Critical Thinking on the Introduction of Digitization Within Engineering Training Systems in the Manufacturing Stage of Cast Parts

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Abstract. The paper aims to present a methodology for the analysis of the engineering training systems at the manufacturing stage of castings through critical engineering thinking. Its use [4, 5] requires the development of procedures capable of responding to the problems faced by engineering training in terms of acquiring the tools and procedures. The structure of the analysis took into consideration the following aspects: the motivation to use the proposed procedure, considerations on the engineering behavior, the design of the reasoning adapted to the analysis of the engineering training systems, the determination of the correlations in the processes of obtaining the cast products, the definition and calibration of the digital experiment, the definition and analysis of the factors influencing the last solidification area (the nature of the alloy, the shape of the mold and the casting geometry).

1. Introduction

1.1. Motivation and presentation of the method of critical engineering thinking

At present, at the manufacturing stage of the molded parts, the specific processes are carried out by using the computer products, both at the level of the constructive conception and at the level of the technological solutions. The justification for including the mentioned aspects at the level of engineering training programs and the modalities of implementation are proposed to be achieved through an analysis in critical engineering thinking.

In view of the importance of critical thinking in solving the specific problems specific of casting manufacturing, the methodology and the spirit of the analyzes carried out by the Foundation for Critical Thinking [4, 5] have been adapted to this paper. The motivation for using this method was determined by the fact that within the foundation there were conducted analyzes of disciplines in "aerospace engineering", "electrical engineering" and "mechanical engineering". From the analysis we have found that there is no "critical thinking" approach to the analysis of the educational programs at the manufacturing level of casting engineering in the "engineer's reasoning guide" [1].

2. Conceiving the reasoning adapted to the analysis of engineering training systems in the field of castings manufacturing

Taking into account the elements of the engineering behavior (the characteristics of the reasoning, the attributions of the engineering activities, the engineering behavior, the way of thinking and the
structuring of the judgments), in this paper we carried out a synthesis of the phasing stage in the study of the use of the engineering reasoning in the modeling of the superior technical training structures in the production of castings [7].

The synthesis used mainly in the reasoning has the following questions structure: 1. What is the essential phenomenon in the process of obtaining the casting?, 2. What is the major problem facing the pieces obtained by casting?, 3. What are the correlations between the areas of last solidification and the compaction of the molded parts?, 4. What are the correlations between the last solidification area and their compactness from the perspective of the constructive and technological solutions?, 5. What are the determinations of the macro-solidification process in the expression of the influence factors? What is the conception of a digital experiment in highlighting the influence factors?, 7. What are the objectives of the digital experiment in validating the results of the analysis?, 8. What are the determinations of the technological influences and how to include them in the experiment? 9. Which are the constructions at the level of the digital experiment?, 10. What are the results obtained in complying with the established objectives?, 11. What are the conclusions of the digital experiment in adapting it to the manufacturing of molded parts?

From the answers formulated, the following aspects are taken into consideration: the appreciation that the solidification represents the essential phenomenon in the process of obtaining castings; compactness is one of the major issues, even if it is not unique; the last solidification area determines, in view of the phenomenology of the process, the occurrence of a lack of compactness in the mass of the alloy; the lack of compactness leads to the appearance of defects in the molded parts, which is why an assessment of the importance of the factors of influence on the macrosolidification process is necessary; the conclusions reached at the level of influence factors can be used at the level of constructive solutions and those of technological nature; the verification of the digital information tool used in the digital experiment is important in the veracity of the conclusions that will result in the analysis; the influences taken into account in the analysis are grouped into the following categories: the nature of the alloy, the nature of the form; casting geometry and casting conditions; the objectives of the experiment aim at visualizing the positioning of the last solidification area in various constructive and technological variants; the experiment aims at tracking - under certain conditions - the influences determined by the nature of the alloy, the nature of the shape and the geometry of the cast piece.

3. Determination of the correlation between the last solidification area and the compaction of cast parts

We considered the area in which the alloy passes from a liquid state into a solid one, within a cast piece or the last solidification area, as the potential for defects primarily linked to the compactness of the material in that area.

In order to determine the correlation mentioned, following the stages established within the critical engineering reasoning, the digital experiment and the practical one were connected to the same constructive-technological structure. In order to verify this hypothesis, some determinations were made on castings in the form of \( T \) intersections [2].

Initially three situations were computationally analyzed, where two walls of different or equal thicknesses intersect perpendicularly within a casting. The three situations, where \( S \) was noted as the thicknesses of the two intersecting walls, are shown in Figure 1.

From the simulation of the solidification of the parts in the three analyzed cases it can be clearly seen that the place of the last solidification is placed in different places depending on the thickness of the intersecting walls, respectively on the ratio between them.

