the injection curve were refined by digital filling and solidification simulation using the

Type of alloy and condition	Tensile strength UTS (MPa)	Yield strength YS (MPa)	Elongation at break E (%)	Brinell hardness BHN 10/1000 or 5/250
As cast	150	80	4	55
AlSi7Mg0.3 T6	220	140	4	75
6082 T6	310	260	6	90

Table 1 – Mechanical properties required on dissection test pieces.

Tabella 1 – Proprietà meccaniche richieste sui pezzi sottoposti a prova di sezionamento.

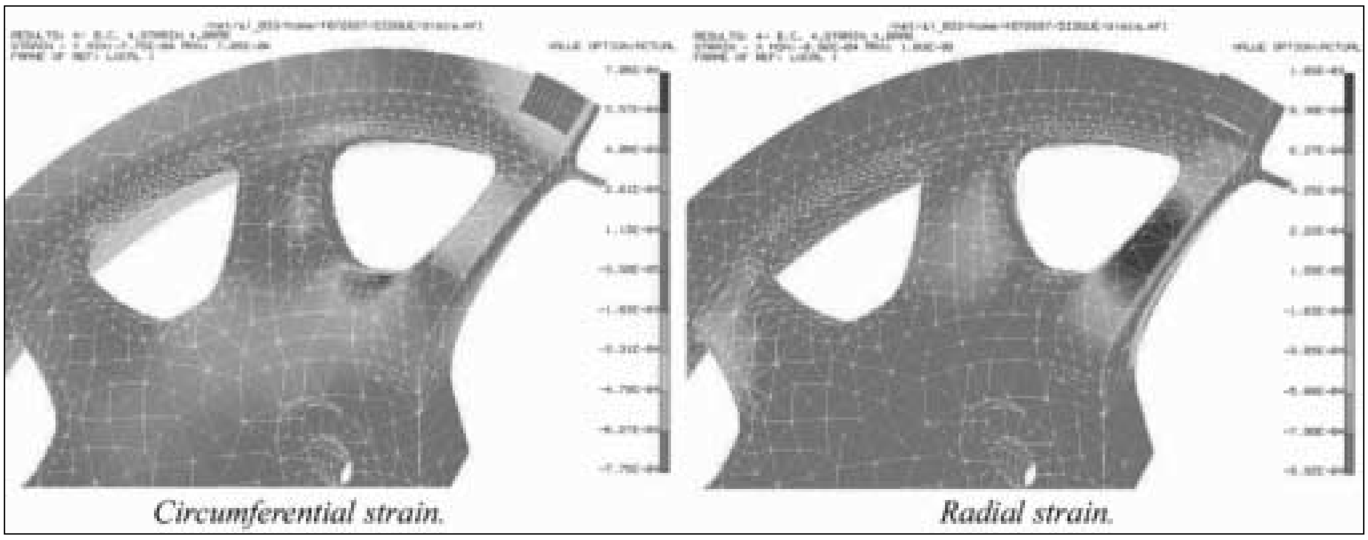


Fig. 2 – Computer models of disc strain.

Fig. 2 – Modello computerizzato delle deformazioni del disco.

Pam-Cast Simulor software in collaboration with PECHINEY. Wheel discs were produced on a 1800 t BÜHLER horizontal press from 5” billets in PECHINEY ALTHIX 67S1 thixotropic alloy (AlSi7Mg0.6 Sr or 357). At the end of the cycle, the part is subjected to T5 treatment (water quench and then aged for 6 hrs at 170° C or 6 hrs at 155°C as applicable). The performance levels of thixoformed parts are compared with the manufacturers' specifications and with the performance levels of parts with identical references which are low-pressure cast or forged.

TECHNICAL/ECONOMICAL POSITIONING

Figure 3 gives the principal material/process solutions chosen to produce the demonstrators after an opportunity study. “Sheet steel”, “sheet aluminium” and Low Pressure permanent mold casting solutions are mentioned for reference purposes for parts manufactured in current production.
For other solutions, the relative weights are estimated from expected fatigue performances. Prices are compared on the basis of 100,000 parts a year, in monthly batches of 10,000 deburred parts that may or may not have undergone heat treatment depending on the case, fully machined, without any protective coating and which comply with all specifications requirements.
An indication of freedom of style is given for each solution. The higher this is, the more angular its geometric representation. The thixocast target proves very attractive.

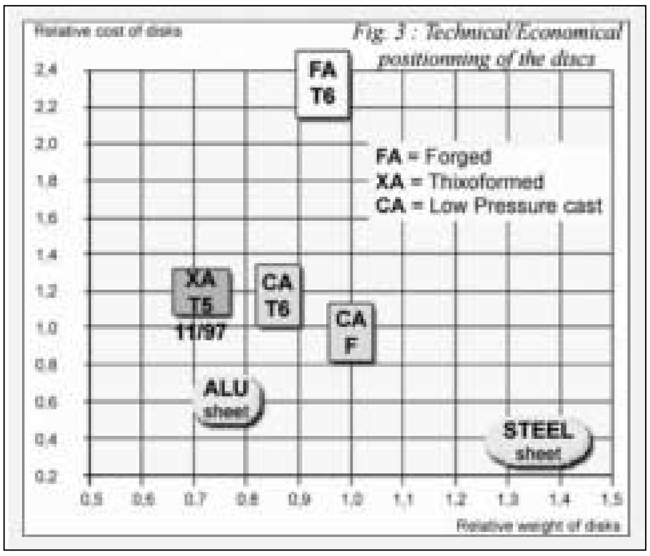


Fig. 3 – Technical/economical positioning of the disc.

Fig. 3 – Valutazione tecnico/economica dei processi del disco.

PERFORMANCE OF THIXOFORMED DISCS

Mechanical properties

They are estimated from two wheel discs per batch, representative of the quality of the batch, on the basis of three

Alloy – Process Condition	Tensile strength UTS (MPa)		Yield strength YS (MPa)		Elongation E (%)		Impact resistance K (J/cm²)	
	$\overline{X}$	w	$\overline{X}$	w	$\overline{X}$	w	$\overline{X}$	w
AlSi7Mg0.6 T5 (6 hrs-170°C) Thixoformed	279	276 to 281	209	200 to 217	6,6	5 to 8	1.0	0,9 to 1.5
AlSi7Mg0.6 T5 (6 hrs-155°C) Thixoformed	271	270 to 273	189	180 to 193	6,0	5 to 7	1,8	1,5 to 2,5
AlSi11Mg0.2 F LP Cast	174	154 to 187	104	100 to 108	5,7	3 to 8	5,3	4,5 to 6,5
AlSi11Mg0.2 T6 LP Cast	245	235 to 253	170	165 to 174	4,7	3 to 5	3,7	3,0 to 4,5
6082 T6 Forged	322	302 to 341	312	294 to 328	15	14 to 17	13,8	11,8 to 17,5

Table 2 – Mechanical properties obtained on dissection test pieces ($\overline{X}$ = average; w = range).

Tabella 2 – – Caratteristiche meccaniche ottenute con i diversi processi.

dissection test pieces per disc and are included in Table N°2. They should be compared with the characteristics of the reference materials studied for the manufacture of discs, i.e.: AlSi11Mg0.2 alloy in F and T6 condition produced by Low Pressure (LP) permanent mold casting and 6082 T6 alloy produced by forging.
The performances of all the solutions studied were higher than the specifications and characteristics obtained on the reference parts fully conform to those corresponding to current standards for this type of part.
The excellent level of characteristics obtained with T5 thixoformed solutions should be noted. Since variation of elongation is in reverse order to YS, there is nevertheless an apparent reversal of the level of elongation according to the aging temperature, attributable to the dispersion of the results. Elongation and impact resistance measurements are lower than the values anticipated.

