Quality of casting and heat treatment processes – an information transfer approach

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Abstract

The present paper presents a stochastic analysis (based on the principle of probability transfer and Markov modelling) aimed to clarify one of the most usual discarding/scrapping causes in the case of an Al-HPDC (aluminium high pressure die casting) process: the material anisotropy. This anisotropy is especially reflected by the higher dispersion of the elongation compared to the yield strength.

When submitted to a heat treatment, a part shows acceptable values for the yield strength and not acceptable or only partial acceptable values for the elongation, the question to answer is if the heat treatment (HT) has been properly applied. The answer could be profane: if a specimen shows perfect values and 1 cm aside (under comparable geometrical conditions) the elongation is not acceptable although the yield strength is, then it has to be 'something else'. In the most cases this 'something else' are defects such as porosity, shrinkage, inclusions which have a greater influence on the elongation and are not caused by the HT. A very persuasive explanation of this influence is provided by [1] "… elongation to fracture is the most sensitive indicator for the presence of porosity or other defects in castings".

The present paper aims to provide an answer based on information transfer methods of analysis. Within the framework of this paper a comparative analysis between an information source with respectively without memory will also be presented.

The present analysis could be interpreted as a contribution to the implementation of the (still ambiguous) concept Industry 4.0 in the field of metallurgical processes, especially in the case of processes based on phase transformations such as casting and heat treatment.

Global process analysis

The HMM (Hidden Markov Model) can be used to analyse the probability state of such a production process. This introduction aims to emphasise the real importance of stochastic calculations based on information transfer for real industrial processes.

An Al-HPDC part is submitted to a tensile test in order to prove the process quality.

The production process has two states: (good, poor).

For example:

- good: at least five specimens are ok
- poor: at least two specimens are not ok.

Being in a good state the process remains so with probability 99%, the poor state is an absorbing state (see Table 1). The absorbing state could be easily reached if (for example) an alloy permanent contamination takes place during the casting process.

Table 1: Matrix of the transition probabilities

$$\begin{pmatrix} & \text{good} & \text{poor} \\ \text{good} & 0.99 & 0.01 \\ \text{poor} & 0 & 1 \end{pmatrix}$$

When in a good state, the product quality is acceptable with probability 100%, and when in a poor state, the probability of acceptable quality product is 0% (see Table 2).

Table 2: Matrix of the emissions probabilities

$$\begin{pmatrix} & \text{accepted} & \text{unaccepted} \\ \text{good} & 1 & 0 \\ \text{poor} & 0 & 1 \end{pmatrix}$$

In case the process starts in a good state with a probability of 100% (see Table 3), the probability of the next x produced parts being of acceptable quality is: see Table 4.

Table 3: Start probabilities (initializing vector)

$$\begin{pmatrix} \text{good} & \text{poor} \\ 1 & 0 \end{pmatrix}$$

Table 4: Probability of the next x produced parts being of acceptable quality

X (parts)	Probability
2	0.98
10	0.9
100	0.37
200	0.13
> 500	→ 0

Although the above depicted process shows extremely favourable premises, one can see that the stochastic analysis shows a very fragile response. In order to improve this result, one has to achieve the following desideratum (see Table 5):

Table 5: Optimum transition probabilities

$$\begin{pmatrix} & \text{good} & \text{poor} \\ \text{good} & 1 & 0 \\ \text{poor} & 0 & 1 \end{pmatrix}$$

This will lead to a perfect process without scrap or increase the level of the probability of acceptable quality product when in a poor state.

In detail analysis: The casting will be regarded as an information source

I) The cast part is considered to be an information source without memory.

Imagine a heat treated HPDC part submitted to a quality test. Seven specimens from the part are to be submitted to a tensile test. In order to confirm the test as positive at least five results are to be ok. A specimen is ok when two criteria are simultaneously fulfilled: yield strength ≥ 120 MPa and elongation ≥ 10%. As a consequence there are 4 possible informational states or messages (N = 4) with the corresponding probability pi = [0,1] with i = [1,4]

$$\sum_{i=1}^{N} p_i = 1$$

S1: A ≥ 10%, Rp ≥ 120 MPa
S2: A < 10%, Rp < 120 MPa
S3: A ≥ 10%, Rp < 120 MPa
S4: A < 10%, Rp ≥ 120 MPa

For the further analysis the above-mentioned numerical values will play only an indirect role; the probability (information) state is perceived merely as ok or not ok.

