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## SIMULATION OF SOLIDIFICATION CONDITIONS IN HIGH QUALITY CASTINGS FOR MINING INDUSTRY

### SYMULACJA WARUNKÓW KRZEPNIĘCIA WYSOKOJAKOŚCIOWYCH ODLEWÓW DLA PRZEMYSŁU GÓRNICZEGO

To obtain a right casting methoding of a yoke used in mining industry, a computer simulation of filling of mould cavity as well as casting solidification has been applied. Analysis of the casting solidification showed, that an initial casting methoding, based on common foundry practice, had to be changed. An initial bottom gating system was changed into a side-bottom one, what allowed smooth filling of mould cavity. Modified risering system enabled proper feeding of the casting. Ensuring high quality casting enable to substitute parts manufactured by forging.

*Keywords:* yoke casting, solidification, porosity, casting simulation

Dla uzyskania właściwej technologii odlewania jarzm dla przemysłu górniczego wykorzystano komputerową symulację zapełniania wnęki formy i krzepnięcia odlewu. Analiza procesu krzepnięcia odlewu wykazała, że zastosowana typowa technologia odlewania musi być zmieniona. Syfonowy układ wlewowy zastąpiono doprowadzeniem metalu z boku u dołu formy, co zapewniło spokojne wypełnienie wnęki formy. Zmodyfikowany układ zasilający zapewnił odpowiednie zasilenie, co gwarantuje wysoką jakość odlewu i wyeliminowanie odkuwek.

#### 1. Introduction

One of the most important part in crushing machines is yoke (Fig. 1). High rotational speed, variable acceleration and failure-free operation in coal mines require the use of materials offering the highest possible quality. The material

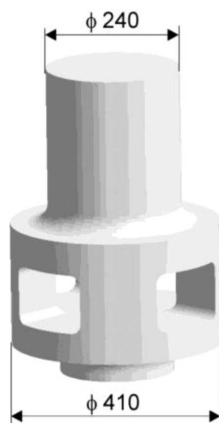


Fig. 1. One of the basic yoke after mechanical tooling and prepared to use in crushing machine, weight 270 kg

used for yokes should be characterized not only by high yield strength (above 1100-1300 MPa), but also by the elongation of 8-10%; it should enable elimination of microporosity

(less than 0,5 mm) and macroinclusions (less than 50  $\mu\text{m}$ ). Right hardness is the essential condition during production of yokes: for mechanical tooling it is required to have maximum 320-330 HB and after quenching and annealing at least 52 HRC. Final heat treatment consists in induction heating of the outer layer, followed by polishing.

The main purpose of the present investigations was to test the possibility of using cast yokes instead of the forged parts. Thereby eliminating very large machining allowances, which significantly increase the cost of manufacture.

This task demands, though not only, the choice of proper chemical composition (the content of C, Cr, Ni, Mo) and heat treatment of castings characterized by diversified wall thicknesses (from 30 to 240 mm). Properly selected chemical composition guarantees the required hardness and tensile strength (YS higher than 1300 MPa and YS to UT ratio above 0,8). It is difficult to obtain the required quality of casting with the applied heat treatment (mainly quenching) due to the formation of microcracks located at part cross-sections and spatially extended together with the shrinkage porosity (Fig. 2), that usual occurs within casting hot spots.

These potential defects in castings should be eliminated not by the trial-and-error method but through computer simulation of the solidification process. This type of technological procedure ensures high quality of casting as well as decreases the production cost.

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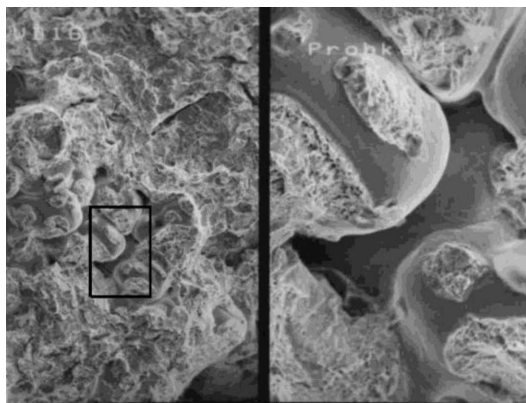


Fig. 2. Example of shrinkage porosity in the cast yoke, magn. 100x left, 500x right

**2. Material and Procedure**

High mechanical properties (YS, UT) combined with proper elongation (min 8%) require proper choice of chemical composition, proper melting process and complex heat treatment. To obtain yield strength above 1200 MPa in castings with the wall thickness of 200 mm (Fig. 1), the Cr-Ni-Mo cast steel according to Table 1 has been chosen. The wide range of carbon concentration values is corresponding to the conditions necessary for an effective adjustment of hardness and elongation.