In order to verify in practice how to place the last solidification site in the case of castings made of an Aluminum alloy in wet cast molds, polystyrene designs have been made, with the shape and dimensions of sections as shown in Figure 2 for the three analyzed cases and lengths equal to 100 mm.
Figure 1. T-shaped wall intersections; a) $S_1 < S_2$, b) $S_1 = S_2$, c) $S_1 > S_2$.

Figure 2. Form and dimensions of castings sections.

After casting, the pieces were sectioned longitudinally in several pieces on each side of the wall intersection area. One of the cast pieces is shown as an example in Figure 3, and the samples obtained by cutting such a piece in Figure 4. For these samples, the specific mass of each of them was determined, considering that for the same material, the differences are mostly determined by the degree of compactness of the piece in the respective area, i.e. the presence of voids in the volume of the analyzed sample. This determination was made by measuring the mass of samples in air and immersed in distilled water (resulting in sample volume) and dividing the two values resulting in specific mass or sample density.

Figure 3. Aluminum-based alloy T-type casting piece.

Figure 4. Samples obtained by longitudinal sectioning of the parts.
The diagram of the cast pieces sections from the three categories of ratios between the wall thicknesses and the determined densities for each sample in the intersection area are shown in Figure 5.

Figure 5. Sections of the pieces and specific mass values determined in kg/m$^3$.

By analyzing the results obtained, it can be easily observed that the smallest density zones, determined on castings, are placed identically with the last solidification areas on the computationally analyzed samples, by the theoretical simulation of the solidification of some parts of the same type of alloy and cast in wet forming molds, thus confirming the premise that the areas with the lowest density within the parts are also the last solidification areas, or that the last solidification areas are the areas with the lowest compactness in a casting.

Figure 6. Shape and dimensions of the samples for the determination of tensile strength.

Figure 7. Tear deformation charts for samples LE1 – LE21.
In order to establish a correlation between the degree of compactness of the cast alloy and its mechanical characteristics, from the pieces resulting from the sectioning of the cast parts, 21 cylindrical samples having the dimensions shown in Figure 6 were made, to determine the tensile breaking strength.

The tear deformation diagrams of the 21 samples, numbered from LE1 to LE21, are shown in Figure 7, and the tensile breaking strength values, according to sample density, are shown in Table 1 [3].

The results of these determinations [3] clearly demonstrate that in the areas of the last solidification of a cast piece, the degree of compactness is diminished, and that this degree of compactness ultimately determines the breaking strength of the material, in the sense of decreasing the values the resistance at the decrease in density, respectively the degree of compactness of the material, this being reflected by the trend of the values of the diagram presented in Figure 8.

**Table 1.** The values of the breaking strength of samples LE1 - LE21, depending on their density.

| No. | ρᵣ [kg/m³] | σᵣ [N/mm²] | No. | ρᵣ [kg/m³] | σᵣ [N/mm²] | No. | ρᵣ [kg/m³] | σᵣ [N/mm²] |
|-----|-------------|-------------|-----|-------------|-------------|-----|-------------|-------------|
| 1.  | 2520        | 119         | 2.  | 2640        | 129         | 3.  | 2600        | 109         |
| 4.  | 2520        | 137         | 5.  | 2650        | 141         | 6.  | 2600        | 117         |
| 7.  | 2550        | 140         | 8.  | 2650        | 134         | 9.  | 2600        | 135         |
| 10. | 2570        | 125         | 11. | 2660        | 123         | 12. | 2610        | 127         |
| 13. | 2580        | 137         | 14. | 2670        | 122         | 15. | 2610        | 138         |
| 16. | 2580        | 135         | 17. | 2670        | 142         | 18. | 2630        | 129         |
| 19. | 2580        | 52          | 20. | 2650        | 128         | 21. | 2640        | 135         |

![Tensile breaking strength depending on the density of the alloy](image)

**Figure 8.** Tensile breaking strength depending on density.

4. **Digital experiment for determining the last solidification area**

The digital experiment is carried out for a constructive-technological structure for the constitution of a tubular piece, on which there is the possibility of tracking the solidification front and positioning of the last solidification areas for the different variants followed in the analysis. Figure 9 shows the location of the last solidification area for the variant if the inner diamond is kept constant, and in Figure 10 if the thickness of the piece is kept constant. The data present in the presentation of the
results of the digital experiment will be used to analyze the factors that influence the last solidification area.

![Figure 9](image1)

**Figure 9.** Moving of the last solidification area in tracking the influence of the geometry expressed by providing a constant inner diameter of the cast piece.

![Figure 10](image2)

**Figure 10.** Moving the last solidification area in tracking the influence of the geometry expressed by providing a constant thickness of the cast piece.