Hardness

For each alloy, ten hardness measurements are taken on the same disc, distributed between the inner surface and the core on a cross section. Five parts per batch are also characterised on the hub bearing-surface, on the basis of 2 measurements per part. The average and range of these 20 measurements are indicated in Table N°3.
All the values are higher than the specifications requirements and correlate well with the tensile characteristics.

Surface quality

Thixoformed parts
For many of them, the surface appearance, particularly on the outer side of the wheel was non-compliant and liable to be detrimental to their use (fatigue resistance in particular) or their design after coating.
The main types of defects observed are:
- Denting at the level of the openings.
- Laps.
- In galling areas, adherent scale on the spokes, openings and on the top of the curvature resulting in a scratched, porous or even poor adherence of the cast skin, in places where the calculated stresses are at a maximum when the disc is under rotating bending stress.

Most of these anomalies probably stem from segregation of the liquid eutectic, associated with problems of friction against the mold when the cavity is filled with the semi-solid alloy.
It should be noted that this wheel disc is 380 mm diameter and weighs 4 kg which reaches the upper feasibility limits of the process using 5” diameter billets. In addition, the “Appearance” specifications are stringent. It is not surprising, therefore, that this type of problem is encountered for a first test. Significant progress can be envisaged from a quality standpoint.

Alloy – Process Condition Status	Brinell Hardness HB 5/250 X̄	w
AlSi7Mg0.6 T5 (6 hrs-170°C) Thixoformed	97	90 to 101
AlSi7Mg0.6 T5 (6 hrs-155°C) Thixoformed	87	76 to 90
AlSi11Mg0.2 F LP Cast	63	62 to 66
AlSi11Mg0.2 T6 LP Cast	84	76 to 90
6082 T6 Forged	110	107 to 114

Table 3 – Brinell hardness on discs.

Tabella 3 – Durezza Brinell sui dischi.

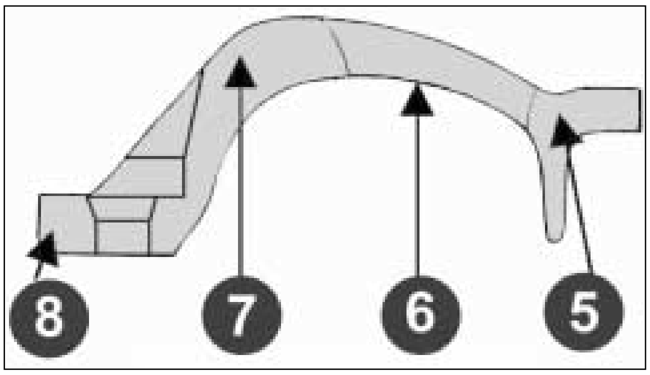


Fig. 4 – Disc radial cross section.

Fig. 4 – Sezione trasversale radiale del disco.

Thus, the parameters to be examined to obtain a compliant surface include:
- Insufficient temperature of the alloy after induction reheating, detrimental to its rheology.
- Inadequate thermochemical treatment of the mold cavity.
- A non-optimised injection cycle.
- An inadequate release agent and lubricant and insufficient control over their application to obtain suitable reproducibility of the Process.

To prevent the endurance tests carried out on the part from being adversely affected by these non-compliant surface conditions, a sort had to be made on the basis of visual observation in order to select only parts with an acceptable appearance.

Internal soundness and metallographic structure of thixocast parts

Metallographic studies are carried out on two parts per batch when received. Two complete radial cross-sections are picked on each part in order to carry out macrographic studies and several specimens for conducting micrographic inspections on the hub bearing surface, the attachment zone and in the fatigue crack initiation and propagation zones at the bottom of the openings (Fig.4)

Macrography on radial cross-section
Crystallisation appears extremely fine, homogeneous and non-dendritic, typical of thixotropic alloy crystallisation. The presence of occasional pockets of eutectic, distributed in a random pattern is observed. Porosity is also detected at the attachment zone and hub bearing surface levels, outside the zones subject to high fatigue stress (zone refs. 5 and 8 on Figure 4).

Micrographic examinations
Examinations are carried out on complete radial cross sections and on specific samples (refs. 5 to 8 on Figure 4).

Porosity and surface cracks
Observations on micrographic cross-sections confirm the presence of cracks detected when the surface of parts is examined, as well as surface zones not adhering well to the matrix (Fig. 5a,b), both on the inner and outer sides of the disc in places where the stress measured is at a maximum when the disc is under bending stress (zone refs. 6 and 7 on Fig. 4). Out of six samples per disc, taken at the bottom of the openings an average of four zones were identified on each side of the disc which showed poor adherence to the matrix, between 0.1 and 1.5 mm in length, representing an average defective length of between 2 and 10% of the length examined on each side of each disc, with a higher percentage on the inner side. These poor adherent zones are rich in eutectic.

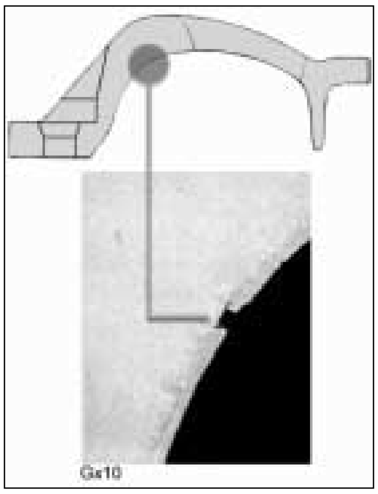


Fig. 5a – Thixoformed AlSi7Mg 0.6 T5 alloy disc. Poor adherence of the eutectic-rich skin.
Fig. 5a – Disco in lega AlSi7Mg 0.6 T5 tixoformato. Scarsa aderenza della pelle ricca di eutettico.