I) The part is considered to be an information source without memory

The ideal state of the (heat treated) part as information source is:

$$S_a = \left(\frac{S1}{p1} \; \frac{S2}{p2} \; \frac{S3}{p3} \; \frac{S4}{p4} \right)$$

$$S_a = \left(\frac{S1}{1} \; \frac{S2}{0} \; \frac{S3}{0} \; \frac{S4}{0} \right)$$

→

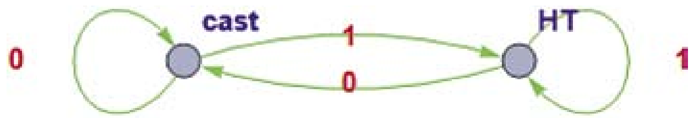

Fig. 1: Transition from 'cast' to 'HT' – ideal case

Fig. 2: Possible real process

- Average information per symbol
  - o $H_{(Sa)} = 0$ bit/symbol
    (because for p = 0 and p = 1 → H = 0)
- Maximum value of the information source entropy
  - o $Hmax_{(Sa)} = \log_2 N = 2$ bit/symbol
- Source efficiency
  - o $\eta_{(Sa)} = H_{(Sa)}/Hmax_{(Sa)} = 0$ %
- Source redundancy
  - o $R_{(Sa)} = Hmax_{(Sa)} - H_{(Sa)} = 2$ bit/symbol
- Relative redundancy
  - o $\rho_{(Sa)} = R_{(S)}/Hmax_{(Sa)} = 100\%$

The daily routine situation can be depicted through the following example:

$$S_b = \begin{pmatrix} S1 & S2 & S3 & S4 \\ p1 & p2 & p3 & p4 \end{pmatrix}$$

$$S_b = \begin{pmatrix} S1 & S2 & S3 & S4 \\ \frac{4}{7} & 0 & 0 & \frac{3}{7} \end{pmatrix}$$

- Average information per symbol
  - o $H_{(Sb)} = 0.985228$ bit/symbol
- Maximum value of the information source entropy
  - o $Hmax_{(Sb)} = \log_2 N = 2$ bit/symbol
- Source efficiency
  - o $\eta_{(Sb)} = H_{(Sb)}/Hmax_{(Sb)} = 0.492614$ %
- Source redundancy
  - o $R_{(Sb)} = Hmax_{(Sa)} - H_{(Sb)}$
    $= 1.01477$ bit/symbol
- Relative redundancy
  - o $\rho_{(Sb)} = R_{(S)}/ Hmax_{(Sb)} = 0.507386\%$

Upshot: the analysis of these two parts which were heat treated under identical conditions shows two very different informational states. This discrepancy cannot be attributed to the HT, but only to a prior operation. This is the main conclusion of the present paper.

II) The part is considered to be a binary information source with one pace memory

The Markov theory will be applied to analyse the information flow.

Fig. 1 represents an ideal process: each casting leaves the state 'cast' with a probability 1 for the state 'HT' which is an absorbing state.

Transition matrix

$$T = \begin{pmatrix} 0 & 1 \\ 0 & 1 \end{pmatrix}$$

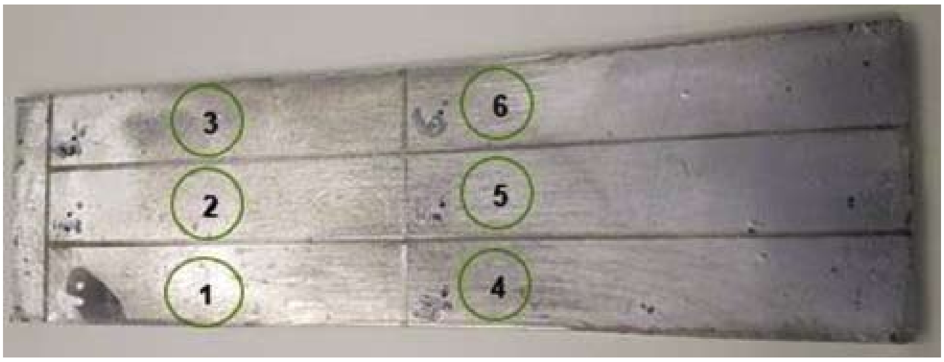

Fig. 3: HPDC plate

The stationary state will be calculated as follows:

$$\begin{cases} [p^*_{cast}\ p^*_{HT}]T = [p^*_{cast}\ p^*_{HT}] \\ p^*_{cast} + p^*_{HT} = 1 \end{cases} \rightarrow \text{stationary state} \begin{cases} p^*_{cast} = 0 \\ p^*_{HT} = 1 \end{cases}$$

This result shows that the ideal case is a stationary system.

The source entropy:

$$H_S = \sum_{i=0}^{1}\sum_{j=0}^{1} p(si)\cdot p\left(\frac{aj}{si}\right)\cdot \log_2 p\left(\frac{ai}{si}\right) = 0$$

i = {0,1} – two possible state of the source
j = {0,1} – each source can transmit two possible messages

Building a source without memory using the stationary state of the present system will lead to a zero level of entropy.

Transition matrix → entropy

$$\begin{pmatrix} S1 & S2 \\ 0 & 1 \end{pmatrix} \rightarrow H_S = 0$$

Fig. 2 represents a possible real process: if the quality of the casting is not acceptable it doesn't leave the state 'cast'; the part leaves the state 'cast' with a probability of 9/10 for the state HT which is not an absorbing state, the scrap will leave (via remeltig) the state HT for the state 'cast' with a probability of 2/10.

