NON-LINEAR NUMERICAL SIMULATION OF THE CONTINUOUS-CASTING PROCESS DURING SOLDIFICATION AND PRODUCT DEVELOPMENT[1]

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Abstract

Recently the power of numerical simulation tools in mechanical engineering and the available computer performance have taken major steps ahead. Because most natural functions are non-linear, modern finite element software allows modeling of complex mechanical and thermal processes, including a wide variety of non-linear effects such as radiation, latent heat effects, thermally caused contact change, plasticity, large geometrical deformations and rotations. These phenomena are all found in the continuous casting process, which is why the process behaviors are extremely non-linear. In order to better understand continuous casting process and improved product quality, this paper provides a brief overview of the developed models and the respective results. The paper deals with coupled displacement-temperature analysis for the simulation of the initial strand solidification, which is dominated by the complex contact and separation behavior in the mold, particularly for "difficult" cross sections such as beam blanks and round sections. These models are used to determine the proper mold taper. The elastic spring-back-effect of strand bending on the strand shell contact pressure in the mold is of great importance in wide slab casters. This can be demonstrated in shell models bent by rigid surfaces. A intensively investigated subject is the identification of stress fields in a number of semi-products during casting that are due to thermal and mechanical loading such as quenching and soft reduction. Three-dimensional models are used for this task. Engineering and design plane models have been created for general straighteners to compute the true unbending roller-force distribution and expected strand spring-back in the run-out area. The examples demonstrate the capabilities of VAI in complex non-linear thermal/mechanical modeling during machine design. It is also important that the models are used for troubleshooting for customer benefits.

Key words: Continuous casting; Numerical simulation.

SIMULAÇÃO NUMÉRICA NÃO LINEAR DO PROCESSO DE LINGOTAMENTO CONTÍNUO DURANTE A SOLIDIFICAÇÃO E DESENVOLVIMENTO DO PRODUTO

Resumo

Recentemente, houve um grande avanço no poder das ferramentas de simulação numérica em engenharia mecânica e no desempenho dos computadores disponíveis. Devido ao fato de que a maior parte das funções naturais é não linear, os modernos softwares de elemento finito permitem a modelagem de processos térmicos e mecânicos complexos, inclusive uma ampla variedade de efeitos não lineares, tais como radiação, efeitos do calor latente, alteração de contato causada termicamente, plasticidade, grandes deformações geométricas e rotações. Todos estes fenômenos são encontrados no processo de lingotamento contínuo, razão pela qual os comportamentos do processo são extremamente não lineares. Visando compreender melhor o processo de lingotamento contínuo e melhorar a qualidade do produto, este artigo apresenta uma breve visão geral dos modelos desenvolvidos e dos respectivos resultados. O artigo aborda a análise conjugada de deslocamento-temperatura para a simulação da solidificação inicial do veio, que é dominada pelo complexo comportamento de contato e separação no molde, particularmente no caso de seções transversais "difíceis", como esboços para laminação de vigas e perfis redondos. Estes modelos são usados para determinar a conicidade adequada do molde. O efeito de recuperação elástica da curvatura do veio sobre a pressão de contato na camada solidificada no molde é de grande importância no caso de máquinas de lingotamento contínuo de placas largas. Isto pode ser demonstrado em modelos de camada solidificada dobrada por superfícies rígidas. Uma questão intensamente analisada é a identificação dos campos de tensão em inúmeros produtos semi-acabados durante o lingotamento, os quais se devem aos esforços térmicos e mecânicos gerados, por exemplo, pela têmpera e pela redução branda. Para este fim são usados modelos tridimensionais. Foram criados modelos de plano de projeto e engenharia para desempenadeiras em geral, visando computar a distribuição real de força nos rolos de endireitamento e a esperada recuperação elástica na área de saída. Os exemplos demonstram a capacitação da VAI na modelagem termomecânica não linear complexa durante o projeto de máquinas. Um outro aspecto importante é que os modelos podem ser usados para a detecção de problemas em benefício dos clientes.

