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Sustainable Optimisation of a Carousel for Foundry Processes

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Abstract

Foundry technology includes a family of processes that traditionally consume high amounts of energy. It is fundamental to apply the principles of Sustainable Manufacturing to increase the energy efficiency of these processes. This paper describes the research activity carried out to improve the efficiency of a carousel, which allows the automatisation of aluminium gravity die casting process, consisting of different phases: die preparation, filling with molten aluminium alloy, solidification time, die opening, and part extraction. It is demonstrated that the efficiency is a function of the disposition of the dies mounted on the carousel, due to the solidification time (which is the limiting process parameter), and different cycle times depending on the realised product. The authors propose an optimised layout, which reduces the cycle time while maintaining the same level of the casting final quality. This reduction in the cycle time significantly improves the sustainability of the foundry process.

Keywords: Aluminium Alloy; Gravity Die Casting; Sustainable Manufacturing; Reduce

1. Introduction

Foundry technology consists of a number of similar processes whose common characteristic is the use of a mould to be filled with metallic alloys, which are typically molten but can also be used in a semi-solid state. Despite the technology being well known and used since ancient times, new processes have been recently introduced, most notably *liquid forging*, where the liquid metals solidify under pressure inside a die, a novel procedure which can be classified as a hybrid process between casting and forging [1] [2]. Less recently, a family of processes named *thixocasting* and *rheocasting* gained larger markets. They utilize high pressure, cold chamber die casting machines and re-usable hardened steel dies where the semi-solid slurry is injected into [3].
Process and product innovations are fundamental for the competitiveness of manufacturing enterprises. Nowadays, the concept of innovation is strictly connected to sustainability: any change in an industrial product or in a fabrication process must increase their sustainability to be considered an effective improvement.
In these days, two main issues are guiding innovation in the foundry industry: Sustainability and Industry 4.0. Sustainability has three dimensions, which have been introduced through the concept of the Triple Bottom Line [4]. In the

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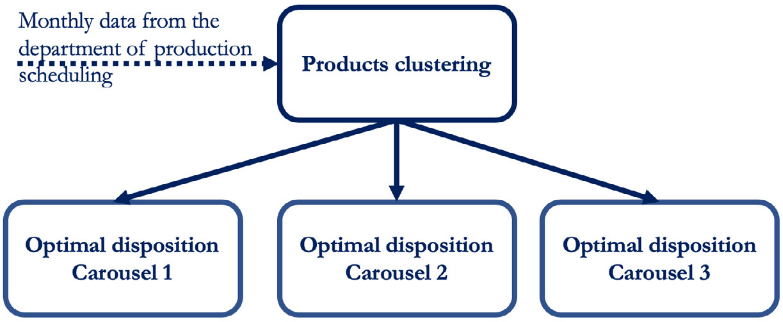

Fig. 1. A Carousel for Gravity Casting (Courtesy FATA Aluminum).

industry realm, the 6Rs framework is universally considered the basis of sustainability in manufacturing. It consists of 6 ways to make industrial production more sustainable: Reuse, Reduce, Recycle, Recover, Redesign, Re-manufacture. In particular, we refer here to the second R: ”Reduction” [5].

A large number of papers concerning sustainability for foundry is focused on energy saving and environmental impact decrease, in terms of increased efficiency and emissions reduction, respectively. In fact, foundry technology includes a family of processes that traditionally consumes high amounts of energy. The reduction of the energy consumption is therefore an important target that must be achieved to make this process more sustainable. Emission reduction can contribute to a real improvement of the work environment and to a decrease of expenses to control pollution effects.

This paper is the initial result of a larger investigation of the industrial case of a small-medium-sized foundry enterprise. In this company a large number of products are realised by the aluminium gravity casting process, even if the enterprise dimension requires easy-to-use tools allowing the scheduling activity to achieve a flexible production. The research activity aimed at improving the efficiency of the production system, which is composed of numerous rotary production machines or carousels. It allows the automation of the process, consisting of different phases: die preparation, filling with molten aluminium alloy, solidification time, die opening, and part extraction. It is demonstrated that the efficiency is a function of the disposition of the dies mounted on the carousel, due to the solidification time (that is the limiting process parameter), and to the longer cycle time. A compromise solution is necessary, due to different cycle times of castings. The authors propose an algorithmic approach to optimise layouts depending on the product mix reducing the cycle time and the related energy consumption per each product. The optimisation takes into account the need for maintaining the same level of the casting final quality. This reduction in cycle time and in energy consumption significantly improves the sustainability of the foundry process.