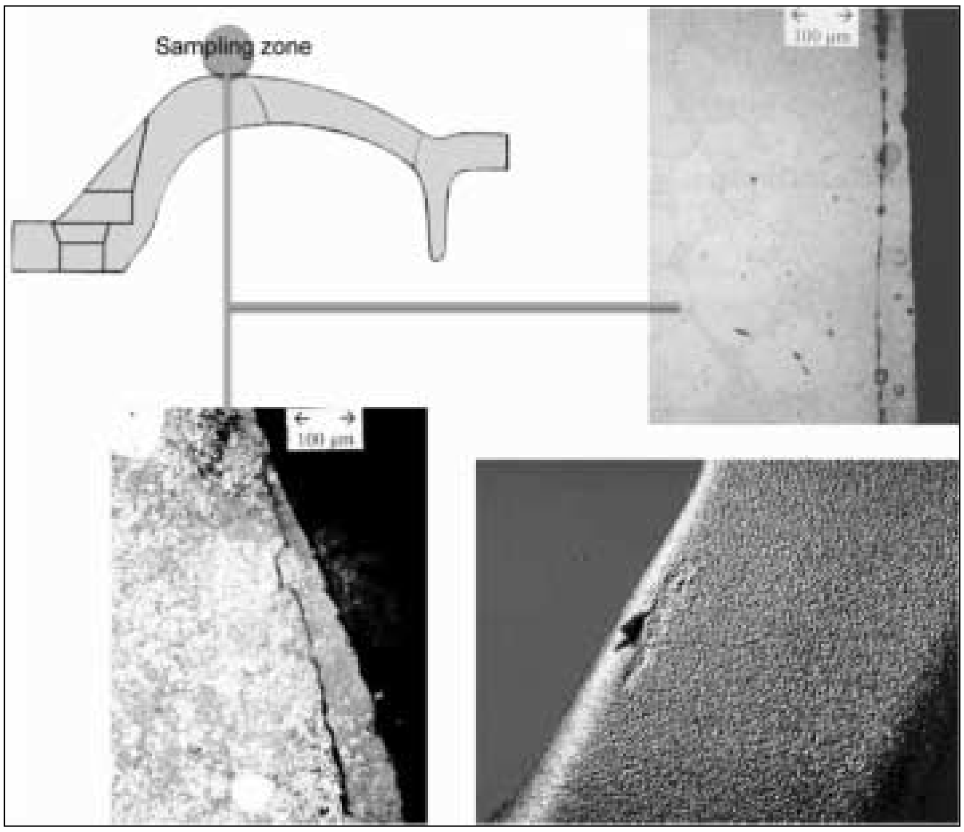


Fig. 5b – Thixoformed AlSi7Mg 0.6 T5 alloy disc. Poor adherence of the eutectic-rich skin.
Fig. 5b – Disco in lega AlSi7Mg 0.6 T5 tixoformato. Scarsa aderenza della pelle ricca di eutettico.

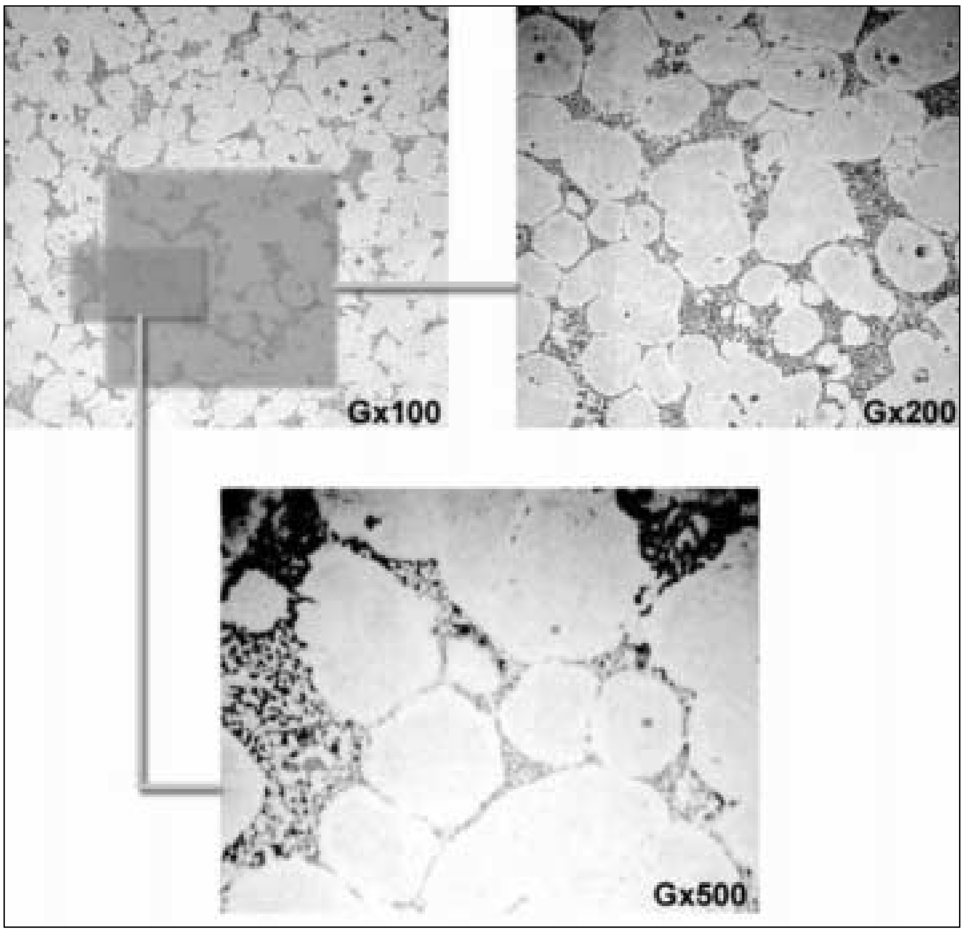


Fig. 6a – Thixoformed AlSi7Mg 0.6 T5 alloy disc. Globular structure of the primary phase α –Al

Fig. 6a – Disco in lega AlSi7Mg 0.6 T5 tixoformato. Struttura della fase primaria α –Al.

Metallographic structure
The structure corresponds correctly to that of the AlSi7 Mg0.6 thixotropic alloy, comprising primary phase α-Al globules, surrounded by fine, modified eutectic (Fig. 6a). The structure is homogenous with a globule size of between 85 and 95 µm.

Surface zones rich in eutectic are also observed in the form of pockets or bands over 100µm long, some as long as 5 mm. Out of six samples examined by side and by disc, taken at the bottom of the openings, it appears that 20 to 25% of the length observed is rich in eutectic on the outer side of the discs and that

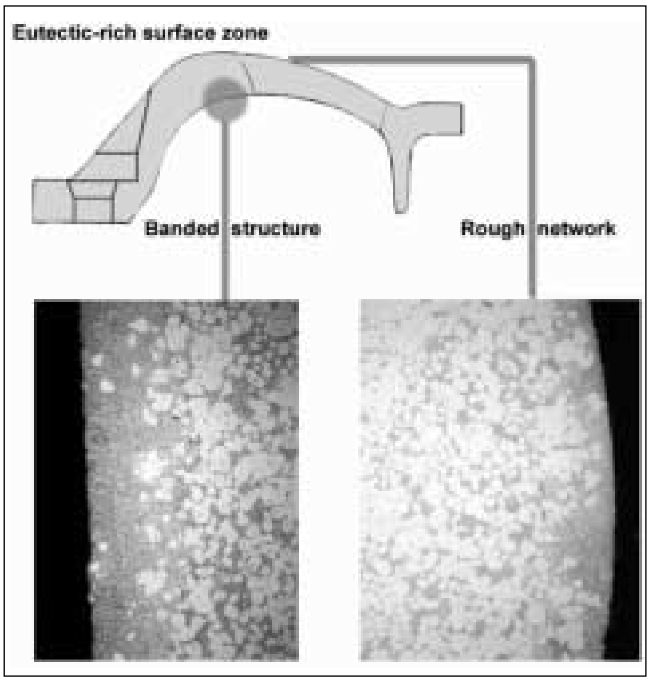


Fig. 6b – Tixoformed AlSiMg 0.6 T5 alloy disc.

Fig. 6b – Disco in lega AlSiMg 0.6 T5 tixoformato.

