LIFE CYCLE ASSESSMENT IN THE AUTOMOTIVE INDUSTRY: COMPARISON BETWEEN ALUMINIUM AND CAST IRON CYLINDER BLOCKS

F. Bonollo, I. Carturan (DTG, Università di Padova, sede di Vicenza, Italy)
G. Cupitò (Centro Ricerche Fiat, Orbassano, Italy)
R. Molina (TeksidAluminum, Carmagnola, Italy)

Abstract

The continuous search for lighter materials in the automotive industry is justified by the environmental advantage deriving from the reduction of fuel consumption and, therefore, lower CO_2 emissions throughout the vehicles' use phase. However, a correct evaluation of the environmental effects related to the choice of "light" materials should involve not only the use but the whole life of the vehicle. This paper presents the results of the comparison between the environmental load of cast iron and aluminium cylinder blocks. The methodological approach adopted for the analysis is Life Cycle Assessment (LCA) since it allows to consider the environmental effects of a product during the production, use and end-of-life treatment phases. The study demonstrates that, while during the production stage the environmental load related to the aluminium block is higher than the one related to the cast iron block, during use and end-of-life treatment the gain of aluminium over cast iron makes the aluminium cylinder block more environment friendly than the cast iron one.

Riassunto

Esiste, da parte dell'industria automobilistica, una continua attività volta all'impiego di leghe leggere, giustificata dai vantaggi ambientali derivanti dalla riduzione dei consumi di carburante e, conseguentemente, dalla riduzione delle emissioni di CO_2. Ad ogni modo, una corretta valutazione degli effetti ambientali associati all'impiego delle leghe leggere dovrebbe essere riferita non tanto al semplice uso del veicolo, quanto piuttosto al suo intero ciclo di vita.
In questa memoria viene illustrato il confronto tra l'impatto ambientale associato alla produzione, all'utilizzo e alla dismissione di un basamento motore in ghisa e di uno in lega di alluminio. L'approccio metodologico adottato per l'analisi è quello del Life Cycle Assessment (LCA). Lo studio dimostra che, mentre nella fase di produzione l'impatto ambientale del basamento motore realizzato in lega primaria di alluminio è superiore rispetto a quello di un basamento in ghisa, nelle fasi di utilizzo e di dismissione la scelta delle leghe di alluminio risulta maggiormente conveniente in termini di eco-compatibilità. Nel complesso, l'analisi del ciclo di vita di un blocco motore in lega primaria di alluminio evidenza significativi vantaggi ambientali rispetto all'utilizzo della ghisa, vantaggi che aumentano qualora si consideri la possibilità di impiegare leghe di tipo secondario.

KEYWORDS

Life Cycle Assessment, LCA, Cylinder block, Aluminium, Cast Iron, Automotive, Environment, Foundry, Casting.

INTRODUCTION

The strong pressure exerted by public opinion and regulations, more and more restrictive, enacted in environmental field in several Countries, lead the automotive industry to make important efforts to reduce the effects of its products on the environment; two important examples are the voluntary agreement CAFE negotiated in 1998 by automotive manufacturers with EU authorities to reduce the level of CO_2 emissions from 185 g/km to 163 g/km in 2003, to 140 g/km in 2008 and to 120 g/km in 2012, and the European Directive 2000/53/EC published in 2000 and defining new standards for the End-of-Life Vehicles (ELVs) treatment which can be applied not only to new vehicles, but also to the existing ones [1-2].

One of the key factors in which automotive manufacturers are investing more and more resources is vehicles light-weighting, which brings important environmental advantages in terms of fuel consumptions and emissions reductions during the use-phase of cars. However the environmental effects of light materials involve not only the use phase, but also production and end-of-life treatment, so that a correct evaluation of environmental advantages – in terms of fuel consumptions and emissions reductions - must be extended to the whole life cycle of the vehicle. Therefore, the objective of the present work is the environmental evaluation of the replacement of cast iron with aluminium in the production of cylinder blocks.