Transition matrix

$$T = \begin{pmatrix} \frac{1}{10} & \frac{9}{10} \\ \frac{2}{10} & \frac{8}{10} \end{pmatrix}$$

The stationary state will be calculated as follows:

$$\begin{cases} [p^*_{cast}\ p^*_{HT}]T = [p^*_{cast}\ p^*_{HT}] \\ p^*_{cast} + p^*_{HT} = 1 \end{cases} \rightarrow \text{stationary state} \begin{cases} p^*_{cast} = 2/11 \\ p^*_{HT} = 9/11 \end{cases}$$

The source entropy:

$$H_S = \sum_{i=0}^{1}\sum_{j=0}^{1} p(si)\cdot p\left(\frac{aj}{si}\right)\cdot \log_2 p\left(\frac{ai}{si}\right)$$

i = {0,1} – two possible state of the source
j = {0,1} – each source can transmit two possible messages

$$H_S = \frac{2}{11}\left(\frac{1}{10}\log_2\frac{10}{1} + \frac{9}{10}\log_2\frac{10}{9}\right)$$

$$+ \frac{9}{11}\left(\frac{2}{10}\log_2\frac{10}{2} + \frac{8}{10}\log_2\frac{10}{8}\right)$$

= 0,67594 bit/symbol

Transition matrix → entropy

$$\begin{pmatrix} S1 & S2 \\ 2/11 & 9/11 \end{pmatrix} \rightarrow H_S = 0.684038$$

Upshot:

- The real process is not from the very beginning a stationary one
- The real process reaches its stationarity state after an information transfer
- The entropy of the source without memory is higher than the entropy of the source with memory

Conclusion and prospects

Fig. 3 represents a HPDC plate submitted to a HT. The target values of the mechanical properties were: A ≥ 10%, Rp ≥ 120 MPa. The results of the six specimens retrieved from the plate and submitted to a tensile test are presented in table 6 and show:

- the $R_{p0.2}$ values lie within the system global tolerance of the measurement uncertainty

Table 6: Results – tensile test

Specimen	$R_{p0.2}$ [MPa]	A[%]
1	167.6	5.2
2	167.5	13.1
3	168	11.5
4	165.4	13.9
5	168	11.2
6	166.5	13.4

• The A values do not lie within the system global tolerance of the measurement uncertainty

o If the value of the 1. specimen would be excluded → the A values lie within the system global tolerance of the measurement uncertainty

• This effective practical experiment underpins the results of the present work.

In the present case one can try to use the Pearson´s coefficient or even the coefficient of determination to analyse an eventual causality between $R_{p0.2}$ and A. This would be not recommended because:

• Correlation doesn´t necessarily mean causality

• Both $R_{p0.2}$ and A are outputs of a causal system depending only of x(n)[i] and/or of previous states x(n-1)[ii], x(n-2)[iii]

• The HT conditions were identical for all the specimens → a different influence of the state x(n) on the A value of the 1. specimen can be neglected → this discrepancy cannot be attributed to the HT, but only to a prior operation.

The use of IT (Information Transfer) methods and algorithms in the field of metallurgical processing could ease and simplify the decision making and for certain applications even eliminate typical metallurgical investigations.

In the case of a Markov chain application one has to remember that the relationship: the state S1 is accessible from the state S2 is transitive. That means that the mathematical analysis has to be in accordance with the physical sense of the studied phenomenon.

These methods can also be applied to model and predict the time evolution of the hardware used in metallurgical factories. Predictive maintenance is only one possibility of application.

Using such methods, the risk and lean management will be positively influenced, and the risk fonds could be reduced.

High pressure die casting defects that cause poor elongation

Dr. Stuart Wiesner, Rheinfelden Alloys, says: "Crash relevant structural components in HP-DC of the alloy AlSi10MnMg have critical quality requirements; especially if they require a T6 or T7 heat treatment. Probably the most critical requirements are distortion and poor elongation. An inadequate heat treatment is only one possible reason: short heat treatment time at relatively low temperatures and slow quenching lead to low distortion but poor material properties. A good compromise between material properties and distortion must be found.

A typical HP-DC defect is pre-solidification of the melt in the shot sleeve. That does not necessarily mean that there are surface defects or porosity, but there might be large intermetallic phases or cold flakes in the part. Another defect occurs if die filling is insufficient (which might be caused by inadequate die design, wrong temperature control of the die or poor evacuation of the cavity). This results in a rough surface, scaling or porosity and thus in bad mechanical properties. Release agents and plunger lubricants may lead to high gas content of the part and blisters after heat treatment. Inclusions in the part can be caused by refractories or other melt inclusions in case of insufficient melt treatment. Last not least a wrong element composition (that might be caused by metal loss) must be avoided."

[i] HT [ii] Casting [iii] Alloy elaboration

Literature

[1] G. K. Sigworth – American Foundry Society, 2011

[2] Coordinator A. Spataru and others – Teoria Transmisiunii Informatiei – probleme, EDP, Bucuresti, 1983