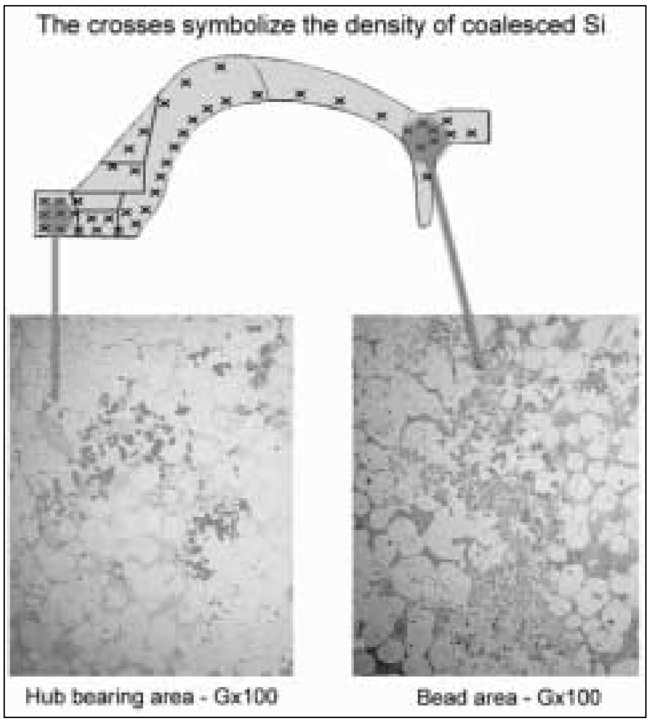


Fig. 7 – Thixoformed AlSi7Mg 0.6 T5 alloy disc. Coalesced silicon.

Fig. 7 – Disco in lega AlSi7Mg 0.6 T5 tixoformato. Coalescenza del silicio.

this percentage reaches 40 to 60% on the inner side (Fig.6b). The cause of the eutectic enrichment of the surfaces can probably be attributed to the squeeze out of the eutectic liquid during the injection phase, leading to this segregation. Since this layer sometimes adheres badly to the matrix, it causes the majority of surface defects previously indicated. The structure also reveals the presence of a significant quantity of coalesced silicon (Fig. 7). This coalesced silicon, stemming from the eutectic, probably results from a too low heating temperature at the core of the slug before the injection cycle and would explain the rather low level of impact resistance and elongation measured on the dissection samples.

Dimension compliance and weight

Several parts from each batch for each material/process solution are verified from a dimension standpoint. On the assumption that results comply with specifications, it is interesting to characterise all the parts by their weight and calculate the associated dispersion in order to estimate the stability of the process. Table N°4 below summarises the results obtained and shows that the Low Pressure casting process offers the best production reproducibility and that the thixocasting process stability is close to that of forging.

Wheel disc fatigue resistance

Experimental procedure

The discs or wheels fatigue resistance is assessed under rotating bending at ambient temperature, at constant load and at a frequency of 14Hz with a stress ratio R = - 0.50 . The disc fatigue life corresponds to the appearance of a crack detectable by a significant evolution of the deflection measured and recorded throughout the test. The test machine is equipped with a stop mechanism triggered at a programmed deflection threshold. Analysis of the recordings and observation of the cracks enable the number of cycles corresponding to the appearance of a crack to be accurately determined. The fatigue resistance is determined on the basis of a Wöhler curve for fatigue lifes between 10^4 and $6x10^6$ cycles. The endurance limit and the associated dispersion are estimated in accordance with the ASTM E739 standard by statistical analysis of the stress results and the log of the number of cycles. Between fifteen and twenty specimens are used for the testing of each alloy with a minimum of five stress amplitudes and three specimens at each stress amplitude.

Results and discussion

The endurance limits at $6x10^6$ cycles, expressed at the confidence level P=95%, are summarized in table 5 along with the potential corresponding weight reductions expressed in relation to the Manufacturer's specification which is 95 MPa at $6x10^6$ cycles. The potential weight reduction is estimated from the Lf^n criterion, with n = 2/3 under rotating bending, according to the expression:

$$\text{Weight reduction (\%)} = 100 - \frac{Lf1^n}{Lf2^n} \times 100$$

The endurance limits of the reference materials agree correctly with literature data [4]. The endurance limit of the thixoformed parts reached a value close to 120 MPa, less than the expected value of 140 MPa and insufficient for it to stand out as the best reference solution to achieve the weight reduction target sought. The dispersion of the results is important.(Fig.8)

Numerous studies have been carried out on the fatigue resistance of cast aluminium alloys. According to the available literature, the fatigue mechanisms of the AlSi7Mg0.3 alloy can be summarized as follows:

	6082 T6 Forged	AlSi11Mg0.2 LP Cast	AlSi7Mg0.6 T5 Thixoformed
Number (n)	130	34	100
Batch standard deviation (g)	15	6	13

Table 4 – Disc mass dispersion.

Tabella 4 – Valutazione statistica della massa ottenuta con i vari processi.

Table 5 - Lf of alloys and potential corresponding weight reduction.

Tabella 5 - Lf delle leghe e corrispondente potenziale di riduzione pesata.

Process - Alloy – Condition	Lf at $6x10^6$ cycles (MPa) – P = 95%	Potential of weight reduction (%)
AlSi11Mg0.2 F LP cast	95 ± 12	0
AlSi11Mg0.2 T6 LP cast	126 ± 15	17
AlSi7Mg0.6 T5 Thixoformed	122	15
6082 T6 Forged	107±17	7

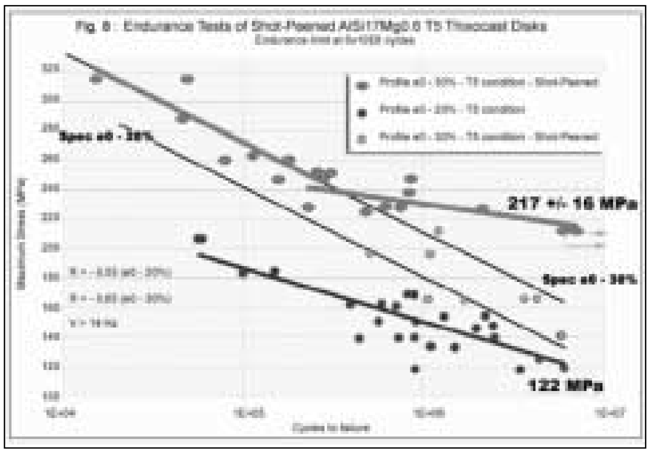


Fig. 8 – Endurance tests of shot peened AlSiMg 0.6 T5 tixocast discs.

Fig. 8 – Prove di fatica di dischi tixoformati in lega AlSiMg 0.6 T5 sottoposti a pallinatura controllata .

- Initiation of a crack from a surface defect, an inclusion or a pore opening onto or located under the surface [5,6,7,8], in particular under plane or rotating bending stresses.
- If the crack starts from a pore, the larger the size of the pore, the lower the fatigue limit [9].
- It is then followed by interdendritic and intradendritic propagation phases [10, 11] and finally breaks.

In an alloy without pores under extremely high fatigue stress (250 Mpa), propagation and crack interruption are attributed to the interaction of cracks with the triple points of the dendritic network [12]. The majority of authors consider that the startup period is negligible in relation to the fatigue life but controversy still exists on this point. Savelli [13] considers the fatigue life is principally controlled by the propagation of cracks and the points where they are blocked on grain joints.

As a result, in line with the micrographic observations carried out in the thixoformed disc zone 6 (figure 4) where the cracks initiate and propagate, the average fatigue resistance performance of these discs (Lf = 122 MPa) and the significant dispersion of the results can be explained by the presence of numerous surface defects, most of which being the rich eutectic zones which adhere badly to the matrix. These observations were confirmed by characterizing the fatigue of a series of 10 parts, selected according to the quality of their surface condition. At 6 x 10^6 cycles, the endurance limit reached a value of 140 MPa and the dispersion of results was halved. Therefore, there is considerable potential for progress in fatigue resistance as much as the quality of the surface condition could be improved by better control over rheology, involving a reduction of eutectic segregation and optimization of process parameters. The potential for progress is even more credible because the structure has a fine grain and there is no porosity which are significant advantages compared with low-pressure cast parts delivered at the acceptance limits in relation to Internal soundness specifications.