The presented method is the first step towards a flexible and easy-to-use system that allows clustering the casting products, depending on the cycle time, on the scheduling, and determining the optimal disposition of the dies mounted on a number of carousels (Fig. 1) with the aim of reducing the overall cycle time.

2. Sustainability for the foundry processes

Manufacturing enterprises are responsible for energy saving and efficiency, but it is generally necessary to find trade-off solutions between an optimisation in terms of energy consumption and the achievement of the highest production rate.

A recent work identifies a number of barriers to increase the industrial energy efficiency in the case of European foundries [6]. The authors underline that ”[...] the perception of the lack of resources to be devoted to improving energy efficiency, and the existence of other priorities such as the importance of guaranteeing business continuity [...]” are relevant aspects to be taken into account. Through interviews with technicians, numerous perceived barriers are listed and quantified by their relevance. The more critical issues are the lack of budget funding, possible poor performance of equipment, other priorities for capital investments. Less relevant obstacles are lack of influence of energy managers, shortage of time and other priorities.

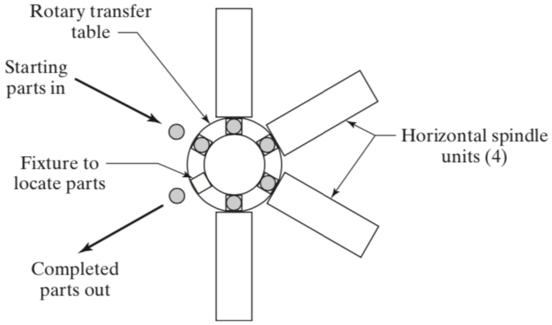

Fig. 2. Scheme of a Rotary Transfer Machine [**?**]

In [7], tools from the lean manufacturing methodology are applied to save energy. A variety of possible direct or indirect techniques are introduced, such as preheating stages by exhaust gases of the ingot and a better control of the metallurgical quality of the molten metal. An accurate evaluation of the casting performance through the application of the so-called ”Ten Rules” ([8]) to achieve a reduced casting yield is recommended. An innovative process based on CRIMSON (Constrained Rapid Induction Melting Single Shot Up-Casting) is considered a valid alternative to more traditional melting routes to reduce energy consumption. In this process, only the right amount of alloy is melt in a closed crucible of an induction furnace and the mould is filled by the counter-gravity filling method. The procedure consists of a rapid melting, minimising the holding time, and a quick bottom filling [7] [9]. In [10], the CRIMSON process is deeply investigated by means of a number of methods: simulations through Computational Fluid Dynamics (CFDs), Life Cycle Assessment (LCA) to estimate the environmental impact, Discrete Event Simulations (DESs) to estimate productivity and, finally, a cost model to achieve a holistic comparison to conventional sand casting. It is demonstrated that the CRIMSON process simultaneously satisfies the need for energy savings and assures a higher productivity at a lower cost.
In [11] the need for a new set of measurements for the evaluations of foundry performances, which include and enrich the traditional energy efficiency metrics, is identified.
This paper deals with the optimal disposal of dies in the case of a carousel applied to aluminium gravity die casting process. It can be demonstrated that the cycle time is dependent on the disposal and the sequence of the dies. The optimal choice leads to a relevant increase of the production rate.
Foundry carousels used for the experimental observations of this work can carry six different dies simultaneously.

3. Transfer Lines and Rotary Transfer Lines

Automated Production Lines are production systems commonly investigated. Transfer Lines (TL) or Rotary Transfer Lines (RTL) are today the most advanced ones, characterised by a higher production rate to achieve mass production. A typical Rotary Transfer Lines (RTL) is shown in Fig. 2 [**?**].

Balancing algorithms to achieve the highest efficiency and algorithms for model launching in mixed-model lines are available for these systems.
Carousels for foundry can be considered RTL but the realised process is not a machining one. In the case of the aluminium gravity die casting process, several dies are mounted on the rotary machine and the process is typically completed in a number of stations that is larger than the number of process stages.
In the next section, a six position carousel is analysed.