Palavras-chave: Lingotamento contínuo; Simulação numérica

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INTRODUCTION

Numerical modeling of the production processes has been very successful for companies around the world. The early applications were mainly two-dimensional (2-D) or for simple geometries. During the 1980s, the numerical process modeling was extended from aerospace applications to a wide range of companies in transportation, energy, civil and mechanical engineering. As a result of rapid improvement of algorithms and computing technologies, three-dimensional (3-D) process modeling became practical during the 1990s. Process modeling is no longer a luxury, but a necessity for an engineering company like VAI. Two goals are in focus: R&D to develop new process features and plant components and the support of our customers in tuning their plants. Since the 70's, VAI has been a frontrunner in the field of numerical simulation, particularly in the development and applications of the finite element codes.

Today, non-linear modern finite element software allows for the modeling of complex mechanical and thermal processes, including a wide variety of non-linear effects, like radiation, latent heat effects, contact problems, plasticity, and large geometrical changes. The continuous casting process simultaneously shows the full range of above-mentioned phenomena. This makes the process behavior extremely non-linear. Advanced finite element modeling has to do with the art of transforming the real problem into a mathematical or finite element model, with the main non-linear effects being taken into account. The question is often how to simplify the real problem in order to get reasonable results with a minimum of time and effort.

In this paper, several examples are given to demonstrate the ways of VAI in dealing with real problems with the finite element models.

TEMPERATURE-DISPLACEMENT COUPLED ANALYSIS OF STEEL SHRINKAGE IN THE MOLD

BEAM BLANK CASTING

The geometrical and thermal mold-conditions are highly important for the initial solidification of the strand to obtain a shell with outstanding surface and internal quality. From this point of view, a proper primary cooling system and a suitable mold taper are necessary preconditions to meet the above requirements. VAI has developed a fully coupled thermo-mechanical Finite-Element model to calculate the temperature and displacement fields of the strand during initial solidification in the mold. This type of simulation gives a deep insight into the complex shrinkage behavior of the strand shell in the mold. Especially for the beam-blank section, it helps to find the correct answer to the question on how to shape the mold inner contour concerning the taper.

Figure 1 exhibits a bottom view of the Peine BB-mold.

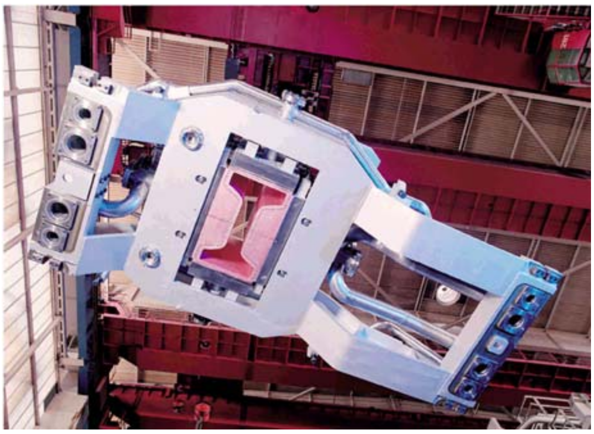

Figure 1. Bottom view of beam blank mold during shop test (Peine)

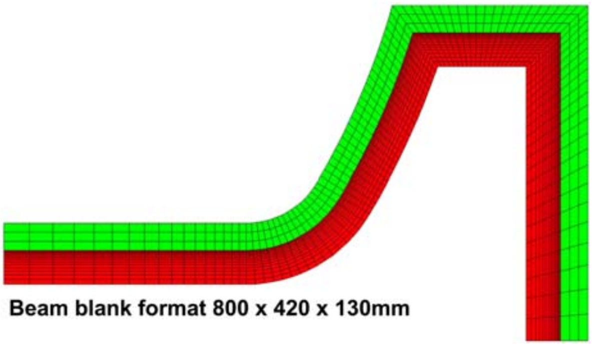

Figure 2. Finite element model for fully coupled temperature-stress analysis.

Figure 2 shows the 2-D FE-model used with the beam blank format 800x440x130 mm as used for the PEINE Beam-Blank Caster. In a coupled analysis, the temperature and displacement fields are calculated simultaneously. By using a transient analysis with neglecting heat flux in longitudinal direction, the temperature and displacements fields are determined. The casting speed is set to 1.1 m/min. The influence of different mold tapers on shell growth, temperature fields and contact pressures due to the shell shrinkage can easily be studied. Figure 3-5 show the calculated shell thickness at the mold exit with different designs of the mold taper.