The "Cost" target in industrial manufacture conditions is not achieved either for this wheel disc, originally designed to be forged (Fig.9).

PRESTRESSING SURFACE TREATMENT

Apart from emerging materials/process solutions offering considerable potential for progress in the field of "fatigue resistance / cost", other routes can also be considered to increase the fatigue resistance of materials at a competitive cost for a wide-scale industrial application such as the manufacture of a wheel disc. Among these, prestressing surface treatments are particularly interesting and are widely used in industry, notably through the technique of shot peening. It has been established [14] that the main reason for improving fatigue life of aluminium alloys is due to residual compressive stresses, rather than surface strain hardening.

The requirements to be met for a wheel disc are however very severe :

- no damage to the surface so as not to reduce fatigue resistance
- the effects of the treatment must still be detectable at a depth of 0.5 mm so as to ensure good resistance to aggressive environments for many years.
- the residual compressive stresses must remain stable under thermal activation (paint curing) and thermo-mechanical stress (heating due to braking combined with drift force)
- the surface roughness after treatment must be compatible with the requirements concerning appearance after surface coating
- no alteration of the environmental resistance of the wheel coating.

After preliminary tests, the maximum acceptable shot peening treatment for parts to achieve a compliant appearance after undergoing the industrial paint coating process, was shown to correspond to treatment with 0.6 mm steel balls, a coverage ratio of 100% and an Almen intensity of F23A - F30A. Surface roughness gives a value of Ra = 11 µm and Rz = 73 µm. This last treatment was the one selected to submit the parts to shot peening before fatigue testing, either on just the discs or on the discs assembled into a wheel. Shot

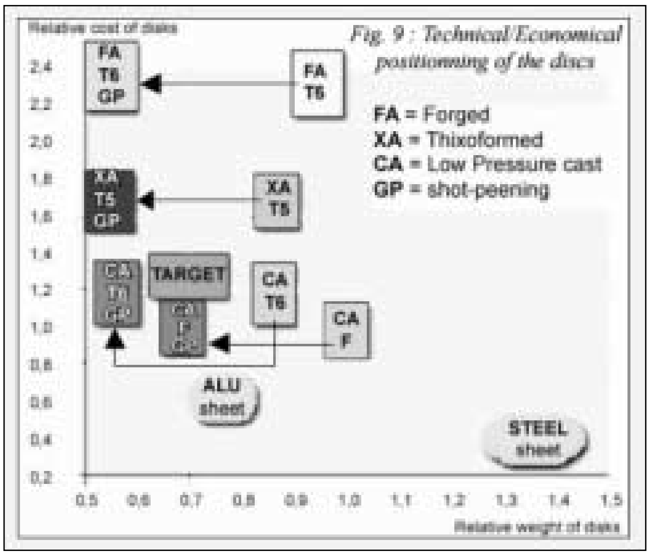


Fig. 9 – Technical/economical positioning of the disc.

Fig. 9 – Valutazione tecnico/economica dei dischi.

peening is carried out by a company called METAL IMPROVEMENT COMPANY on both sides of the disc and the disc/rim welding bead (for wheels).

Prestressed wheel disc fatigue resistance

The thickness of the discs was reduced by machining of the internal face according to the expected fatigue performance increases. For each alloy, the fatigue characteristics were tested for five to ten parts with a nominal thickness of e0, prestressed with the same treatment, in order to check in each case the validity of the model linking stress to weight reduction for the same load.

Results and discussion

For each alloy, the endurance limits at $6x10^6$ cycles in prestressed and non-prestressed conditions, the thickness reductions really implemented and the potential thickness reductions in relation to the specifications are indicated in table 6. For all the solutions studied, significant increases in the endurance limits are observed, allowing substantial weight reductions which are greater than those expected and implemented in these tests. Examination of the Wohler curves provides an explanation of the origin of this performance. Indeed, whatever the material studied, a slope change is observed for the relation S-log N between 10^5 and 10^6 cycles which appears characteristic of the shot-peening prestressing treatment and leads to remarkable performance in terms of long- life fatigue (Fig. 8,11). Thus, at $6x10^6$ cycles, the endurance limit of pre-stressed thixoformed discs achieves a value close to 220 MPa. This corresponds to an increase in their fatigue resistance of 95Mpa, which is much higher than the result obtained for LP cast discs. As a result of these observations, a specific patent was filed covering the shot peening of thixotropic alloys [16] in several countries. This patent has already been granted in the US [22].

Several wheel discs have low fatigue lifes and statistically different in relation to the S-N line for pre-stressed parts. These results are distributed within the envelope of the parts not treated by Shot-Peening, as if the parts had not been shot peened (Fig. 8). This abnormal performance can principally be attributed, as mentioned before, to the presence of eutectic rich zones which adhere poorly to the matrix (Fig. 5a,5b).

This confirms recent conclusions by certain authors [15], i.e. that Shot Peening has a beneficial effect on the fatigue resistance of parts only if the length of surface cracks is less than the depth prestressed. It is accepted that the treatment introduces residual compressive stresses which prevent the initiation and propagation of cracks [17, 18]. Residual stresses were measured at the bottom of the disc openings, using the incremental drilling method [19] which enables characterization of the main stresses profile along the depth, directly on mechanical parts. Additional measurements were also taken on the surface by X-ray diffraction.

The profiles obtained on wheel discs, treated by shot peening at an Almen intensity of F35A-F45A associated with a 100% coverage ratio are given in Figure 10. The maximum compressive stress is located at a depth of 0.2 mm for the three alloys and its value appears in direct proportion to the yield strength of the material prior to Shot Peening treatment (Fig. 12). It reaches 220 MPa for the forged 6082 T6 alloy and its effect is to increase its endurance limit at $6x10^6$ cycles to the remarkable level of 230 MPa for an initial va-

Process-Alloy Condition	Lf at 6x106 cycles MPa – P = 95% Non-prestressed	Prestressed	Thickness reduction achieved (%)	Potential thickness reduction (%)
AlSi11Mg0.2 F LP cast	95 ± 12	173 ± 13	20	33
AlSi11Mg0.2 T6 LP cast	126 ± 15	210 ± 16	30	41
AlSi7Mg0.6 T5 Thixoformed	122	217 ± 16	30	42
6082 T6 Forged	107 ± 17	229 ± 11	30	44

Table 6 – Lf of alloys and thickness reduction.

Tabella 6 – Lf delle leghe e riduzione di spessore.