4. Carousels for foundry processes

Carousels for aluminium gravity die casting are production machines that are characterised by a rotary indexed table divided in sectors or stations. Each station is occupied by a die and is dedicated to realise an operation or a

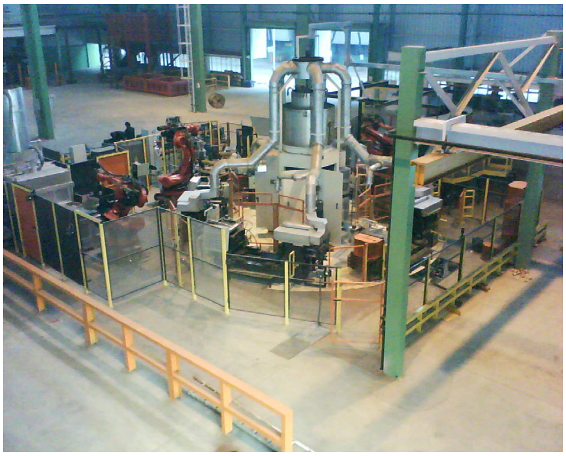

Fig. 3. A Carousel for Gravity Casting (Courtesy FATA Aluminum).

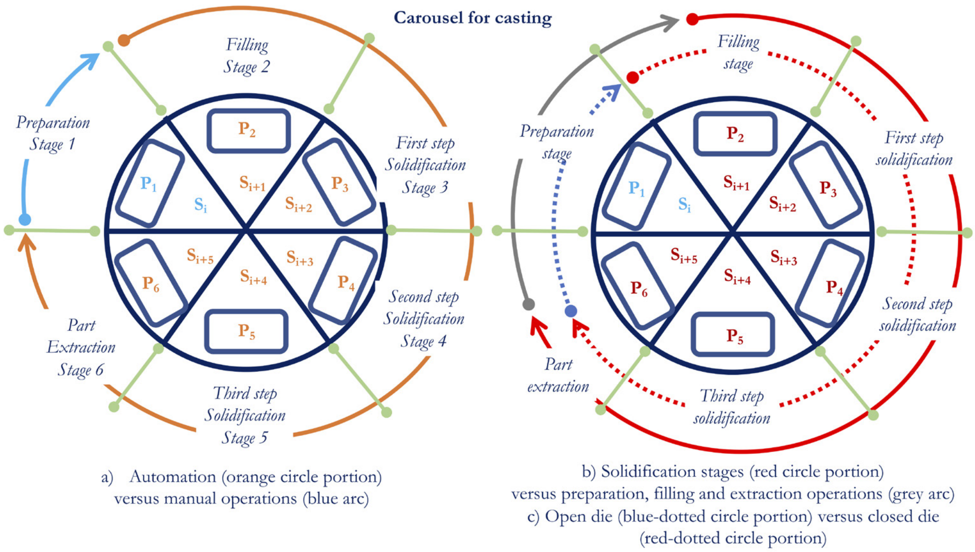

Fig. 4. Scheme of a carousel for casting

number of collected elementary operations. Certain stations are automatised, while some critical operations had better be manually done. For example, the handling of the sand cores is hazardous due to the brittleness of these fragile parts, so it is convenient to manage them manually. In the examined case, cores are manufactured through the shell moulding technology that uses resin covered sand and, even if they can be automatically assembled to the mould, manual assembly is generally preferred to avoid the introduction of complex control system, which can guarantee the right handling of these fragile components.

In Fig. 3 a carousel is shown. The scheme of the examined rotary machine is sketched in the following Fig. 4. The dies are pointed out by a capital letter and they identify a product to be cast: P_i and i= 1, ..., 6. Six different castings can be realised simultaneously or, in the case the production rate is not sufficient to satisfy the demand, several identical dies can be mounted on the rotary table of the machine. This arrangement of positions has been empirically defined, based on a general assumption that considers a determined proportion between the solidification time and the sum of the other processing times and that depends on the typical weight.

