Experimental Simulation of the Solidification of Steel at Higher Cooling Rates

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ABSTRACT: Today, continuous casting is the common technology for casting commercial steel grades. Conventional casting processes, like slab casting, are characterised by a moderate heat withdrawal and a rather low solidification velocity and cooling rate. Linking the casting and the rolling process demands a higher casting velocity, an increased heat withdrawal and thus, a higher local cooling rate. The absence of phase transformations during cooling and reheating before the rolling process makes the solidification microstructure more important for the behaviour of the steel during rolling and for the final product properties.

Over several years the Christian Doppler-Laboratory for “Metallurgical Fundamentals of Continuous Casting Processes” has developed an experimental setup for the simulation of solidification at higher cooling rates. The experiment is based on the principle of a dipping test under inert gas atmosphere inside a vacuum induction furnace. Recently, this apparatus has been equipped with a pyrometer in order to measure the temperature of the solidified sample during the subsequent cooling phase and also with a furnace in order to simulate different cooling and heat treatment strategies.

Thus, it is possible to reproduce solidification and subsequent cooling of the cast material in casting-rolling processes and to characterize the microstructure and the mechanical properties of the solidified samples. The present work will give an overview on heat transfer in conventional casting processes, present a laboratory scale simulation of solidification at higher cooling rate, touch some aspects like the numerical simulation of the experiment and conclude with some results and an outlook on further planned work.

1. INTRODUCTION

In 2007, 92% of the 1.35 billion tons of the worldwide produced steel have been cast in continuous casting machines, 7% to ingots and less than 1% to castings [1]. The part of other solidification processes is marginal.

Presuming a classification of the industrial solidification processes for steel by the cooling rate (or the heat withdrawal during initial solidification), “rapid solidification processes” for steel comprise mainly spray deposition and powder metallurgical processes. These processes have the split-second solidification of small scale particles in common.

In conventional continuous casting, the time for the solidification of the strand ranges between a few minutes and an hour.

A very slow going solidification process is the casting of large forging ingots with a weight of up to several hundred tons. The solidification may take a time of more than a day. Further slow going solidification processes are the remelting processes, namely the electro slag remelting (ESR) and the vacuum arc remelting (VAR) process.

Between the rapid solidification processes and the classical continuous casting processes a new group of casting processes established itself during the last decades. At the beginning this group of processes was commonly termed “near net shape casting”, comprising the thin slab casting and rolling processes (TSCR), the direct strip casting (DSC) and the thin strip casting processes (TSC). Today, the terminology “near net shape casting” seems misleading as more frequently and in other respect used in the foundry technology.

But the cooling rates in the TSC, DSC and TSCR process are also far away from “rapid solidification processes”. This conceptual uncertainty leads to the increasing use of the terminology “solidification processes at higher cooling rate”. In the following, the “processes at higher cooling rate” will be classified within the other casting processes by means of a quantitative comparison of the heat withdrawal during initial solidification.

2. HEAT WITHDRAWAL IN INDUSTRIAL CASTING PROCESSES

In conventional continuous casting the steel is either cast to billets, blooms or slabs. The initial solidification is mainly controlled by a thin mold flux film in between the strand surface and the mold. This film minimizes the friction and controls the heat withdrawal. In billet casting oil is used as lubricant, too. Depending on different parameters like e.g. format, casting velocity, mold flux viscosity and mold flux break temperature the average heat flux ranges roughly between 0.6 and 3.0 MW/m².

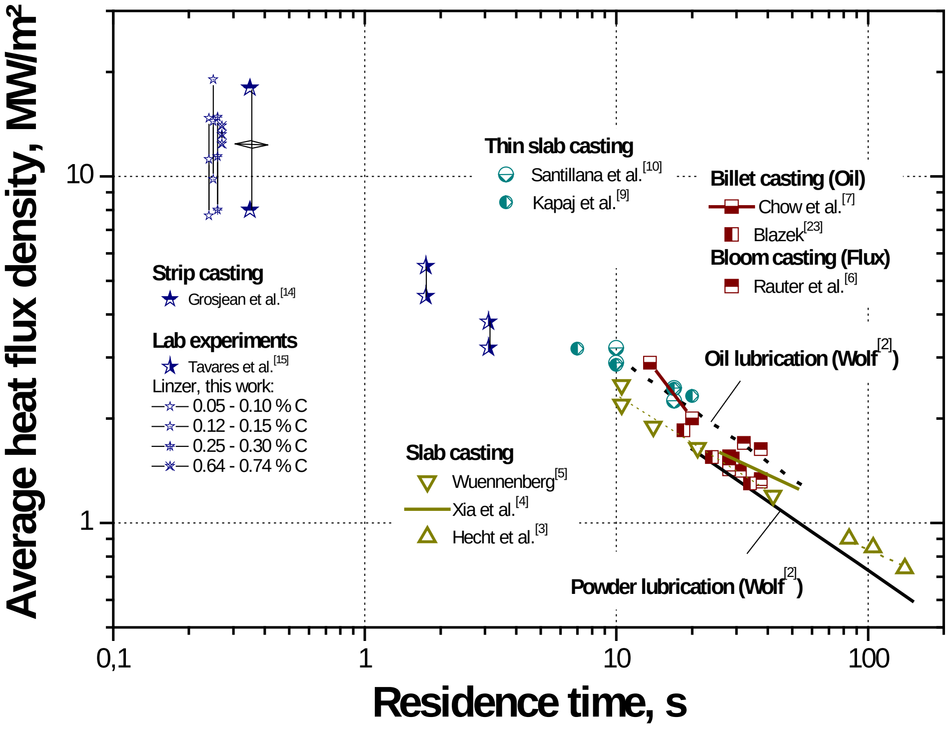


Fig. 1: Average heat flux vs. residence time in mold for different casting processes