5. **Factors which influence the area of last solidification**

The area in which the solidification of the last alloy quantities takes place, in a cast piece, known as the last solidification area, is determined by several factors, the most important of which are: the nature of the cast alloy, the nature of the mold, the geometry of the part, geometry of casting, position at casting, and so on.

5.1. **Nature of the alloy**

In order to determine the influence of the alloy on the last solidification area, simulations of the solidification process of three aluminum alloys with different thermophysical characteristics were
made. These alloys with their characteristics are shown in Table 2, the meaning of the notations being:
TL – liquidus temperature, [°C]; TS – solidus temperature, [°C]; ΔT – solidification interval, [°C]; λ – thermal conductivity of the alloy [W/m·°C]; cp – specific heat, [J/kg·°C]; ρ – specific mass, [kg/m³]; a – coefficient of thermal diffusivity, [m²/s].

**Table 2.** The values of the thermophysical characteristics of the analyzed alloys at the temperatures corresponding to the solidification interval.

| Alloy   | TL [°C] | TS [°C] | ΔT [°C] | λ [W/m·°C] | cp [J/kg·°C] | ρ [kg/m³] | a [m²/s·10⁻⁵] |
|---------|---------|---------|---------|------------|-------------|-----------|--------------|
| AC-AlSi7Mg | 617     | 566     | 51      | 181.5      | 1157        | 2500      | 6.25         |
| AC-AlSi12 | 581     | 558     | 23      | 168        | 1225        | 2500      | 5.48         |
| AC-AlSi9Cu3| 610     | 523     | 87      | 108        | 1142        | 2570      | 3.67         |

In the digital experiment for the study of the influence of the nature of the alloy, the elements of characterization of the nature of the shape, the geometry of the part and the casting conditions were kept constant. The evolution of the solidification front and the positioning of the last solidification area for the three types of alloys analyzed is shown in Figure 11.

![Figure 11](image1.png)

**Figure 11.** The influence of the alloy on the position of the last solidification area, for the situation of the constant inner diameter of the piece: (a) the distance from the inner surface to the thermal axis; (b) adimensional displacement of the thermal axis relative to the semi-thickness of the assessed wall.

In the case where the internal diameter is constant and the thickness of the piece increases, the nature of the alloy, expressed by diffusivity (Table 2), influences the positioning of the last solidification area (Figure 11.a) by the fact that the lower diffusion alloy (Al9SiCu3) has a greater constant of the distance of the last solidification area relative to the inner wall of the piece, in relation to the thickness. It is observed that the other alloys (AlSi7Mg and AlSi12) have a higher increasing slope, which determines a variation in the distance of the last solidification area proportional to the thickness of the wall. From a technological point of view, in alloys with a higher diffusivity coefficient, the location of the last solidification area is established with great difficulty, which can create additional technological problems for the piece obtained by the casting. Adimensional reporting of the difference between the thermal axis and the geometric axis (Figure 11.b) of the alloy, using the data of the digital experiment, shows that the alloy with the highest thermal diffusivity (AlSi7Mg) has a lower approximation between the two axes than the alloys with lower diffusivity (AlSi12 and AlSi9Cu3). At the same time, it is observed that for a piece thickness close to 70 mm, the diffusivity does not influence the position of the last solidification zone, the thermal axis coinciding with the geometric axis.
5.2. Nature of the shape

One of the factors which significantly influences the conditions of cooling and solidification of the cast alloys is obviously the nature of the mold, which, by the thermophysical characteristics, firstly determines the cooling and solidification rate of the cast alloys. An important coefficient in the cooling processes of cast alloys is the coefficient of heat accumulation by the shape, $b_f$, which is a coefficient which takes into account the values of thermal conductivity, the specific heat and the specific mass of the material from which the casting is made,

$$b_f = \sqrt{\rho_f \cdot c_{pf} \cdot \lambda_f} [Ws^{1/2}/m^2\cdot\circ C].$$

In order to show that these parameters, respectively the nature of the mold, have an influence on the position of the last solidification area, simulations have been made, of the solidification of an Aluminum-based alloy in three types of shapes: classical - wet molding, metallic (gray iron) and graphite. The characteristics of these materials taken into consideration for the analysis are shown in Table 3.

### Table 3. The values of the thermophysical characteristics of the materials for the analyzed molds.

| Material of the mold | $\lambda$ [W/m°C] | $c_p$ [J/kg°C] | $\rho$ [kg/m$^3$] | $b_f$ W·s$^{1/2}$/m$^2$·°C |
|----------------------|-------------------|----------------|-------------------|-----------------------------|
| Green Sand           | 0.9              | 549            | 1550              | 875                         |
| Grey Iron            | 50               | 500            | 7200              | 13 416                      |
| Graphite             | 135              | 600            | 1922              | 12 477                      |

While maintaining the alloy characterization elements and casting geometry, the evolution of the solidification front and the location of the final area were observed for each situation. Their presentation, for the analyzed cases, is shown in Figure 12.