In the following section, the common case of an arrangement consisting of six different dies is considered. In Fig. 4 the performed operation is also displayed for each station. The six operations are listed below:

- S_1, position of the station for preparation operations (stage #1)
- S_2, position of the filling station (stage #2, solidification can begin here)
- S_3, position of the first station for solidification (stage #3)
- S_4, position of the second station for solidification (stage #4)
- S_5, position of the third station for solidification (stage #5)
- S_6, position of the station for the part extraction (stage #6, solidification can be completed here)

The here described carousel presents a manual stage (S_1) consisting of several elementary operations that are manually realised. A worker prepares the die for the new cycle of filling with the molten aluminium alloy and for solidification. The following stations are automatised and assisted by robots that fill the cast with the molten metal and extract the casting from the die at the end of the production cycle. This initial operation includes cleaning and verifying the state of the die, assembling and arranging the cores inside the die, cleaning the die to avoid that sand particles can remain entrapped in the mould, assembling and arranging the filter inside the die and, finally, closing the die. After completing his tasks, the worker leaves the rotating machine to proceed with the next station. A Programmable Logic Controller (PLC) establishes if the rotation is possible, depending on the completion of the production cycle of the die corresponding to the extraction station. The control logics makes a verification based on the time between the filling and the extraction or it allows the rotation if the die in the S_6 position completed the solidification time and the extraction time. It is also necessary that the filling operation is completed in the S_2.

5. Optimisation of Dies disposition to reduce cycle time

In this section, a method to reduce the cycle time by sorting parts in the launching sequence is presented. The aim is to find a ”pseudo-optimal” solution through a very small number of iterations, avoiding scanning the whole space of possible permutations. The technique is articulated in two different steps, i.e. initial ordering and resorting of products.
The case of six different products to be manufactured in a carousel with six stations is investigated; the hypothesis is that each station of the carousel is always occupied by a product (i.e. the launching sequence consists of six positions without repetitions).

5.1. Determination of the time steps

The sequence of the N products P_i in the carousel can be represented by means of an array Q (Eq. 1):

$$Q = [P_1, P_2, ..., P_i, ..., P_n] \tag{1}$$

Each product is characterised by an array of times (T_i, Eq. 2) containing the minimum time required for the preparation of the mould ($T_{p,i}$), the minimum time required for casting ($T_{c,i}$), the time required for solidification ($T_{s,i}$) and the time required for the extraction of the product ($T_{e,i}$).

$$T_i = [T_{p,i}, T_{c,i}, T_{s,i}, T_{e,i}] \tag{2}$$

As above mentioned, the number N of products is assumed to be equal to the number of stations (in the following N=6). The carousel will rotate after a time step T_R that depends on its current position. In fact, if the product P_i is in the preparation stage, it is necessary to guarantee that the preparation of the product P_i is completed before rotating the carousel. At the same time, it is also needed to ensure a sufficient time for the extraction of the product P_{i+1} and the casting of the product P_{i-1}. We can thus define a minimum time step for the rotation $T^*{}_{R,i}$ (Eq. 3):

$$T^*{}_{R,i} = \max(T_{p,i}, T_{c,i-1}, T_{e,i+1}) \tag{3}$$

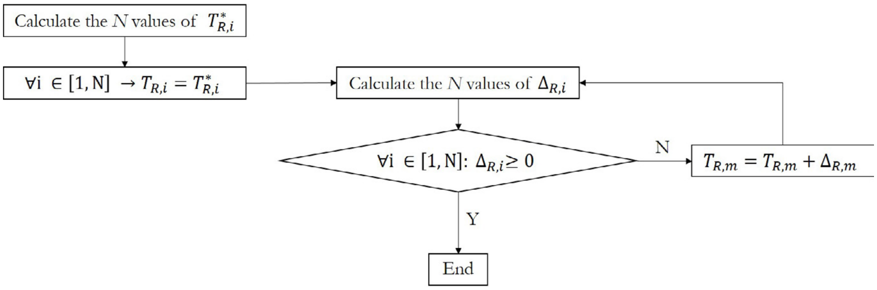

Fig. 5. Flow chart of the time step determination procedure

Due to the periodicity of the problem, i-1 is equal to N in case i=1; i+1 is equal to 1 in case i=N.
The rotation time $T_{R,i}$ must guarantee that the product P_{i+1} completed the solidification and reached the adequate temperature for extraction by avoiding possible part distortions. This condition can be written as in Eq. 4.