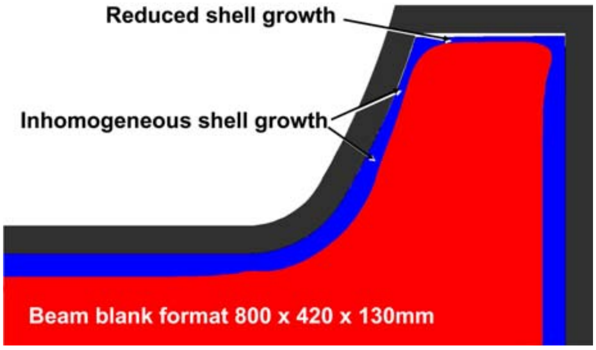

Figure 3. Shell thickness for a too small taper in the fillet and shoulder area, mold exit.

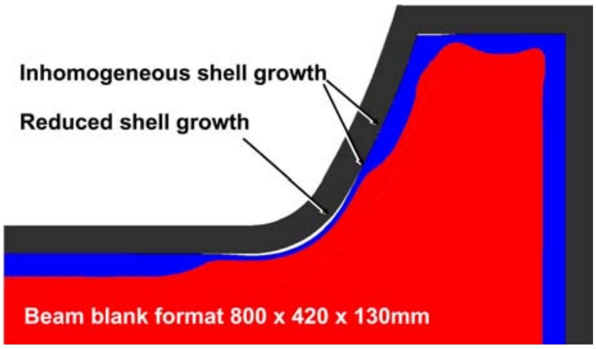

Figure 4. Shell thickness for a too strong taper in the flange and flange tip area, mold exit

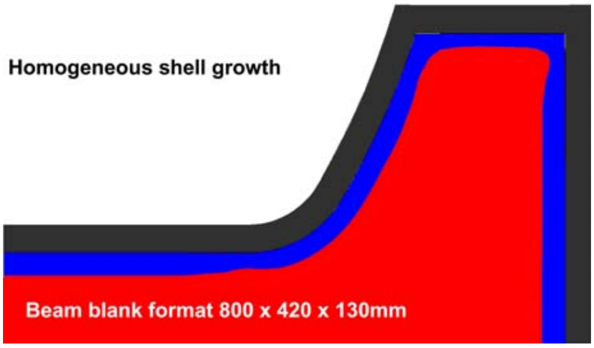

Figure 5. Shell thickness for an optimized taper, mold exit.

ROUND CASTING

The same procedure as applied for the beam-blank analysis is also used for the simulation of the casting process of a round format. Casting of the round format is very difficult due to the fact that no preferred deformation directions of the cross section exist as in the cases of square or rectangular cross sections. Under the ferrostatic pressure, the strand shell of a square or rectangular format deforms in the preferred directions, which ensures the contact of the strand surface with the copper plate of the mold. In the case of round casting the ferrostatic pressure just causes small membrane stresses (no bending stresses), which cannot generate enough radial deflections of the strand shell to ensure contact with the mold. Therefore, the strand shell can easily lose contact with the mold. A proper adjustment of the casting speed and the corresponding mold taper is important. The numerical simulation can help in finding out the optimal casting speeds and mold taper for different steel grades. This can avoid the formation of an inhomogeneous shell thickness in the mold, which is often the reason of breakouts in the casting of round formats.

In Figure 6**,** the used finite element model for the round format is shown. The diameter of the strand is 230 mm. The considered casting speed is 1.5 m/min. For high carbon steel, Figure 7 shows a homogeneous temperature distribution in the strand at the mold exit. With the same mold taper and casting speed, Figure 8 shows that the temperature distribution is disturbed for a peritectic steel grade. Figure 9 shows the calculated inhomogeneous shell thickness at the mold exit. In Figure 10, the observed breakout strand shell shows the same pattern as the calculated strand shell.

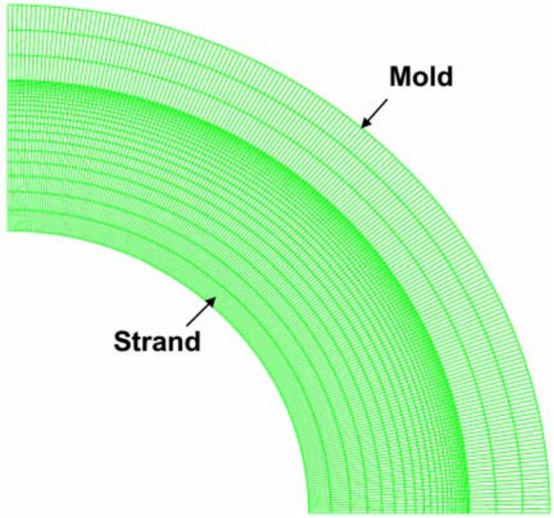

Figure 6. Finite element model for round casting (Ø=230mm, v_C=1.5m/min).