THE CASE STUDY

The block considered by the analysis is a "four cylinders in line" (cylinder capacity 1600 cc) for a "C Segment" vehicle having the typical specifications listed in Table 1.

The choice of maintaining the same functional unit both for cast iron and aluminium cylinder blocks is a consequence of the need to minimize the number of variables to obtain homogeneous and so comparable results. Under this conditions, the only elements of differentiation between the two alternatives are the material (which is the relevant variable for the analysis) and the manufacturing process (which is a consequence of the material choice).

As regards the cast iron cylinder block, the material used is a grey iron, particularly suitable for this application because of its excellent workability and its good level of thermal conductivity and wear resistance. The foundry process adopted is sand casting, the only available one for the realization of very complex castings, such as cylinder blocks. For the aluminium cylinder block, the material used is a primary aluminium alloy with 9% silicon and 3% copper, while for the liners a grey iron is used to compensate the low wear resistance of the aluminium alloy. The manufacturing process chosen for this second cylinder block is high pressure die casting, which is the most suitable process for very complex and high volume aluminium castings and therefore the most representative process for aluminium foundry in automotive industry.

TABLE 1: SPECIFICATIONS OF THE VEHICLE ON WHICH THE BLOCK IS ASSEMBLED

Segment C Vehicle		
Mass	1250 kg	
Power	75 kW	6000 rpm
Torque	145 Nm	4000 rpm

METHODOLOGY AND SOFTWARE TOOLS

In order to achieve a holistic view, the Life Cycle Assessment (LCA) approach was applied, since it enables to consider the *complete* life cycle of the cylinder blocks consisting of the production, use and end-of-life treatment. In the course of the study, material and energy flows for all relevant processes were collected systematically and were interpreted to finally express the environmental load of a car (or of a single part) through a unique indicator, allowing the comparison between several alternatives [3-6]. The study was developed according to the ISO 14040 series standards on LCA, and consists of four steps:

1. *Goal and scope definition*: from a planning point of view, this is the most important step, since the functional unit, system boundaries, Data Quality Indicators (DQI) and the main assumptions are defined.
2. *Life Cycle Inventory Analysis (LCI)*: in the Inventory phase a model is made of the complex technical system that is used to produce, transport, use and dispose of the cylinder block. This results in a flow sheet with all the relevant processes; for each process all the relevant inputs and outputs are collected. The result is a very long list of inputs and outputs that is often difficult to interpret.
3. *Life Cycle Impact Assessment (LCIA)*: LCIA is defined as the phase in LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system; it is characterized by the shift from the objective information of the LCI phase to an environmental damage judgement through the application of a Impact Assessment Method, according to which classification, characterization, normalization and weighting are made. For the cylinder block analysis the Eco-Indicator 99 method was chosen since it allows the representation of the environmental damage through a unique value, making the comparison between the two alternatives and sensitivity analysis easier. It is based on a damage-oriented approach and leads to the evaluation of environmental impacts as the sum of the

contributions associated to Human Health (HH), Ecosystem Quality (EQ) and Resources (R). The possibility of obtaining a unique indicator is given by the normalization phase, whose aim is making the damages estimated during the characterization phase homogeneous; in the normalization phase, those damages are divided by reference values (that are the total damage produced during a year in the geographical area considered in the analysis), thus obtaining a-dimensional values measured in Pt (Points). Only at this point all the contributions relating to different Impact Categories can be added to obtain the final Eco-Indicator.

4. *Life Cycle Interpretation*: this is the final part of a LCA study, whose aim is on one hand the recognition of the most critical processes from an environmental point of view and on the other hand the proposal of actions that should be undertaken in order to reduce the environmental load of the cylinder block

Since the environmental evaluation of a product is characterized by a very large number of calculations during LCI and LCIA phases and by the need of environmental data which are often difficult to collect, a LCA study is usually supported by a so-called "LCA software tool"; for the cylinder block analysis *SimaPro 6.0* was chosen since on one hand there is a huge amount of data stored in its databases all over the world and on the other hand it automatically aggregates the LCI results according to one of its multiple Impact Assessment Methods in order to obtain an environmental damage indicator [7].