$$\Delta_{R,i} = T_{R,i} - \sum_{k=1}^{N} T_{R,k} - T_{R,i+1} - (T_{c,i+1} + T_{e,i+1}) \geq 0 \tag{4}$$

The calculation of the generic time step $T_{R,i}$ depends in turn by each time step of all the other phases of the cycle (Eq. 4). Therefore, a recursive calculation has to be adopted to establish the actual minimum time of each step.
First, the values $T^*{}_{R,i}$ are calculated as in Eq. 3 and their values are assigned to the time steps $T_{R,i}$. Then, the differences $\Delta_{R,i}$ between time steps and minimum solidification times are calculated by Eq. 4.
If all the N values of $\Delta_{R,i}$ are major or equal to zero, the solution can be accepted.
In the case that one or more $\Delta_{R,i}$ are minor than zero, the maximum negative value $\Delta_{R,m}$ is selected and its absolute vale is summed to the corresponding $T_{R,m}$. The procedure is repeated until all the $\Delta_{R,i}$ are major or equal to zero. Fig. 5 provides a flowchart of the described procedure.

5.2. *Calculation of the initial sequence*

To determinate the initial sequence, we first build a matrix M_{Te} where the generic element is defined as in Eq.

$$M_{Te}[i, j] = (T_{p,i} - T_{e,j}) + (T_{p,i} - T_{e,j}) \tag{5}$$

The values of M_{Te} on the principal diagonal (i.e. for i=j) are omitted. The cell $M_{Te}[i, j]$ gives an information of the effects arising in the launched product $T_{p,j}$ after $T_{p,i}$ at the time steps $T_{R,i}$ and $T_{R,i+1}$. A positive value of the cell indicates that the preparation time is predominant on the extraction and casting times, thus giving to the product the time to solidify in stations B and F (cf. Fig. 4). On the other hand, if the value of $M_{Te}[i, j]$ is less than zero, the product will wait in the station A for the extraction/ filling stage to be completed; this situation is undesirable, as the part doesn't have the opportunity to solidify in the preparation stage. At the same time, in order to reduce the whole cycle time, the waiting times of each phase should be limited.
Basing on previous considerations, the algorithm starts by selecting the minimum non null value of the matrix M_{Te} (excluding the principal diagonal), indicated in the following as $M_{Te}[i^*, j^*]$. Products P_{i^*} and P_{j^*} are assigned to the first and second position, respectively, of the launching sequence. Then, the raw j^* of M_{Te} is scanned to find the minimum non-negative value of unassigned columns; if no value is found, the maximum among negative values is selected. The index of the selected column is added at the end of the launching sequence and substituted to j^*. The procedure is repeated until all the positions in the launching sequence have been assigned.
Fig. 6 shows an example of the determination of the initial sequence.

5.3. *Reordering of the sequence*

Once the initial sequence has been defined, as described in 5.2, the corresponding time steps can be calculated according to 5.1. Based on the iterative calculation described in 5.1 and Fig. 5, the time steps are corrected using