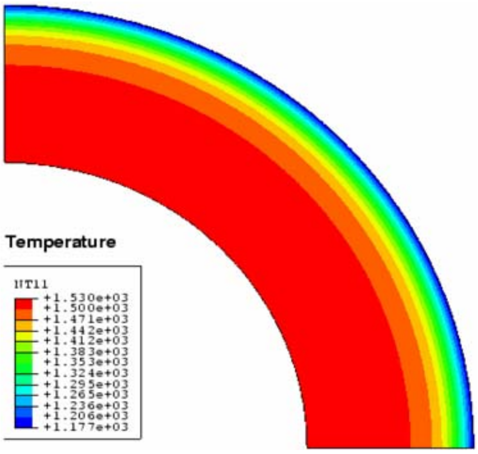

Figure 7. Temperature distribution for high carbon steel grade.

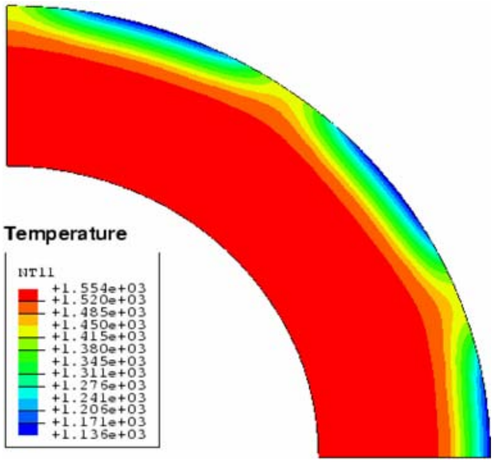

Figure 8. Temperature distribution for peritectic steel grade.

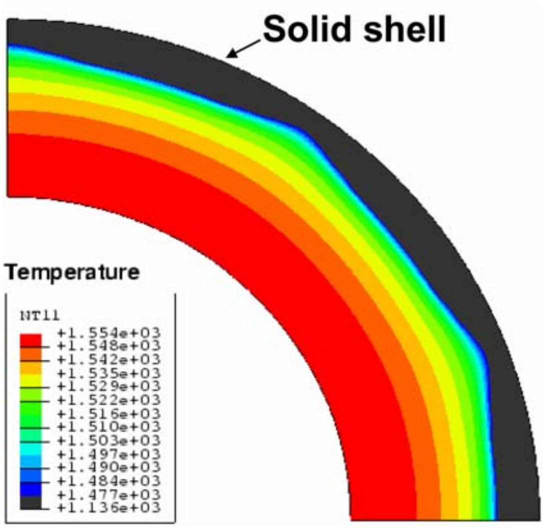

Figure 9. Computed strand shell of a peritectic steel grade.

Figure 10. Real break out strand shell of a peritectic steel grade.

SIMULATION OF THE CASTING PROCESS WITH EXTENDED SECONDARY COOLING TREATMENT (1)

The beneficial application of inline charging from the caster to the rolling mill is frequently restricted by surface quality problems, which originate from a coarse cast grain structure. The extended cooling treatment (quench technique) of the strand results in a layer of fine corn structure (caused by thermal induced $\gamma-\alpha$ -phase transformation) in the strand surface region, compare Figure 11. Consequently, the occurrence of defects in the further rolling process is significantly reduced. On the other hand, the extensive cooling treatment can also cause thermal cracks in the strand (see Figure 12). Numerical analyses can help to optimize the operation parameters and to avoid inadequate usage of the quench technique.