MAIN RESULTS OF THE ANALYSIS

The graph in Fig. 1 summarizes the main results obtained through the analysis in SimaPro 6.0.

The first column refers to the cast iron cylinder block production; it shows that the Eco-Indicator value for this phase is 6,23 Pt, 80% related to Fossil Fuels Impact Category. As we can see in Fig. 2, the damage is mainly due to electricity consumption (2,81 Pt) for the running of the furnace, of the core and sand production lines and to coke, natural gas and carbon black consumption (1,54 Pt) for the running of the cupola furnace. A relevant contribution is given also by fuel consumption during the transport from foundry to engine plant and from engine plant to vehicle assembly plant (0,76 Pt) and by phenolic resins used for the cores production (0,29 Pt). In figure 3 only the processes that give the main contributions are visualized; all other processes, whose contributions are quite irrelevant, have been omitted.

As regards the aluminium cylinder block production, the Eco-Indicator value rises to 19 Pt, showing a bigger environmental load. In this case, the Impact Categories mainly affected are Fossil Fuels and Minerals about Resources and Carcinogens and Respiratory Inorganics about Human Health. As far as the damage source, we can see in Fig. 3 that the main responsible is primary aluminium production (22,77 Pt) which is characterized by an high utilization of bauxite mines, an high amount of electricity in Hall-Heroult process, the need of disposing the red mud separated in Bayer process

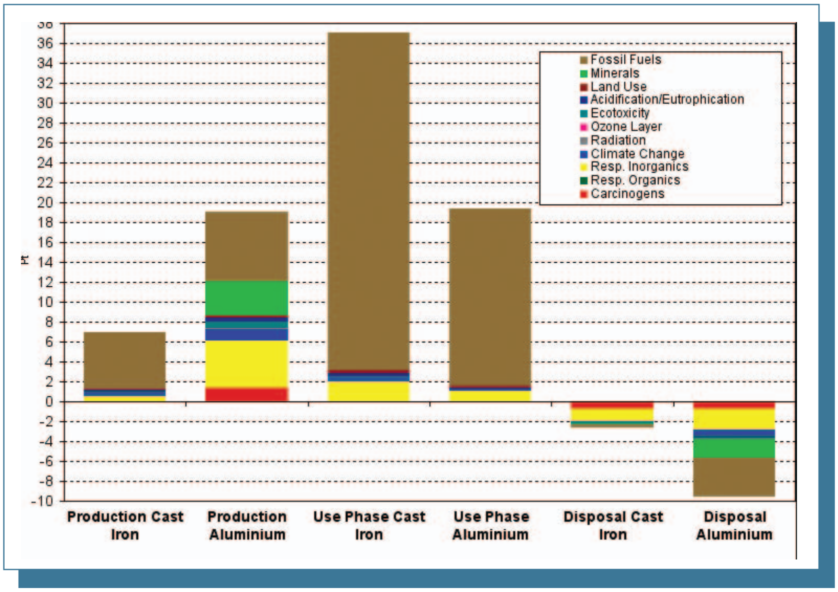

Fig. 1: Comparison between the values of the Eco-Indicator related to the two cylinder blocks (the life cycle is subdivided in production, use and disposal phases).