Fig. 1 summarizes selected published values on the average heat flux density in casting processes. Wolf [2] proposed two relations between the dwell time of the strand in the mold and the average heat flux for lubrication with oil or mold powder, respectively.

The lowest heat transfer is observed for the casting of thick slabs with a thickness of between 300 and 400 mm at casting speeds between 0.3 and 0.5 m/min [3]. This type of casting machines is commonly used in the production of heavy plates. Depending on the slab thickness, the average heat transfer ranges between 0.75 and 0.9 MW/m².

For conventional casting machines with a slab thickness of about 250 mm, Xia et al. [4] proposed a function between heat flux and the casting velocity: For casting velocities between 0.8 and 1.6 m/min, the heat flux amounts to 1.25 – 1.59 MW/m².

Wuennenberg reported heat flux values between 2.2 and 2.5 MW/m² for slab casting at velocities of up to 4 m/min [5]. The published values for the heat flux in slab caster are therefore in good correlation with the formula proposed by Wolf over a wide range of casting speed (0.3 – 4.0 m/min).

In bloom casting with powder lubrication the observed heat flux ranges in the order of magnitude of the slab casting process: A casting velocity of between 1.2 and 1.8 m/min results in a heat flux of 1.3 – 1.6 MW/m² [6].

In billet casting with oil lubrication, the average heat flux in the mold is higher: Chow et al. [7, 8] reported values of 2.0 – 2.9 MW/m² for casting velocities of between 3.2 and 4.4 m/min. Again, the proposed formula by Wolf seems to describe the heat flux well.

It should be noticed that the heat flux is not only a function of the contact time between strand and mold but also influenced by the individual casting practice: Thermo-physical properties of the mold flux, the oscillation philosophy as well as the mold taper and the steel composition influence the heat withdrawal. To quote only one example: peritectic steels are cast with an up to 30% lower heat flux compared to low or high carbon steels, even though all often conditions are the same.

In the 1980s the process of the linking between casting and rolling process was firstly realized in industrial scale. Today, the TSCR process is state-of-the-art. Presumably, the totally installed capacity already exceeds 60 Mio. tons/a. The TSCR technology is based on an oscillating mold and powder lubrication. At present, the typical maximum casting velocity for a TSCR plant is 6 m/min [11, 13]. An increase to 8 m/min resp. 9 m/min is squarely faced by some plant operators [11, 12]. The maximum casting speed of 12 m/min is reported to be achievable – at least for a short time [9]. 8 – 10 m/min are reported as maximum possible casting speed in a system with oscillating mold by other authors [16, 17].

The main limiting factor in a further increase of the casting speed is the steadily decreasing mold powder consumption and the consequently increasing friction between mold and strand. The heat flux in TSCR molds amounts to 2.3 - 3.2 MW/m².

The direct strip casting and the thin strip casting process are commonly operated without lubricant and always without relative motion between mold and strand: Rolls or a belt move at the same velocity as the strip. In TSC the heat transfer is regulated by the wetting of the roll surface by the liquid steel. The roll surface roughness, the surface coating or even the surrounding inert gas atmosphere have an important influence on the heat flux.

The heat flux is thus much higher and ranges for the TSC process - depending on different parameters - between 8 and 20 MW/m² [e.g. 14]. The wide scattering of the measured heat flux values results from the difficulties in the fast and precise temperature measurement. An increase of the contact time reduces the heat flux to between 3.2 and 5.5 MW/m² [15].

The solidification of the steel at higher cooling rate not only has technological consequences: The higher cooling rate results in a fine solidification microstructure. Structure parameters like dendrite spacing or grain size are known to be considerably smaller compared with the conventional cast semis. Segregation – at the micro- as well as on the macroscopic scale – is also less pronounced. Even precipitations, forming during or immediately after solidification are smaller and may thus also contribute to a grain refinement. The achievement of certain strip properties therefore demands the adjustment of the entire production technology.

A first step in this adjustment process is the small scale experimental simulation of solidification at higher cooling rate. In 2002, the Christian Doppler – laboratory for “Metallurgical fundamentals of continuous casting processes” started the development of a simulation experiment that will be described in the following.