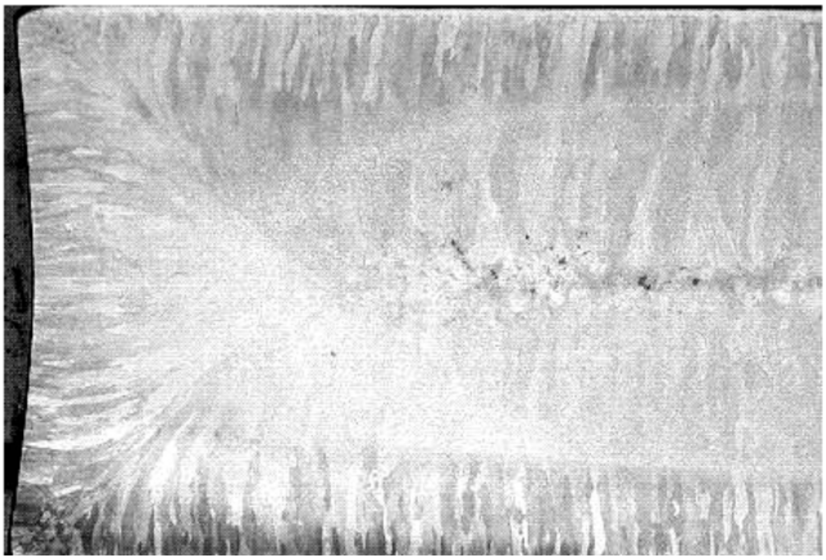

Figure 11. HCl etching of a slab cross section. The region close to the surface appears brighter due to thermal induced phase transformation.

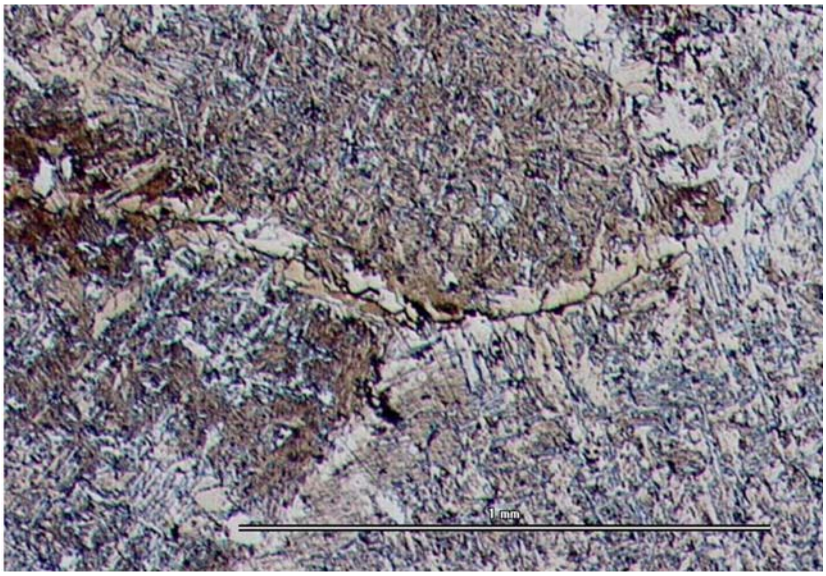

Figure 12. Corner cracks caused by improper thermal treatment of the strand.

The following example shows the finite element analysis of the process with the commercial program package ABAQUS.(2) Figure 13 shows the finite element mesh of the model for a slab of medium carbon steel treated by extended secondary cooling zones. Due to the symmetry, only a fourth of the slab cross section is modeled. The analysis includes two steps. In the first step, the cooling conditions are applied to the strand surface to produce the actual temperature history of the strand material, as shown in Figure 14 for some interesting positions in the strand. In the second step, the thermal deformations of the strand are calculated by applying the calculated variations of the temperature field.