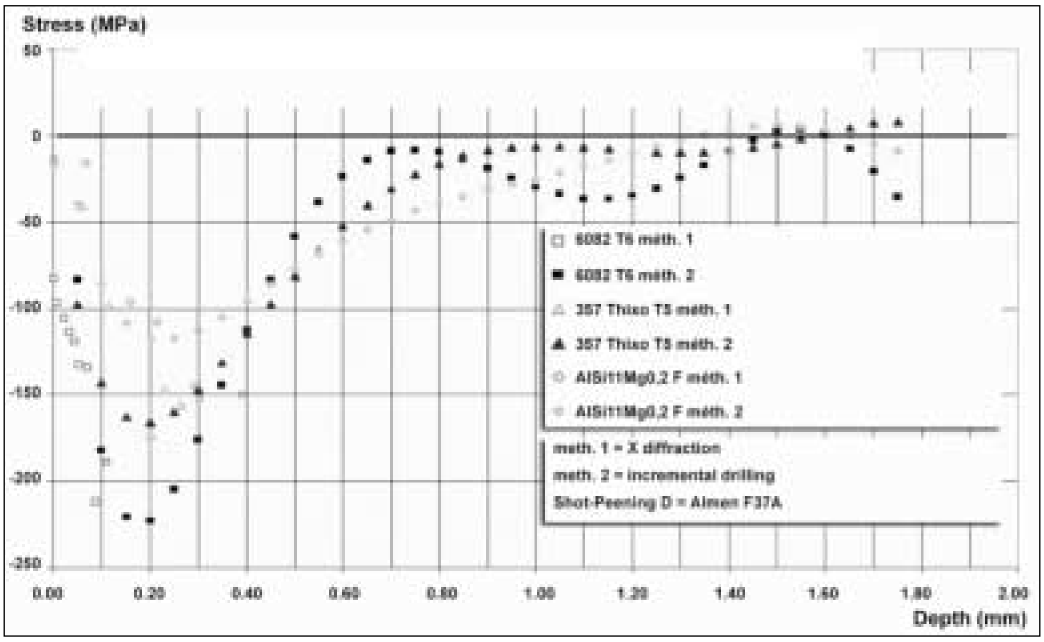


Fig. 10 – Residual stress measurements after shot peening.

Fig. 10 – Dati relativi alle tensioni residue dopo pallinatura controllata.

Fig. 11 – Endurance tests of shot-peened AlSi11Mg 0,2 F low pressure cast discs.

Fig. 11 – Prove di fatica di dischi in lega AlSi11Mg 0,2 F prodotti mediante getto a bassa pressione e sottoposti a pallinatura controllata.

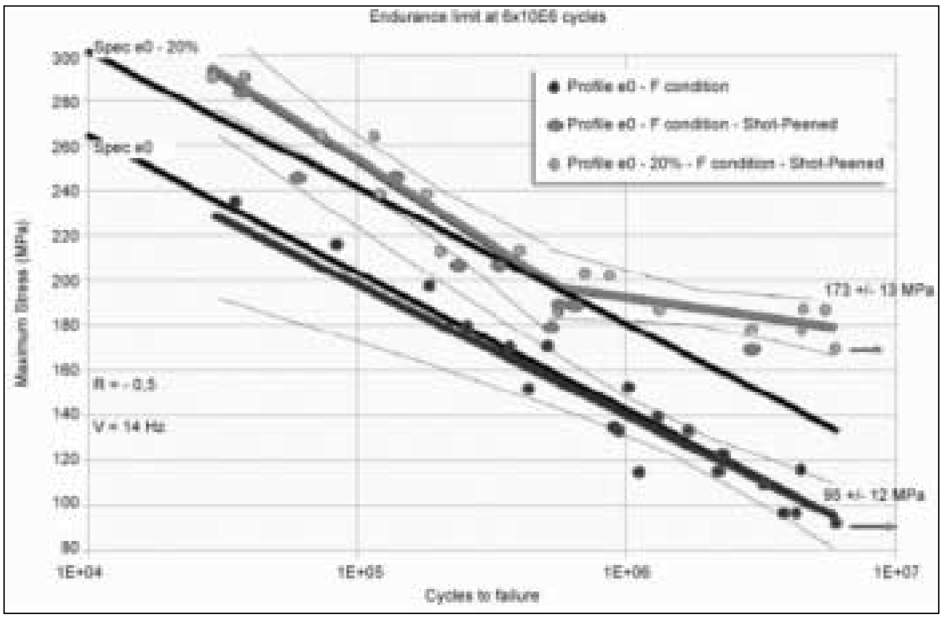
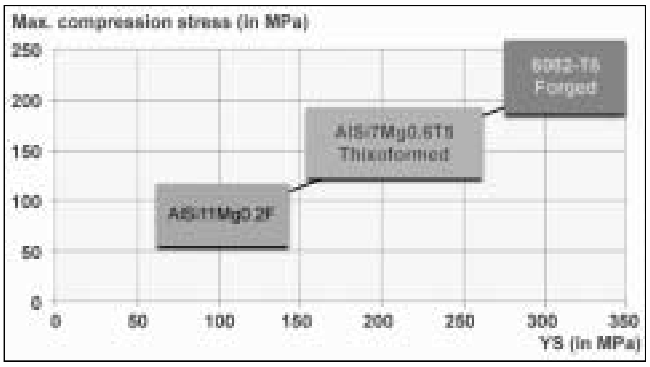


Fig. 12 – Maximum compressive stress versus the yield strength.

Fig. 12 – Relazione fra massimo carico di compressione e carico di snervamento.



lue of 107Mpa (Fig.12).
For the three alloys, the compressive stresses still present a significant level up to a depth of 0.5 mm, which corresponds to the objective targeted, in order to guarantee a given lasting performance level with respect to potential external aggression.
For treatment at an Almen intensity of F23A-F30A, optimised as a first approach for a wheel disc application and adopted in this study, the stress profiles compared to the previous ones can be summarised as follows:
For each alloy:
- the maximum compressive stress is unchanged but it is at a depth of 0.15 mm instead of 0.20mm
- Compressive stress still presents a high level down to a depth of 0.4 mm, instead of 0.5mm

Other requirements are also necessary to comply with the certification file for a wheel disc, i.e.:
- stability of the residual stresses in service
- environmental resistance of the protective coating
- resistance to kerb impacts.

Stability of residual stresses

Residual compressive stresses introduced by pre-stressing surface treatment with shot peening is only advantageous if it remains stable in service.
The relaxation of residual stresses introduced by shot peening may occur under thermal effect or mechanical effect or the two ones combined.
While running, the disc is mainly subjected to mechanical stress in the domain of low-stress fatigue. Therefore, there is no risk of relaxation in this domain. On the other hand, two events may occur in the heat domain:
- The first is linked to paint stoving,
- The second is linked to considerable overheating of the wheel disc hub-bearing surface, due to exceptional braking conditions combined with drift force.

Fatigue tests

Parts made of each alloy, pre-stressed at an Almen intensity of F23-F30A, with 0.6 mm steel balls and a coverage ratio of 100 %, were therefore subjected to relaxation treatment for 10 minutes at 180 °C to simulate paint stoving, followed by heating for one hour at 140 °C, in order to reproduce overheating due to exceptional braking conditions.
The stability of compressive stresses is characterised by the residual resistance of these discs to fatigue, the results of which are given in Table 7.

Results and discussion

Relaxation of compressive stresses is characterised in these tests by the fatigue resistance of parts subjected to the heat tests described above.
The following can be observed:
- For the AlSi11Mg0.2 T6 LP cast alloy – a decrease in fatigue limit of 10%.

Table 7 – Disc endurance limit in prestressed and prestressed + relaxed condition.

Tabella 7 – Limite di fatica del disco in condizione di pre-tensionamento e pre-tensionamento+ rilassamento.

Process Alloy Condition	PRESTRESSED Lf at $6x10^6$ cycles (MPa) – P = 95%	PRESTRESSED AND RELAXED (10 min at 180°C + 1 hr at 140°C) Lf at $6x10^6$ cycles (MPa) – P = 95%
AlSi11Mg0.2 F LP Cast	173 ± 13	Non-significant effect
AlSi11Mg0.2 T6 LP Cast	210 ± 16	190
AlSi7Mg0.6 T5 Thixoformed	217 ± 16	Non-significant effect
6082 T6 Forged	229 ± 11	Non-significant effect

- For the other alloys, the heat tests have no significant effect on their fatigue resistance.