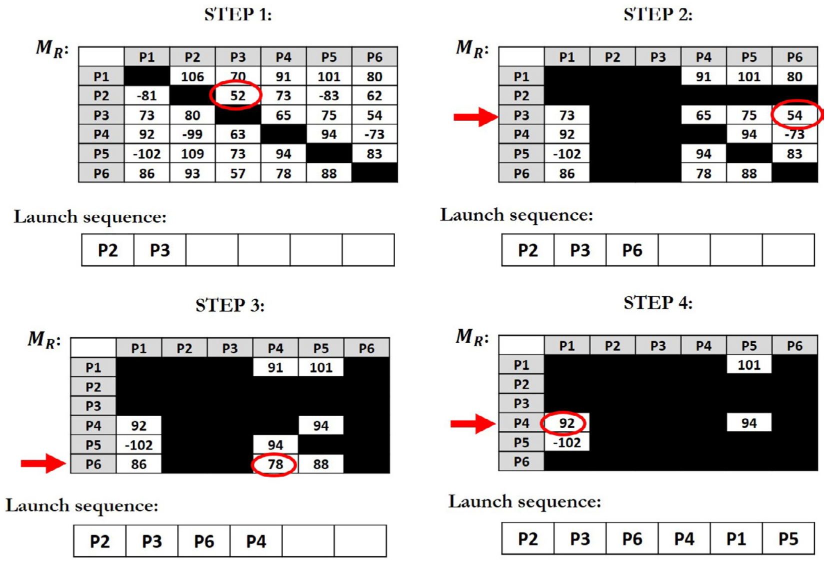

Fig. 6. Example of initial sequence determination

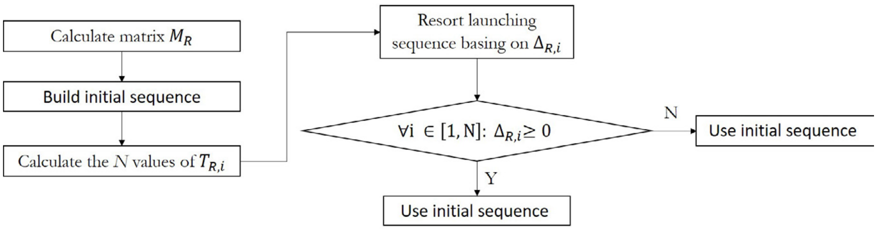

Fig. 7. Flow chart of the whole procedure

the minimum value of Δ_R calculated at each iteration; the extra time summed to the step $T_{R,i}$ contributes to the solidification time of all the parts, except the one that is in the preparation stage.
To achieve a more gradual increment of time, the sequence deriving from the initial ordering can be rearranged on the basis of calculated values of $\Delta_{R,i}$. More precisely, if P_i is the product in the preparation stage at the time step $T_{R,i}$, a benefit on the whole production time may be obtained reordering parts for descending values of $\Delta_{R,i}$. In case reordering reduces the time of the whole cycle, it is used as final solution, otherwise the initial order is maintained.
The number of operations in the proposed method is thus fixed and can be summarised as in Fig. 7

6. Application of the algorithm

In order to observe the benefits achievable by means of the presented technique, the performance of the obtained sequence is compared with the minimum achievable time calculated through brute force. In particular, the case of six products on six different stations is analysed, so that a total number of $\frac{N!}{N} = 120$ permutations have to be compared. The values of time arrays T_i have been randomly generated within a predetermined range for T_p, T_c, T_s and T_e. Five different sets of ranges have been considered; for each set, 1000 cases have been evaluated. Tab. 6 summarises the results.

The results present significant variations according to the selected ranges for T_i generation, which, in turn, affect the duration of the entire cycle.

Table 1. Results of algorithm application [sec]

$[T_{p,min}, T_{p,max}]$	$[T_{c,min}, T_{c,max}]$	$[T_{s,min}, T_{s,max}]$	$[T_{e,min}, T_{e,max}]$	Err_{av}	Err_{stdev}
[30, 90]	[6, 20]	[180, 300]	[15, 45]	1.87	5.48
[30, 60]	[15, 25]	[180, 240]	[40, 80]	5.56	6.74
[20, 100]	[10, 30]	[180, 300]	[20, 60]	3.37	7.80
[45, 150]	[10, 40]	[100, 400]	[30, 50]	0.12	2.77
[60, 180]	[20, 40]	[300, 600]	[45, 90]	2.60	10.05

7. Conclusion

Foundry is an energy-intensive technology, whose sustainability depends, in particular, on the energy consumed. This preliminary research work is focused on the optimisation of a carousel for foundry, in order to reduce the cycle time and, therefore, to decrease the energy consumption of the process. To optimise the carousel, a method consisting in sorting the parts in the launching sequence has been presented. Products are initially ordered, then resorted. This technique has been applied to carousels consisting of six stations and manufacturing six different products, whose cycle time has been compared with the one of non-optimized carousels. The efficiency of the optimised carousel is higher, because it is a function of the disposition of the dies mounted on it.
The proposed solution is more sustainable and does not influence the characteristics of the final product, because the reduction in cycle time does not affect the casting final quality. It is then recommendable to analyse and optimise the disposition of the moulds in carousels used in foundry enterprises, in order to decrease production time and to save energy. Further research is sought to verify the optimisation algorithm here proposed, applying it to foundry carousels with a different number of dies or stations.

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