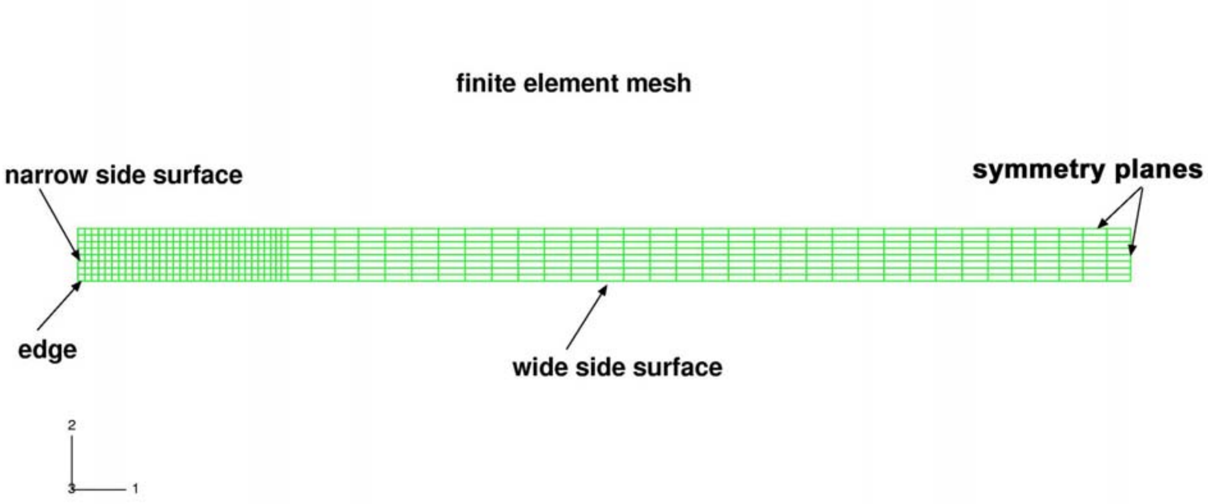

Figure 13. Finite element mesh for the model analyzing a strand treated by extended secondary cooling zones.

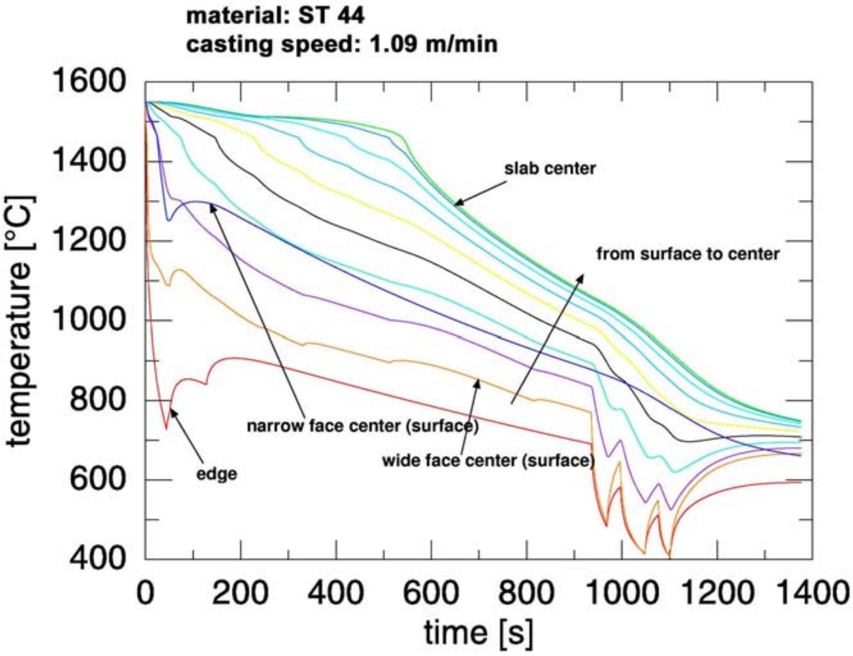

Figure 14. Temperature variations at different positions in the strand

Figure 15 shows a contour plot of the temperature variations during the casting process at a position about 80 mm from the corner of the strand. The temperature from the surface to the center is shown. The extended cooling begins at a strand length of 17m and has a length of 3 m. The equilibrium temperature for proeutectoid ferrite transformation lies at 804°C. According to the phase transformation simulations, the proeutectoid ferrite formation actually begins at the temperature of about 711°C. Figure 15 shows how the quench treatment reaches a depth of about 25 mm, which is in good agreement with the measured value. This depth, which depends on the treated material, the entry temperature and the cooling intensity in the quench box, is crucial to the quality of rolling process.