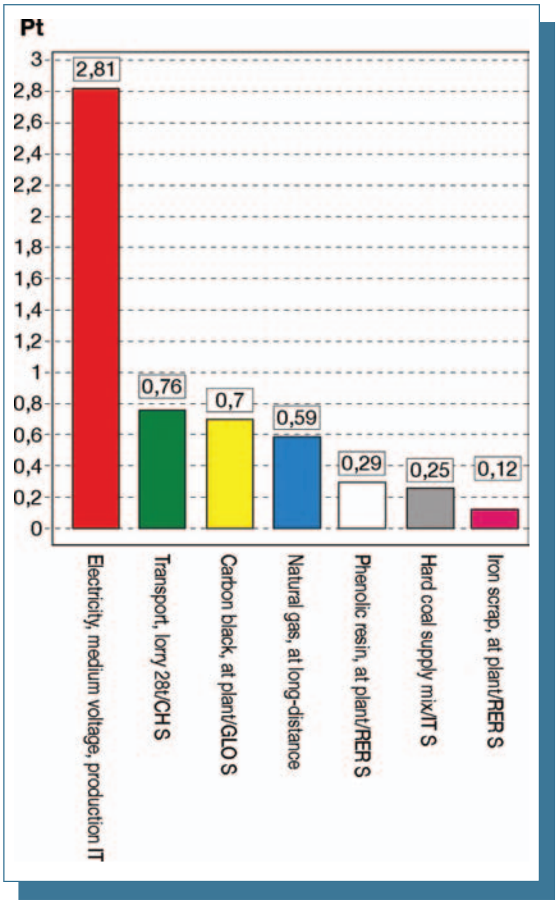

Fig. 2: Eco-Indicator values related to the production processes of the cast iron cylinder block.

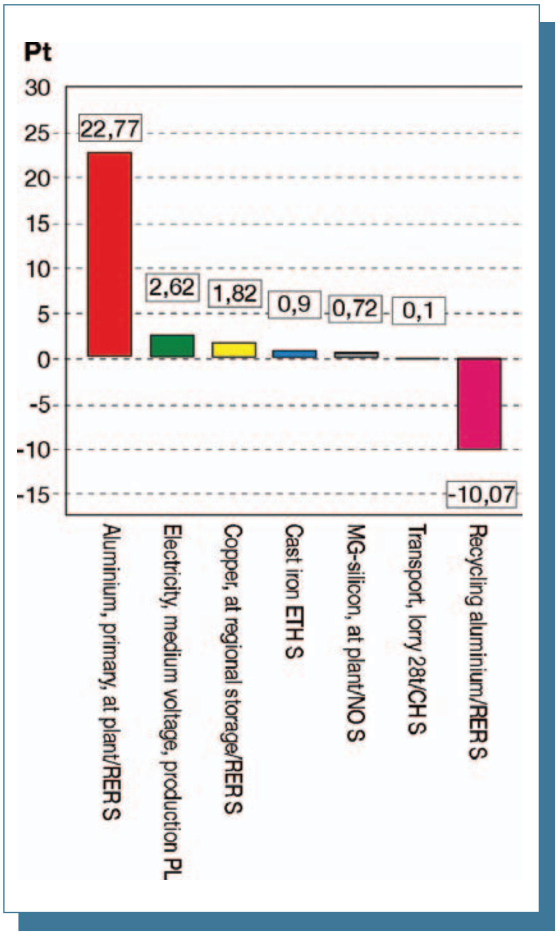

Fig. 3: Eco-Indicator values related to the processes involved in the production of the aluminium cylinder block.

and the emissions of fluorides. For all these reasons it is very important to recycle the aluminium solidified inside the runners: in fact, recycling aluminium avoid primary aluminium production and this is the reason for which “recycling” in Fig. 3 gives a negative contribution (-10,07 Pt) to the Eco-Indicator, reducing the damage caused by primary aluminium production. As for figure 3, all the processes that give an irrelevant contribution to the total damage have been omitted.

Examining the use-phase, the situation changes completely since the Eco-Indicator related to the cast iron solution is higher than the value related to the aluminium block (respectively 37 Pt and 19,3 Pt). In this case, 90% of the Indicator value is determined by Fossil Fuel Impact Category connected to fuel consumption, followed by Respiratory Inorganics connected to emissions. The reason of a so high difference between cast iron and aluminium cylinder block is the lower weight of the second solution (16,4 kg for aluminium block and 31 kg for cast iron block), which allows an important reduction in terms of fuel consumption and emissions, considering 150000 km as total life for a vehicle.