![Figure 12. The influence of the nature of the shape on the position of the last solidification area, for the situation of the constant inner diameter of the piece: (a) the distance from the inner surface to the thermal axis; (b) adimensional displacement of the thermal axis relative to the semi-thickness of the assessed wall.](image)

From the analysis of the graphs shown, we notice that for the shapes in the forming mixture the positioning of the last solidification zone –"LSZ" is approximately constant at the dimensional level with the increase of the wall thickness, instead of the gray cast iron and graphite forms there is a maximum of the "LSZ" positioning, after which the location approaches the inner edge of the wall, the one that is in contact with the core. The technological conclusion shows that for the molds in the mixture the final positioning area is constantly located at about one third of the thickness of the cast piece. In contrast, for cast iron (metallic) shapes, the variation in the position of the last solidification area is much higher, basically from the geometric axis to the edge of the wall. From the practical point
of view, it is found that the pieces obtained in forms of the mixture of formation are less sensitive to the effects of the discontinuities. Instead, castings in metallic or graphite forms are very sensitive to the presence of discontinuities in the active areas to be processed in the surface areas. Therefore, in the technological design of castings in the molds, particular care must be taken to position the discontinuities in areas that do not affect their safety or machinability that provide the final dimensions, or to provide higher processing additions.

Under the same conditions, the analysis of the case where the wall thickness of the piece is constant, the two diameters (inside and outside) are modified accordingly. The results of these solidification simulations are shown in Figure 13 for the influence of the alloy and in Figure 14 for the influence of the mold material on the position of the last solidification area.

![Figure 13](image1.png)

**Figure 13.** The influence of the alloy on positioning of the last solidification area, for the situation the wall thickness of the constant piece: (a) the distance from the inner surface to the thermal axis; (b) adimensional displacement of the thermal axis relative to the semi-thickness of the assessed wall.

![Figure 14](image2.png)

**Figure 14.** Influence of the nature of the mold on the position of the last solidification zone, for a constant thickness of the piece wall: (a) the distance from the inner surface to the thermal axis; (b) adimensional displacement of the thermal axis relative to the semi-thickness of the assessed wall.

In the case of a constant wall thickness (Figure 13), the influence of the alloy is not a major one on the positioning of the last solidification area. Therefore replacing the alloy and keeping the thickness constant should not cause problems in positioning the area of last solidification, with the potential for defects to occur. Regarding the influence of the mold material, we notice that it is much more pronounced than that of the alloy, with being significant differences in the location of the last solidification zone, especially between the shapes in the mixture of formation as compared to the other two.
5.3. Geometry of the piece
The influence of casting geometry is followed by the digitization of the following situations: in the first case by maintaining the inner diameter of the piece constant and the variation of the outer diameter so that its thickness varies, and in the second case by modifying the two diameters so as to keep constant the wall thickness of the piece. Analyzing the results of the two variants presented above for different alloys as well as materials of different shape, it can be seen that in parts with the same wall thickness the differences between the last solidification areas for the alloys analyzed are almost insignificant but as the thickness of the walls increases, the difference between the positioning areas becomes larger. Regarding the influence of the formation mixture in the two situations, it can be seen that by increasing the thickness of the wall of the cast piece, the area of last solidification distances more and more from the geometric axis of the wall, instead when increasing the inner diameter, the area of last solidification comes closer to the geometrical axis, respectively the radius being increasingly bigger, the situation tends towards the behavior of a planar wall.

6. Conclusions
From the point of view of the proposed objective, the paper highlights the fact that the introduction of digitization at the level of the engineering training programs is important now, because the manufacturing of the castings cannot be achieved without a good knowledge of the way in which IT applications influence the development of processes.

Highlighting this aspect does not favor the replacement of the phenomenological knowledge with the tools of informatics, the optimal solution is expressed in this paper by the need to optimize and harmonize the educational offer with the two tendencies that are manifested, the traditional emphasis on the phenomenological part and the one determined by the strict use of the simulation software for the physical phenomena present in the given technologies. The engineering critical thinking, currently used, represents a tool in optimizing the two tendencies. We believe that the model proposed in the paper can lead to a real knowledge of the casting process, the phenomenological interpretation made by the use of critical engineering thinking in the design of the digital experiment gives us the opportunity to acquire the skills for accurate constructive and technological solutions.

7. References
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