Close monitoring of the melting process aims mainly at obtaining the possible lowest content of sulphur and phosphorus, as well as hydrogen, nitrogen and oxygen. To maintain these parameters at the required level, special melting conditions were provided: during oxidizing period the content of carbon was reduced to a minimum of 0,28%C to eliminate hydrogen and phosphorus, and during refining period, slag was continuously added (a mixture of CaO-CaFe-FeSi-C) to remove sulfur and oxygen. Special attention was paid to thorough deoxidizing of the steel in ladle and its successive modification. At a final stage of the technological process, molten steel in the ladle was deoxidized with an addition of Al+Fe-CaSi and modified with ferro-vanadium. Then, after the lapse of 3-5 minutes, it was subjected to stirring with argon for the time of maximum 4 minutes.

The mechanical test specimens were cut from the cast-on test bar. After machining, the rollers 12 mm in diameter, were normalized at 920°C and then they were quenched from 880°C in 8% Polihartenol E8 water solution. For understanding the

heat treatment effect on the mechanical properties, the rollers were tempered in range of temperatures 420÷600°C. Then the rollers were turning for obtain final shape of round bar tensile specimen.

**3. Computer simulation**

Computer simulation of casting solidification was carried out using MAGMASOFT® software. The simulation included filling of mould cavity as well as subsequent casting cooling and solidification, taking into account casting-mould heat transfer as well as solidification kinetics, mainly driven by casting geometry. Results of casting solidification enable to have insight at any cross-section of the casting to estimated possible shrinkage problems, both macro- as well as microporosity. Casting free of macroporosity or other shrinkage defects is a pre-condition for such a reliable part as yoke. Simulation of casting solidification enables to localize hot spots, predict shrinkage defects and eliminate them in next simulation runs, ensuring proper feeding and/or directional solidification. It is well known, however, that centerline microporosity can occur despite very good feeding of a critical region of casting. To find the regions where such microporosity might occur, Niyama criterion [1] was used mould (Fig. 3). This well-known criterion is commonly used to this aim (e.g. [2]).

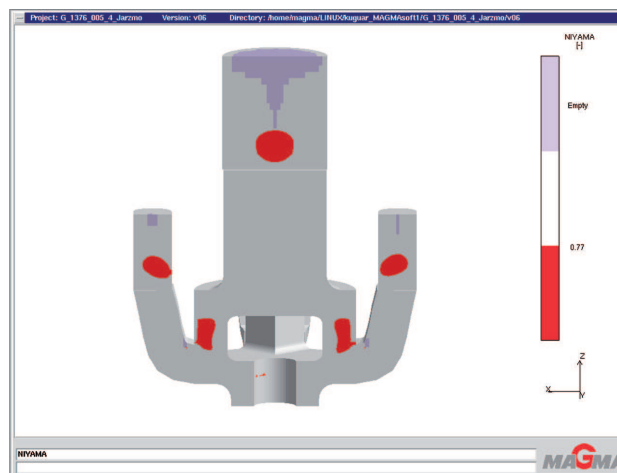


Fig. 3. Niyama criterion – initial version of casting methoding. Red area shows danger of microporosity. The critical value 0.775, instead of 1.0 by Niyama [1], follows replacing minutes by seconds and centimetres by millimetres

Chemical composition of the examined cast steel suggested as a cast material for yokes

TABLE 1

	Chemical composition, wt.%										
	C	Mn	Si	P	S	Cr	Ni	Mo	V	Al	Fe
Proposed	0.28-0.40	1.1-1.4	0.4-0.6	≤0.03	≤0.02	0.9-1.2	1.5-2.4	0.2-0.4	-	-	balance
Obtained	0.35	0,82	0.38	0.007	0,005	1.10	1,90	0.30	0.05	0.034	balance

Casting (250 kg without risers) has been checked according to the following criteria:

- mould cavity filling process,
- shrinkage defects (controlled by feeding of the casting from risers),
- microporosity at hot spots inside the casting (using Niyama criterion).