As regards the disposal of the two cylinder blocks, it gives in both cases a negative contribution since it was assumed that both blocks are recycled at the end of their life cycle; as the environmental advantage connected to the recycling of a metal is proportional to the environmental load due to the primary metal production, the disposal phase even more benefits the aluminium solution; in fact, the contribution related to aluminium (- 9,47 Pt) is more negative than one related to cast iron block (- 2,55 Pt).

Adding up the contributions reled to each phase, we obtain a value of 41,3 Pt for the cast iron cylinder block and of 28,9 Pt for the aluminium solution; these values demonstrate the concrete environmental advantage of the shift to aluminium in the automotive industry, since any bigger environmental load during the aluminium block production phase is then balanced during the use and the disposal phases.

THE EFFECT OF KILOMETRES COVERED

Since at the end of the production phase the Eco-Indicator value related to the aluminium block is higher than the cast iron one, while at the end of the life cycle it is lower, a sensitivity analysis based on the kilometres covered was carried out to find the break-even point between the two alternatives (Fig. 4).

The analysis demonstrates that there is a linear correlation between the Eco-Indicator and the life of the vehicle, expressed as kilometres covered; from an environmental point of view, the two cylinder blocks are equal in correspondence of 43965 km covered, that is less than one third of the total life of the vehicle.

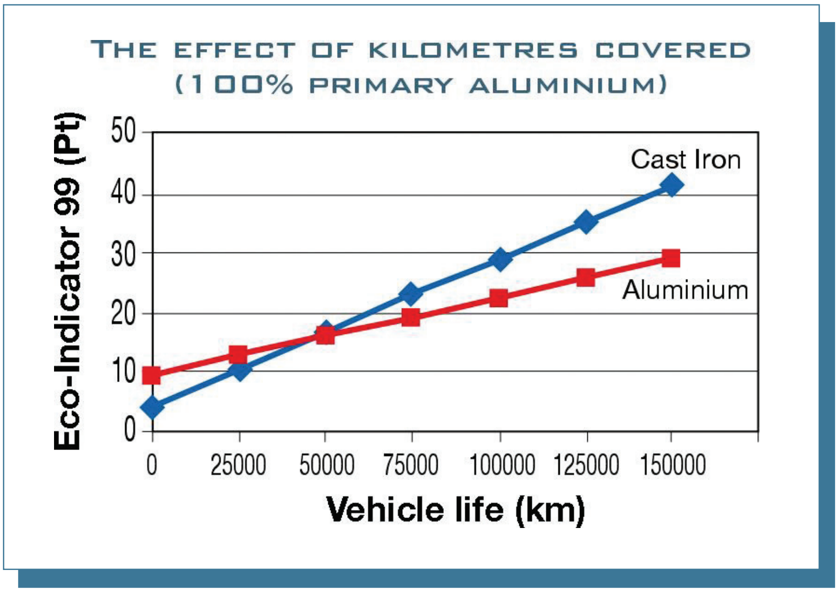

Fig. 4: Break-even point between the two solutions, expressed as kilometres covered.

THE EFFECT OF SECONDARY ALUMINIUM

The previous analysis was carried out considering a percentage of 100% of primary aluminium alloy as raw material for the block; however, as the primary aluminium production causes an high environmental load, a second sensitivity analysis based on the secondary aluminium percentage was carried out.

The percentages of secondary aluminium considered are 0%, 25%, 50%, 75% and 100%. The analysis involves only the production phase, since use and disposal are not influenced by this parameter. The Eco-Indicator values are summarized in Table 2.

Table 2 shows that the Eco-Indicator value decreases in correspondence of an increase in the percentage of secondary aluminium until it gets the negative score of –2,4 Pt in case of 100% of secondary alloy.

The environmental advantages of aluminium recycling are several:

- Electricity consumption reduction with regard to primary aluminium production (the electricity needed to produce 1 kg of secondary aluminium is about 5-7% of the electricity needed to produce an equal amount of primary aluminium).
- Lower utilization of non-renewable natural resources.
- Lower quantity of refuses released on the environment and consequent reduction of the damage related to the disposal.
- Reduction of bauxite mining and of socio-economical impacts related to the utilization of natural resources.

