

POSSIBILITIES OF OPTIMISATION OF PRODUCTION OF TOOL STEEL FOR FORGING ON THE RAPID FORGING MACHINE

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Abstract

The paper presents research of possibilities of optimisation of production of tool steel of X40CrMoV5-1 grade for forging on the rapid forging machine, which was directed on conditions of casting with focus on macroporosity and micro-porosity in the ingot body. Metallographic analyses of ingot structures prove that internal discontinuities in ingots may be formed as a result of volume changes of liquid and solid phases, of carbidic segregations and micro-cracks in segregations. Assuming similar conditions and parameters for casting of X40CrMoV5-1 steel grade, numerical simulations of casting, solidification and cooling of two types of identical shape of cross-section, of similar diameter and taper of the forging ingot from the melt without rejects and with occurrence of rejects from the final forged piece were performed in MAGMA program. Design of new shape of ingot mould was created after evaluation of the achieved parameters and numerical simulation of casting with modified taper of the forging ingot was performed with preservation of other original parameters.

1. INTRODUCTION

The extension of orders executed using the rapid forging machine (RFM) at Vítkovice Heavy Machinery a.s. (VHM a.s.) by the capability of tool steel production and processing provides additional significant extension of product portfolio for this new production plant. X 40 tool steels ranking among alloyed steels require specific metallurgical and technological production procedures throughout the production stage.

2. ANALYSIS OF ACTUAL STEELMAKING PRODUCTION OF X40CRMOV5-1 TOOL STEEL

The analysis of actual steelmaking production of X40 tool steel covering all the production stage was made on a selected heat without rejects and heat with occurrence of rejects from the final forged piece of X40CrMoV5-1 tool steel grade. Following the assessment of technological procedures and final results in terms of achievement of the required forging ingot class based on UT, heat No. 1 cast into V4 ingot moulds was classified as one with rejects while heat No. 2 cast into V5 ingot moulds was classified as one without rejects. The standardized chemical composition of X40CrMoV5-1 used in Magma software and of the heats cast into V4 and V5 ingot moulds is summarized in **Table 1**. The forging reduction of ingots from V4 and V 5 ingot moulds was 5.25 and 7.48, respectively. All the data provided was subjected to a detailed analysis according to the latest scientific findings in the field of metallurgical and technological procedures in steelmaking and forging production.

In order to analyze the effect of steelmaking production, numerical simulations of casting were made in MAGMA program for heats No. 1 and No. 2 focusing on central discontinuities of ingots. **Table 1** shows chemical compositions of X40CrMoV5-1 tool steel according to the standard included in detailed VHM a.s. operating procedure applied in Magma software and heats No. 1 and No. 2 cast into V4 and V5 ingot moulds.



Table 1 Chemical composition of X40CrMoV5-1 steel

		С	Mn	Si	Р	S	Cu	Ni	Cr	Мо	v	Ti	AI	N	Nb	Sn
VHM a.s.	min.	0.35	0.25	0.80	-	-	-	-	4.80	1.20	0.85	-	-	-	-	-
standard	max.	0.42	0.50	1.20	0.030	0.020	-	-	5.50	1.50	1.15	-	-	-	-	-
Magma		0.40	0.40	1.00	0.035	0.035	-	-	5.00	1.00	0.30	-	-	-	-	-
Heat No. 1	V4 ingot	0.38	0.33	0.90	0.007	0.001	0.13	0.22	4.95	1.28	0.936	0.004	0.025	0.0058	0.020	0.004
Heat No. 2	V5 ingot	0.38	0.33	0.92	0.006	0.001	0.11	0.23	5.33	1.26	0.913	0.004	0.025	0.0077	0.009	0.008

3. DEFINITION OF PARAMETERS FOR SIMULATIONS OF CASTING OF HEATS PRODUCED

Numerical simulation - heat No. 1, V4 ingot mould, V4 refractory top, V4 assembly