Applying the initial gating system design (Fig. 4), two jets of melt formed non-uniform temperature field in the mould cavity (Fig. 5). Solidification of the casting leads to macroporosity formation (Fig. 6). The reason of it is non-directional solidification (Fig. 7). In interdendritic spaces, the effect of strong segregation is observed, and the intersecting arms of secondary dendrites "cut off" the feeding flow, thus making local feeding impossible and resulting in the formation of bridging's. In these places the very small porosities are forming, and are difficult to detect by X-rays. In the case of the casting discussed here, such dangerous areas in the directional solidification has been observed, in the places designated by circle in Fig. 7.

A change of gating system has efficiently eliminated this problem (Fig. 10).

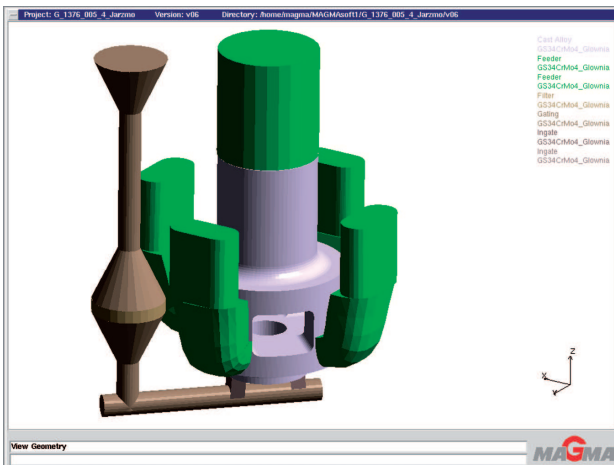


Fig. 4. Initial casting methoding

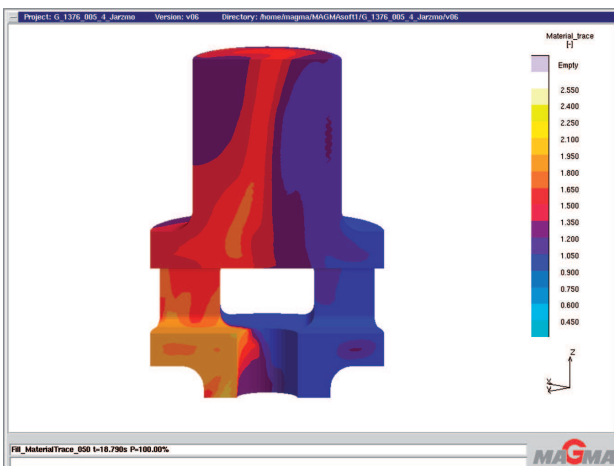


Fig. 5. Material trace result obtained with bottom ingate system. Yellow colour means melt flowing into mould cavity by left ingate, while blue one by right ingate. The two melt streams mix themselves in the upper part of the mould cavity rather poor

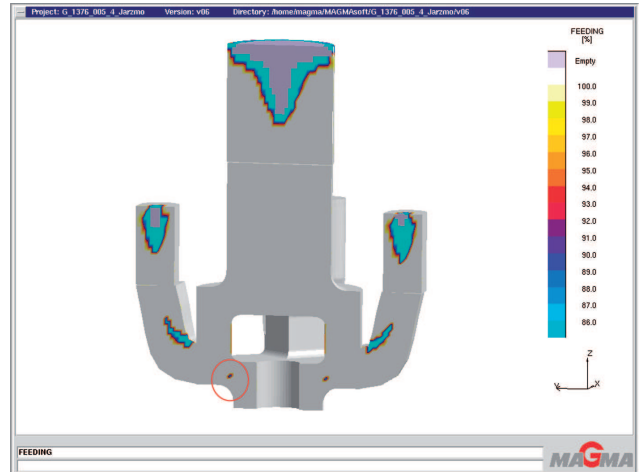


Fig. 6. Initial casting methoding does not ensure sound casting (macroporosity in casting marked by the red circle)