For all these reasons, the use of secondary aluminium, when purity requirements allow it, is better than the use of primary alloys at least from an environmental point of view.

Subsequently, the values just found were compared to the one related to the cast iron cylinder block to establish which is the percentage of secondary aluminium in correspondence of which the two solutions are equal from an environmental point of view. The results of the comparison are summarized in Fig. 5.

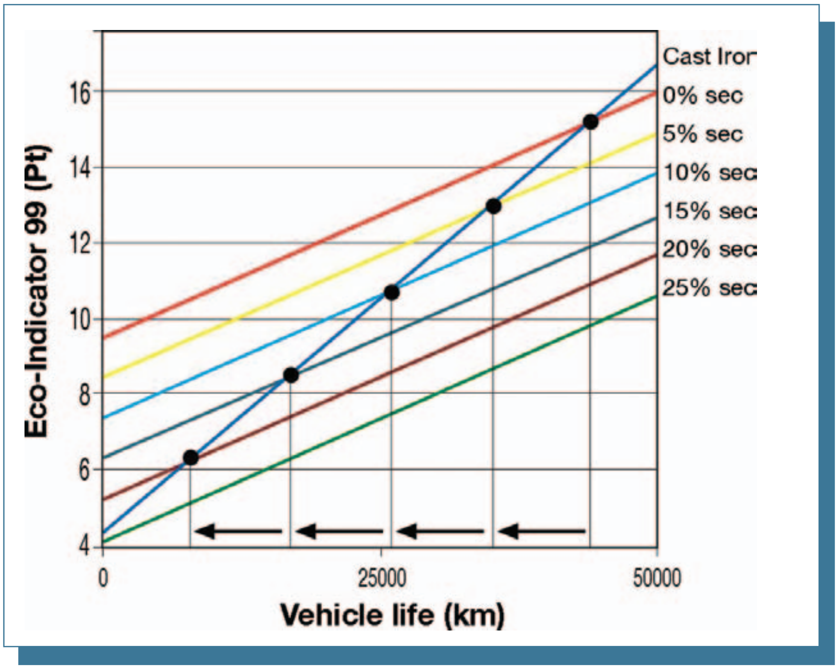

Fig. 6: Relation between the break-even point (expressed as kilometres covered) and the percentage of secondary aluminium.

TABLE 2: : ECO-INDICATOR VALUES RELATED TO THE PRODUCTION PHASE OF THE ALUMINIUM BLOCK, CALCULATED IN CORRESPONDENCE OF SEVERAL PERCENTAGES OF SECONDARY ALUMINIUM USED

Secondary aluminium	**Eco-Indicator**
(%)	(Pt)
0	19
25	13,7
50	8,32
75	2,96
100	- 2,4

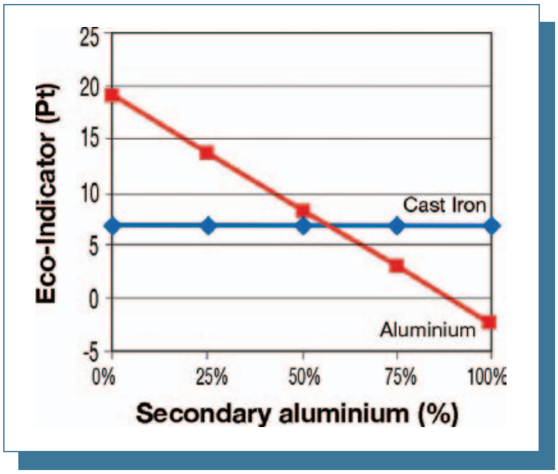

Fig. 5: Relation between the Eco-Indicator and the percentage of secondary aluminium (only the production phase has been considered).