- For examples of ingot mould dimensions see **Fig. 1** and for V4 assembly positions see **Fig. 3**.
- 4 ingot moulds were placed on the stool.
- The ingot moulds were arranged crosswise on the stool with 850 mm distance between the sprue pin axis and ingot mould axis see **Fig. 3**.
- Casting conditions
 - Casting temperature: 1,545.6 °C (range fixed by applicable operating procedure: 1,540 1,550 °C)
 - Body casting time: 5.30 mm.s⁻¹
 - Head casting time: 2.35 mm.s⁻¹
- Ingot head insulation
 - Insulating board (non-exothermic): 30 / 250 mm
 - Exothermic insulating backfill: 6 kg (Al₂O₃ + Al + SiO₂)
 - Insulating backfill: 1 kg Nermat (SiO₂)
- Ingot
 - Head height: 180 mm





Numerical simulation - heat No. 2, V5 ingot mould, V5 refractory top, V5 assembly

- Fig. 2 provides examples of ingot mould dimensions and examples of V5 assembly position are presented in Fig. 4. 4 ingot moulds were placed on the stool.
- 4 ingot moulds were placed on the stool.
- The ingot moulds were arranged crosswise on the stool with 900 mm distance between the sprue pin axis and ingot mould axis see **Fig. 4**.
- Casting conditions
 - Casting temperature: 1,536.8 °C (range fixed by applicable operating procedure: 1,535 1,545 °C)
 - Body casting time: 8.00 mm.s⁻¹
 - Head casting time: 3.00 mm.s⁻¹
- Insulation of ingot head
 - Insulating board (non-exothermic): 30 / 250 mm,
 - Insulating backfill (exothermic): 6 kg (Al₂O₃ + Al + SiO₂)
 - Insulating backfill: 1 kg Nermat (SiO₂)
- Ingot
 - Head height: 200 mm



4. NUMERICAL SIMULATION OF CASTING OF FORGING INGOTS PRODUCED

The graphic representations made based on the calculations of numerical simulation in MAGMA program [1] using the parameters set for the heats produced were focused on macro- and micro-porosity areas in the ingot body which were to be analyzed. **Fig. 5** shows temperature fields of the cast steel at 98 % ingot mould filling supplemented by velocity vectors for V4 ingot mould assembly. **Fig. 6** shows temperature fields of the cast steel at 98 % ingot mould filling supplemented by velocity vectors for V4 ingot mould assembly. **Fig. 6** shows temperature fields of the cast steel at 98 % ingot mould filling supplemented by velocity vectors for V5 ingot mould assembly. The detailed representation of velocity vectors on **Fig. 5** and **Fig. 6** closely illustrates the melt flow character just before the casting completion.





The simulation of steel solidification provided a calculation for V4 ingot mould assembly indicating that the solidification of the cast steel finished within 132 minutes in case of V4 ingot mould assembly and within 159 minutes in case of V5 ingot mould assembly. In the final stage of the ingot solidification, an undesirable reduction of width of the semi-liquid core running from the head to the ingot depth was observed. **Fig. 7** shows semi-liquid core of V4 ingot mould assembly with 2.25 % of liquid phase of the cast steel reaching inside the ingot body. **Fig. 8** shows semi-liquid core of V5 ingot mould assembly with 1.40 % of liquid phase of the cast steel reaching inside the ingot body.





The deep semi-liquid core running from the head into the ingot body increases the probability of closing of the semi-liquid phase of cast steel in the ingot body. This closing prevents the liquid phase feeding from the ingot head which results in generation of volume discontinuities in the ingot body.



The probability of generation of volume discontinuity was confirmed after the completion of numerical simulation of casting and subsequent graphic representation of total porosity and micro-porosity in the ingot body. Total porosity of V4 and V5 ingot mould assemblies are depicted on **Fig. 9** and **Fig. 10**, respectively. The micro-porosity location in the ingot body for V4 and V5 ingot mould assemblies are depicted on **Fig. 11** and **Fig. 12**, respectively.