The origin of the relaxation observed for the alloys lies in the microstructure by the rearrangement of dislocations and is linked to a heat-activated process with which activation energy Q can be associated [20].
This heat relaxation problem should principally be taken into account for stresses introduced by surface shot peening [21].
It has also been established that stress relaxation is linked to the material microplasticity resistance (R_i). The R_i value is all the more higher since there are barriers to the dislocations movement: grain joints, very fine precipitate, second phase, foreign atoms, stable configuration of dislocations.

Environmental resistance of the protective coating of prestressed wheel discs

In addition to its style and appearance function, the coating also plays an important role in protecting wheels during use against various types of aggression such as spray from water, salt, mud, gravel, hydrocarbons, etc.
Since the resistance requirements to this type of aggression are very stringent, wheel manufacturers have had to develop specific surface treatment and coating lines in order to satisfy homologation tests. The following principal operations are generally implemented:
- Degreasing
- Conversion treatment
- Coating with a powder primer
- Coating with metallic lacquer
- Coating with varnish.

In view of the complexity of the installations and high capital outlay required for setup, it is important to verify that a change in substrate (type of alloy), heat treatment or mechanical treatment applied to wheels does not alter the environmental resistance properties of the coating. Shot peening, by modifying the roughness and nature of chemical species and increasing the density of crystalline defects (vacancies, dislocations, etc.) on the surface of the part, also increases the reactivity of the surface. As a result, the coating may prove less efficient or inadequate to protect the substrate. It is necessary, therefore, to adjust the treatment line operating parameters or considerably modify some of them which may rapidly become a handicap difficult to overcome.

Results and discussion

The discs to be studied were introduced onto the industrial surface treatment line which was set up to receive a passenger car wheel coat of paint, according to the current specifications. The study was made on the following parts:
- Specimen Low Pressure cast AlSi11Mg0.2T6 discs
- Pre-stressed, Low Pressure cast AlSi11Mg0.2T6 discs
- Thixoformed AlSi7Mg0.6T5 discs
- Pre-stressed, Thixoformed AlSi7Mg0.6T5 discs.

The Pre-stressing treatment of the parts prior to coating was carried out by shot peening at an Almen intensity of F23A-F30A, as described precedently.
After coating, the parts were subjected to the tests required by the car manufacturer. The results given in Table 8 indicate that the pre-stressed Low Pressure cast and Thixocast parts satisfy homologation tests and shot peening does not adversely affect the coating's aptitude to provide efficient protection for the cast or thixocast substrate. Pre-stressed solutions can, therefore, be homologated.

Gravel shot resistance test: Results after second gravel shot treatment. Mesure of average number of impacts to the support medium per dm^2.

Technical-economical positioning of prestressed wheel discs

All the solutions studied enable the 20% weight-reduction performance sought to be achieved or exceeded. However, this performance is only validated for the thixocast solution if the parts have a surface condition that complies with specifications.
As regards cost, only Low Pressure cast solutions fulfil the objective (Fig. 9).

Application to the 6j15 reference wheel used in this study

The bi-metal wheel concept is quite suitable in order to optimise the disc and rim separately. The choice of a rolled aluminium sheet rim in a 5000 series such as 5454, which is

Test	Expression of the results	Requirements	Results AlSi11T6 Reference	Results AlSi11T6 pre-stressed	Results 357T5 THIXO Reference	Results 357T5 THIXO Pre-stressed
Adhesion / Grid	% surface peeled	<= b	a/b	a	a	a
1000 hrs salt spray						
Oxidation	Dimensioning	0	0	0	0	0
Blistering	Dimensioning	0	0	0	0	0
Peeling when scratched	mm	<= 3	0-0,5	0-0,5	0	0-2
Oxidation of edges	%	0	0	0	0	0
Gravel shot resistance	Dimensioning	<=3	3	3	3	2
	No/dm^2	<= 300	220-230	200-220	200-220	200-220
Cupro-acetic salt spray 72hrs						
Overall corrosion ratio	%	<= 1	0	0	0	0
Local corrosion ratio	%	<= 30	0	0	0	0
Peeling when scratched	mm	<= 3	0	0	0	0
Oxidation of edges	%	0	0	0	0	0
Resistance to Immersion in water for 21 days						
Blistering	Dimensioning	0	0	0	0	0

Table 8 – Results of environmental resistance of discs coating pre-stressed or otherwise prior to coating.

Tabella 8 – Confronto dei risultati della resistenza all'ambiente della ricopertura dei dischi pre-tensionati con e senza ricopertura.

then spin formed, allows a weight-reduction of around 20% to be combined with adequate ultimate tensile strength and high ductility, all the more necessary since the tyres are qualified as low-aspect ratio. The cost of this type of rim is particularly advantageous.
A disc produced according to one of the best of the above solutions, welded to a spin-formed rim using MIG technology, with the disc and welding bead then pre-stressed, enables a reduction in the weight of the wheel of between 17 and 24% to be obtained, assuming that the thickness reduction can be applied to between 40 and 70% of the disc weight. In the case in point, the weight of the bi-metal wheel produced in this manner is 5 kg, to be compared with 6.2 kg, the weight of the reference part.

CONCLUSION

This prospective study of wheel disc weight reduction shows that the technology of thixocasting complies with wheel specifications, providing surface quality is under control and has the best potential among the material-process solutions studied for causing a change in the asymptote ‘’weight reduction-freedom of style’’ at a competitive cost, but without achieving the weight reduction aimed for.
For this part, originally designed to be forged, the thixocast solution is less competitive economically than the low pressure cast solution.
The most pertinent wheel dimensioning criterion, confirmed by experiment, is the rotating bending endurance limit with exponent n = 2/3.
Pre-stressed treatment at an Almen intensity F23-F30A on both sides of wheel discs made of the thixoformed AlSi7Mg0.6 T5 alloy, the 6082 T6 forged alloy and the low pressure cast AlSi11Mg0.2 F alloy introduced high intensity compressive stresses, the values of which appear in direct proportion to the yield strength of the material prior to prestressing treatment. For the three alloys, maximum compressive stress is reached at a depth of 0.15 mm and a significant level (100 MPa) is still present at 0.4 mm.
Treatment at an Almen intensity F23-F30A, compatible with all requirements of the wheel specifications, strongly increases the fatigue life of thixocast AlSi7Mg0.6 T5 discs as well as discs made of low pressure cast and forged alloys. Fatigue Lives differences between pre-stressed and non-prestressed discs are all the more greater the lower the stress amplitude. For each alloy, the S/log N straight line presents a slope change between 10^5 and 10^6 cycles which seems typical of the Shot peening effect. Therefore, the endurance limits at $6x10^6$ cycles for pre-stressed thixoformed or forged discs can reach 220 to 230 MPa, which corresponds to a high potential weight-reduction in the region of 40% in relation to the specifications.
For a wheel-disc application and, more generally, for any fatigue-dimensioned part operating at ambient conditions, these initial results using impact surface prestressing treatments point to several certifiable and industrializable solutions which are well positioned in terms of modification of the "weight reduction-freedom of style-cost" asymptote. For parts with a net weight of less than 3 to 4 kg, thixocasting and, even more, rheocasting, show the best potential, as long as the surface quality of the parts is under control and complies with specifications.

ACKNOWLEDGMENTS

The authors are grateful to Gilbert Gauthier, Lucien Messiet, Robert Ducroux, Denis Jubert and his calculation team (David Dean, Denis Morin), Christian Chanet and the shop machining team from our research department and the PECHINEY research foundry team for their expert support. Thanks are also due to the STAMPAL thixocasting team for their expertise to produce those experimental parts and to the companies CETIM and MIC.