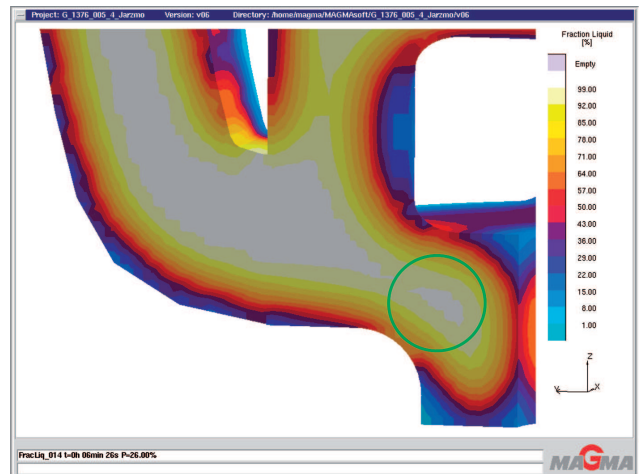


Fig. 7. The reason of macroporosity shown on the Fig. 6 is non-directional solidification. Liquid fraction on the casting cross-section distribution shows hot spot marked by green circle

Since the initial casting methoding cannot ensure part neither free of macro- (Fig. 6) as well as microporosity (Fig. 3), a modified casting methoding has been applied (Fig. 8). Instead of bottom run filling, a tangential single ingate has been applied.

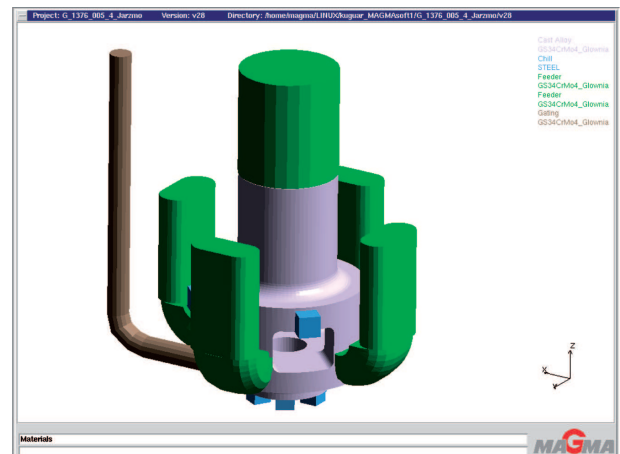


Fig. 8. Redesigned casting methoding: tangential attached single ingate; modified riser neck; chills applied

Figure 9 compares filling process for both initial as well as improved casting methoding using so called traces particles showing movement of melt stream. It is clear, that the improved methoding enables more uniform distribution of melt within mould cavity.

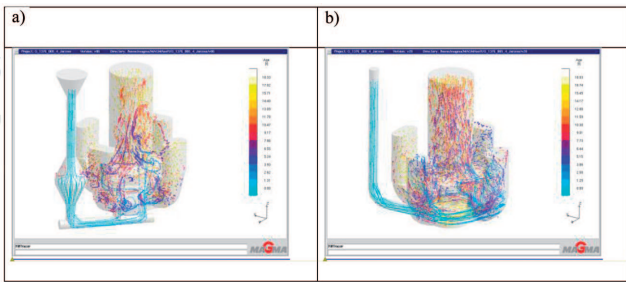


Fig. 9. Tracer particles showing mould filling process – a) initial casting methoding, b) redesigned casting methoding. Light colours indicates melt that entered into mould cavity at the beginning of mould filling, while dark colours indicate melt entering into mould cavity later

The redesigned casting methoding has significantly changed solidification process. Figure 10 shows directional solidification in the casting region, where macroporosity occurred before (Fig. 6). As a result, the proper casting is free of macroporosity; shrinkage is present in the attached risers only (Fig. 11). These results are consistent with the measurements taken in practice and defect identification done by the X-ray technique which has not revealed any discontinuities in the matrix (defects of a diameter above 0,5 mm). Niyama criterion shows (Fig. 12), that – applying the improved casting methoding - risk of centreline microporosity has been practically eliminated.