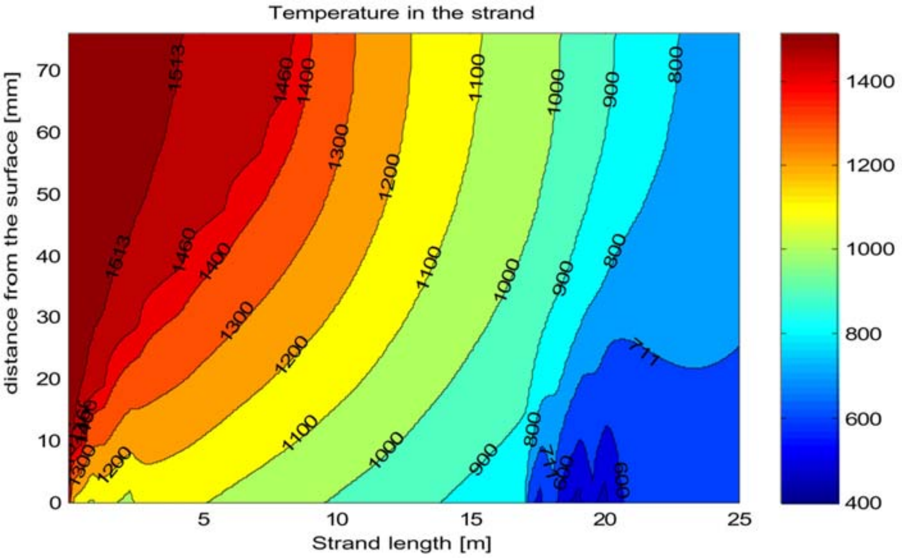

Figure 15. Temperature distribution from surface to center in the near corner area.

Figure 16 shows the stress in the width direction caused by the quenching process and the subsequent warming up of the strand. In the first part of the quench box, the phase transformation does not yet take place. The intensive cooling causes a strong contraction of the material on the surface, which results in a high tensile stress in the surface region. With the further cooling, the γ–α-phase transformation takes place and causes a strong expansion of the material in the transformed region. The result is high compression stress in this region. Since the material beneath this region has the tendency to contract due to the temperature drop, high tensile stresses exist there. After the quench box the compression stress in the surface region is reduced significantly, since due to the warming up of the surface region, no further transformation takes place. With the further warming up of the strand surface region, the compression stress increases again, whereas in the center region of the strand a high tensile stress is caused.

The stress in the casting direction has the similar tendency as the stress in the width direction.

Improper entry temperature and cooling intensity in the beginning of the quench box can cause very high tensile stress, which is often the reason for the surface cracks observed in the practice. For the internal quality, the length and cooling intensity of the quench box play an important roll. The numerical analyses shown above can help to minimize the stresses in the strand. By using optimal operational parameters, the strand can get sufficient quench depth without inducing any defects in the strand.

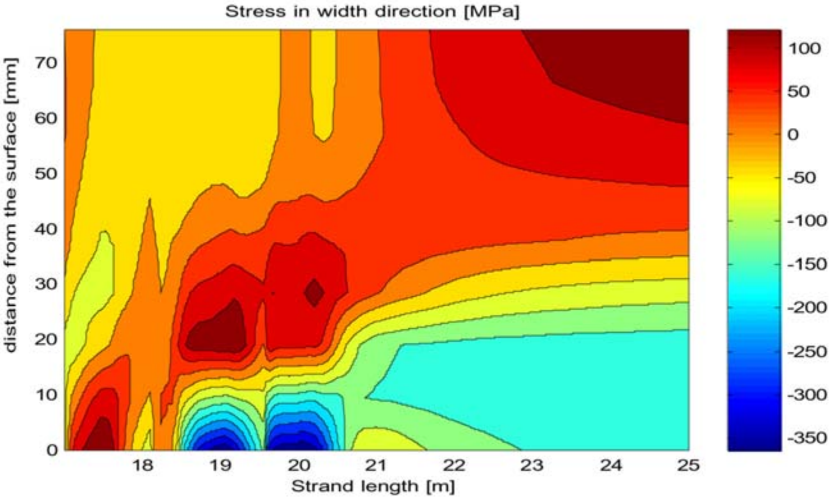

Figure 16. Stress in the width direction in the near corner area

CONCLUSION

The presented examples of numerical modeling demonstrate the power of modern computer and software capabilities. These tools are an essential basis for new product development and in the first step allow a “digital prototyping”. Weak points of any mechanical or thermal design can be quickly identified without machining and testing a real part. This can save a lot of money and avoid many troubles. Due to the high temperature and heavy loads, practical measurements are often very difficult and sumptuous. In many cases, a deep insight into the continuous casting process can only be gained by numerical modeling.

OUTLOOK

As real nature is non-linear and coupled (temperature, displacements, fluid flow etc.), the future development of modern simulation tools is moving to combine the different disciplines in order to map the real behavior as well as possible. With the extended capabilities of the state of the art software, the demands for engineers are nowadays increased.
But each engineering tool in the world is only as good as the knowledge base of the engineer who is working with it. The combined knowledge in numerical modeling and practical continuous casting experience is the key to successful “digital prototyping”.

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