5. EVALUATION OF RESULTS OF HEATS PRODUCED USING NUMERICAL SIMULATION AND PROPOSED OPTIMISATION OF CASTING PROCEDURE FOR X40CRMOV5-1 TOOL STEEL FOR RAPID FORGING MACHINE

The evaluation of results of X40CrMoV5-1 tool steel heats produced using simulation for prediction of, in particular, total porosity (see **Fig. 9** and **Fig. 10**) as well as micro-porosity (see **Fig. 11** and **Fig. 12**) showed the porosity occurrence was more acceptable in case of V4 ingot mould assembly from heat No. 1 where the input analysis recorded rejects in the final forging shape. The result for V5 ingot mould assembly from heat No. 2 was less acceptable although the input analysis did not record any rejects in the final forging shape. This can be attributed to different forging reduction of the ingots. The ingot forging reduction was 5.25 in case of V4 ingot mould assembly. The achieved result testifies to the issue of high forging reduction (7 and higher) restricting the processing of large forgings due to inadequate equipment to fix the ingot and excessively increasing the production costs faced actually.

Based on the results of numerical simulations the options of composition and execution of the final simulation of ingot from V5 assembly were assessed. The following two options were assessed.

- Modification of the ingot mould assembly shape
- Modification of the parameters for ingot casting

The decision on the next steps to achieve the set objectives was based on analysis of the actual tool steel production technology in the sphere of casting conditions focusing on macro- and micro-porosity in the ingot body, study of literature on tool steel production technology [2], [3] and results of numerical simulations of X40CrMoV5-1 tool steel casting into V4 and V5 ingot mould assemblies.



Final numerical simulation in MAGMA program was made for heat No. 2 focusing on macro- and micro-porosity in the ingot body using modified V5 ingot mould assemblies with unchanged ground plan of the ingot mould bottom, modified taper and application of refractory top for V7 and V8 ingot mould assemblies. The new ingot mould assembly was named V 5 m. **Fig. 13** shows temperature field of the cast steel at 98 % ingot mould filling supplemented by velocity vectors for V5 m ingot mould assembly closely illustrating the melt flow



character just before the casting completion. Under these conditions, the simulation provides a characteristic view of temperature field of the cast steel where the melt fed at the end of casting is directed straight to the ingot head. The simulation of steel solidification provided a calculation for V 5 m ingot mould assembly indicating that the solidification of the cast steel finished within 189 min. **Fig. 14** shows semi-liquid core of ingot from V5 m assembly with 1.36 % of liquid phase of the cast steel in the final stage of the ingot solidification in which an undesirable reduction of width of the semi-liquid core running from the head to the ingot depth is observed.

The deep semi-liquid core running from the head into the ingot body thereby increasing the probability of closing of the semi-liquid phase of cast steel in the ingot body was not confirmed for V5 m ingot mould assembly. The fully acceptable condition of the ingot body as far as the porosity and micro-porosity is concerned shown on **Fig. 15** and **Fig. 16**.



CONCLUSION

The approach to the fulfilment of the specified tasks was based on analysis of the actual tool steel production technology in the sphere of casting conditions focusing on macro- and micro-porosity in the ingot body, study of literature on tool steel production technology and results of numerical simulations of X40CrMoV5-1 tool steel casting into V4 and V5 ingot mould assemblies. The numerical simulation in MAGMA software environment representing V4 and V5 ingot mould assemblies showed that the semi-liquid core reached too deep in the ingot body during the solidification of a few last per cents of the cast steel which is usually the first sign of generation of material discontinuities. The generation of macro- and micro-porosity in the ingot body confirmed that V4 and V5 ingot mould assemblies are not suitable for X40CrMoV5-1 steel casting under the analyzed conditions.

A modified ingot mould assembly with increased taper named V5 m was designed and numerical simulation maintaining the original input parameters was performed. This resulted in development of an ingot body fully acceptable in terms of total porosity and micro-porosity. The modified V5 m ingot mould and general modification of ingot mould stock is one of the most appropriate ways to successful improvement of the forging



ingot casting technology with respect to the forging technology applied on the rapid forging machine at VHM a.s.

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