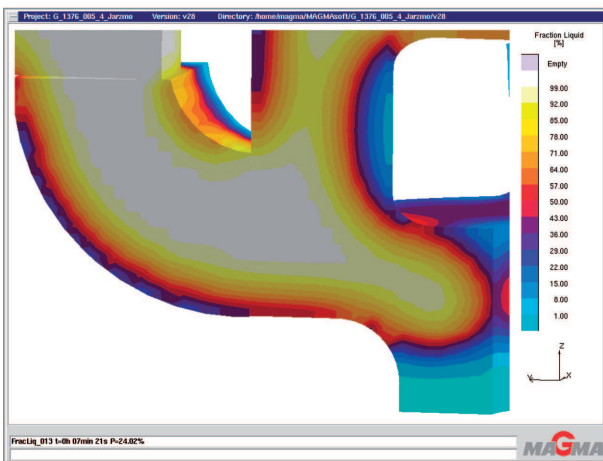


Fig. 10. Directional solidification within the analysed region of casting (compare the Fig. 8)

Practical application of the above mentioned casting methoding enables elimination of porosities. In two series of castings (2x5 pieces of castings), an X-ray inspection has proved any porosities more than 0.5 mm.

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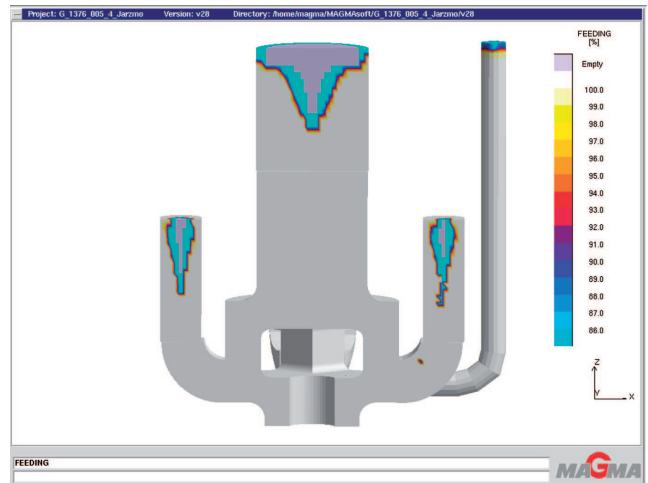


Fig. 11. Redesigned casting methoding ensures sound casting

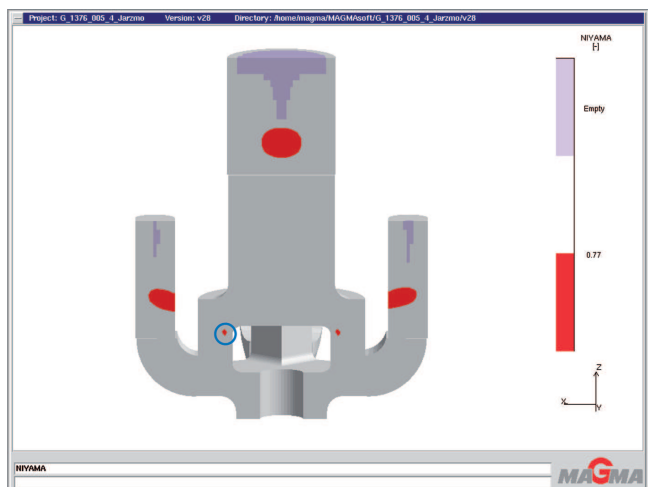


Fig. 12. Niyama criterion for improved casting methoding: risk of microporosity significantly reduced comparing to the initial casting methoding

#### 4. Conclusions

1. Applying smooth and uniform filling of mould cavity as well as directional solidification enable elimination of the shrinkage porosity defects in cast yokes.
2. Computer simulation of mould cavity filling and subsequent casting solidification enables elimination of costly “trial-end-error” methods of production.
3. Ensuring high quality of cast yoke enables to substitute the forged elements.

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