Obviously, the Eco-Indicator related to the cast iron cylinder block isn't influenced by the percentage of secondary aluminium alloy and so it presents a constant score of 6,23 Pt; as regards the aluminium block, its trend is represented by a straight line with a negative gradient which crosses the value 6,23 Pt in correspondence of a percentage of 57% of secondary aluminium as raw material for the cylinder block. Thus, for percentages higher than 57%, secondary aluminium is more competitive, at least from an environmental point of view, than cast iron already at the end of the production phase.

A last consideration should be done taking again into account the whole life cycle of the cylinder blocks to understand how the point of equality between the two solutions, expressed as kilometres covered, changes in correspondence of a change in the percentage of secondary aluminium alloy. The results of this analysis are summarized in Fig. 6. The graph shows that in

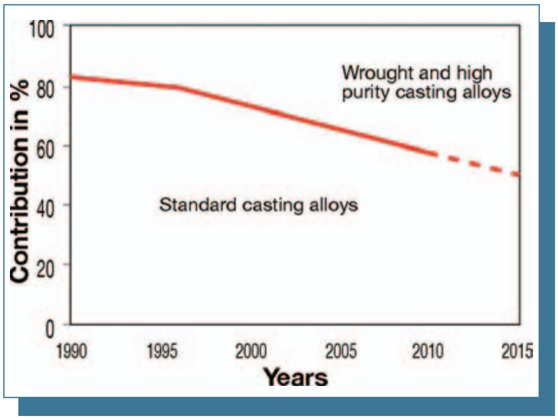

Fig. 7: Trend of standard and high purity aluminium alloys use in the automotive industry (EAA).

correspondence of an increase in the percentage of secondary aluminium alloy, the point of equality shifts towards left, anticipating the environmental gain of aluminium towards cast iron. It is particularly interesting to notice that for percentages of secondary aluminium higher than 25% the environmental gain of the aluminium solution is even unrelated from the use phase: in fact even if we set to zero the amount of kilometres covered, the Eco-Indicator related to the aluminium block is lower than the one related to the cast iron block. Besides, while in Fig. 5 only the production phase was considered, Fig. 6 involves also the use and the disposal phases, and just this last phase is responsible of the further environmental gain of the aluminium solution; in fact the percentage of secondary alloy which makes aluminium more competitive, from an environmental point of view, than cast iron decreases from 56%, obtained considering only the production phase, to 25% related to the whole life cycle.

Actually the percentage of secondary aluminium used in the automotive industry goes beyond 50% and so the environmental advantages of aluminium towards cast iron are perceived, on average, at the end of the production phase. However, in the last years, the attempts to extend the use of aluminium alloys also to components historically realized with traditional materials made the purity requirements of the alloys more and more restrictive, determining the use of primary alloys (Fig. 7). Anyway this reversal of trend doesn't necessarily entail a reduction in the secondary aluminium market: in fact, because of the bigger production volume, it is characterized by a constant growth.

CONCLUSIONS

The work carried out pointed out that, considering the whole life cycle of the cylinder block, the aluminium solution is less injurious, from an environmental point of view, than the cast iron one. In particular, the environmental advantage comes from the lower weight of the cylinder block due to the use of an aluminium alloy which allows a reduction both in fuel consumption and in CO2 emission during the use phase. Therefore, although during the production phase the indicator of the environmental damage related to the aluminium block is higher than the one related to the cast iron block, the so high gap between the two Eco-Indicators related to the use phase establishes the concrete environmental gain of the shift to aluminium in the automotive industry. However the environmental advantage of this material doesn't dry up with the use phase: in fact the environmental credits deriving from the disposal scenario of the aluminium cylinder block are clearly higher than the ones related to the cast iron block. This situation can be explained considering that every kilogram of secondary metal avoids the production of one kilogram of primary metal and that the environmental load deriving from the production of primary aluminium is clearly higher than the load related to the production of cast iron. Further, this case study underlines that the environmental gain related to a kilogram of aluminium is so high that it balances the fact that firstly the amount of kilograms of aluminium alloy sent to recycling is more or less half than the amount of kilograms of cast iron and secondly the loss of material during the phases of separation and remelting is bigger for aluminium since recycling technologies can be further improved.

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