CONTACT

Gilles Grillon graduated from Paris and Clermont-Ferrand University like metallurgical engineer with a surface treatment degree and works for Michelin since 1969. Contact Grillon by email at: jeanne-marie.jocaille@fr.michelin.com

REFERENCES

[1] “Vers une rupture technologique” (Towards technological breakage), Prospective File - R&D (Avril 1997).
[2] R.L. Klimisch, Auto and Light Truck Group, The Aluminium Association, J.C. Benedyk - The 21st Annual Automotive Aluminium Design & Fabrication Seminar – “Automotive aluminium – Protecting what’s important” - Light Metal Age (February 2001).
[3] M.F. Ashby, “Materials and shape” – Acta Metall. Mater. vol. 39, n° 6 (1991).
[4] ASTM International, “Fatigue data book – Light structural alloys” (1995).
[5] M.J. Couper, A.E. Neeson, J.R. Griffiths, “Casting defects and the fatigue behaviour of an aluminium casting alloy” – Fatigue & Fracture of Engineering Mat. & Str. 13-3 (1990).
[6] K.J. Miller, “Initiation and growth rates of short fatigue cracks”, University of Sheffield. Fatigue Fract. Engng Mater. Struct. Vol. 10. N°. 2. , 1987
[7] C.H. Caceres, B.I. Selling - Material Science & Engineering A, vol. A220 (1996).
[8] G.O. Rading, - AFS Transactions, vol. 102 (1994).
[9] M. Garat, “Evolution des alliages d’aluminium destinés aux roues d’automobile” (Evolution of aluminium alloys for car wheels)– Revue SIA (Avril 1992).
[10] G.W. Powell, “The fractography of casting alloys materials characterization”, 33 (1994).
[11] C. Verdu, H. Cercueil, S. Communal, P.Sainfort, R. Fougeres, “Microstructural aspects of the damage mechanisms of cast Al-7Si-Mg alloys” ICAA5 - Mat. Science Forum, Part3 (1996).
[12] A. Plumtree, S. Schäfer, “Initiation and short crack behaviour in aluminium alloys castings”, EGF Publication (1986).
[13] S. Savelli, J.Y. Buffière, R. Fougères, “Approche quantitative de la fatigue d’un alliage d’aluminium de moulage AlSi7G 0,3”(Quantitative approach to fatigue in the AlSi7G0.3 aluminium casting alloy)– Matériaux & Technique n° 5-6 (2000).
[14] R.B. Waterhouse, B. Noble, G. Leadbeater, “The effect of shot peening on the fretting-fatigue strength of an age hardened aluminium alloy (2014A) and austenitic stainless steel” – J. Mech. Working Technol. 8 (1983).
[15] E.R de los Rios, M. Trooll, A. Levers, Improving the fatigue cracks resistance of 2024-T351 aluminium alloy by shot peening. University of Sheffield, Department of Mechanical Engineering (1999).
[16] European Patent Request N° EP 1 063 033 A 1 dated 08/06/1999. G. Grillon, Société De Technologie Michelin- Procédé de fabrication d’une pièce métallique, telle qu’une partie de roue destinée au roulage d’un véhicule, et une telle roue (Production process for a metal part, notably part of a wheel or the wheel itself enabling a vehicle to roll)

[17] P.K. Sharp, J.Q. Clayton, G. Clark, " Fatigue resistance of peened 7050-T7451 aluminium alloy – Repair and re-treatment of a component surface" – Fatigue, Fract. Engng. Mater. Struct., vol. 17 (1994).
[18] C.P. Diepart, "Modelling of shot peening residual stresses – Practical applications" – Materials Science Forum, vol. 163-6 (1994).
[19] J. Lu, A. Niku-Lari, J-F. Flavenot, "Récents développements de la mesure des contraintes résiduelles par la méthode du perçage incrémental" (Recent developments in the measurement of residual stress by the incremental drilling method) – Matériaux & Techniques (Déc. 1985).
[20] O. Vohringer, "Abbau von Eigenspannungen." - Symp. Eigenspannungen Karlsruhe (1983).
[21] M. Bousseau, G. Brault, Ch. Mas, "Influence d'un maintien isotherme sur les contraintes de grenaillage. Conséquences sur la tenue en fatigue" (Influence of shot peening stress on isothermic maintenance. Consequences on fatigue resistance) - Mém. et Et. Sci. Rev. Mét.9 (1984).
[22] G. Grillon, Société De Technologie Michelin. United States Patent N° US 6,372,063 B1, Apr. 16, 2002. Process For Manufacturing Metallic Component And Such Metallic Component.

ABSTRACT

RIDUZIONE DEL PESO MEDIANTE TIXOFORMATURA ASSOCIATA A PALLINATURA CONTROLLATA

KEYWORDS:
aluminium and alloys, thixocasting, shot peening

La memoria riporta i risultati di uno studio sulla riduzione del peso applicato al disco di una ruota di automobile. Dopo aver valutato le potenzialità delle più importanti tecnologie di formatura dei materiali fra quelle esistenti e quelle emergenti, la tixoformatura delle leghe di alluminio risulta essere una soluzione molto valida per modificare la relazione "Riduzione del peso-Libertà di design-Costo". Il livello di prestazione delle parti tixoformate è stato confrontato con i requisiti dei costruttori di automobili in termini di caratteristiche metallurgiche quali finitura superficiale, resistenza all'impatto e alla fatica e resistenza alle prove ambientali della ricopertura protettiva.

Si sono anche paragonati i livelli di prestazione dei pezzi tixoformati con quelli di parti identiche prodotte mediante colata a bassa pressione o forgiatura. La resistenza a fatica osservata sui prototipi tixoformati, che è risultata più bassa del previsto per i dischi (Lf = 120 MPa a 6x106 cicli) a causa dell' insufficiente controllo della finitura superficiale, sembra non permettere di raggiungere la necessaria riduzione di peso. In termini economici per questo disco, originariamente progettato per essere forgiato, la tixoformatura risulta essere meno competitiva rispetto alla colata a bassa pressione con stampo permanente. Per raggiungere la riduzione di peso richiesta (20% rispetto alle migliori soluzioni di riferimento), è stato effettuato un trattamento superficiale di pre-tensionamento mediante pallinatura controllata ad una intensità Almen di F23-F30A, compatibile in termini di rugosità superficiale con una ricopertura protettiva e decorativa certificata da un produttore di automobili. Se trattati in questo modo i dischi migliori mostrano elevati limiti di fatica, che consentono una potenziale riduzione di peso anche superiore al 40%. Purtroppo tale risultato non è stato raggiunto da tutti i dischi e questo fenomeno può essere attribuito alle insufficienti finiture superficiali prima della pallinatura controllata. E' stato dimostrato che le tensioni residue di compressione hanno il giusto livello necessario per resistere alle tensioni termomeccaniche alle quali i dischi sono sottoposti. E' stato anche verificato che la pallinatura controllata non altera le proprietà della ricopertura applicata per un'efficace resistenza all'ambiente. Questi risultati iniziali possono sfociare in diverse soluzioni certificabili e realizzabili a livello industriale che prevedano l'impiego di trattamenti di pre-tensionamento con un soddisfacente rapporto "Costo-Riduzione del Peso-Libertà di design ". La tixoformatura e ancor più il processo di formatura allo stato semi-solido (rheocasting) presentano le migliori potenzialità, a condizione che la qualità superficiale delle parti sia sotto controllo e sia conforme alle specifiche.