3. EXPERIMENTAL

The simulation experiment is based on the principle of a dipping test, as for example already realized by Mahapatra et al. in the 1990s [18,19]. A substrate, made from a conventional mold copper alloy - coated with Cr or Ni and with controlled surface roughness - is submerged into a steel melt at high velocity, Fig. 2. The experiment is performed inside a vacuum induction furnace under inert gas. The rectangular substrate is surrounded by a non-wetting, insulating refractory brick that prevents the solidification of the steel. Thus, a 80 mm x 40 mm flat, rectangular sample solidifies at the surface of the substrate under conditions close to the simulated process. During the dwell time in the melt – typically ranging from 0.25 s to 10 s (depending on the simulated process) - the shrinkage of the thin sample induces friction forces between the sample and the substrate.

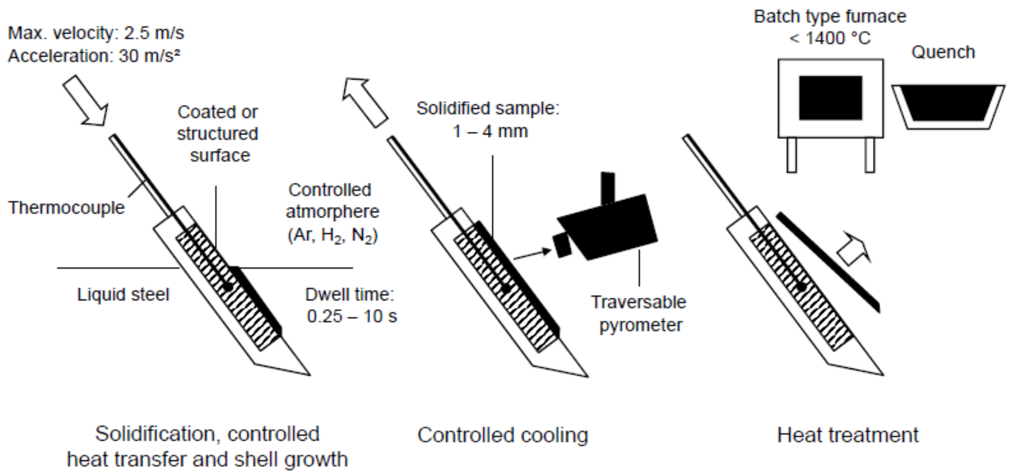


Fig. 2: Experimental procedure

The temperature increase inside the substrate is measured with thermocouples and the measured temperature is used to calculate the heat flux at the interface between substrate and sample during solidification. Fig. 3 compares different heat flux histories: A typical maximum heat flux for the dipping experiments described in this paper (Ni-coating, surface shot-blasted) amounts to 12 MW/m². The maximum heat flux is achieved after only 0.1 s of solidification. The average heat flux amounts to 6.25 MW/m² over a total solidification time of 0.75 s and fits with the tendency depicted in Fig. 1. At the Chair of Metallurgy at Leoben University different other experiments were developed: Fig. 3 shows also some typical heat flux histories from the co-called Submerged Split-Chill Tensile experiment [e.g. 22]. In this experiment, a steel substrate is submerged into the liquid steel. The substrate is spray coated with a thin isolating zirconium oxide layer. The solidification at the surface of uncoated steel substrates typically results in a maximum heat flux of between 5 and 6.5 MW/m². The average heat flux during 10 s of solidification amounts to 2.5 – 3.5 MW/m². This heat flux comes very close to the conditions in the TSCR mold. An increasing isolation thickness lowers the heat flux and thus allows the simulation of solidification in all conventional casting processes.

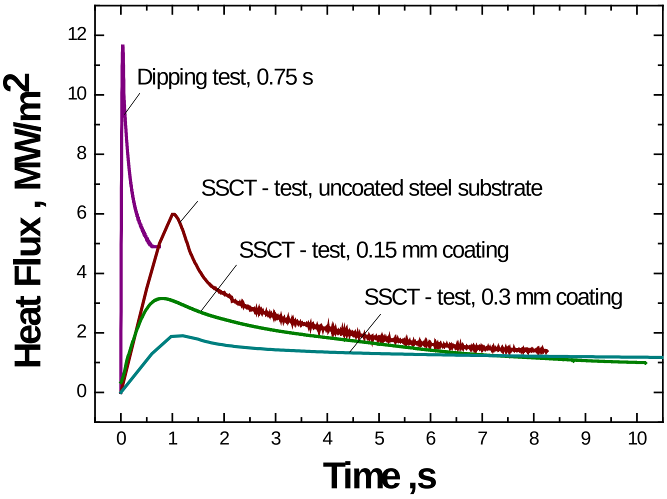


Fig. 3: Heat flux for different experiments

The heat flux at the interface between the substrate and the sample is the thermal boundary condition for a 2D-FE-model of the experiment, based on the commercial software calcosoft 2D. The numerical model enables the calculation of shell growth during solidification and the subsequent cooling of the sample. A new pyrometer system allows the measurement of the temperature of the sample after emerging from the melt. This provides the basis for the validation of the numerical model. Fig. 4 gives an example for measured and calculated shell thickness (for solid fraction 0.2) after 0.25, 0.75 and 2 s of solidification. The longer residence time in the melt results in a higher shell thickness of the bottom part of the sample. The handling of the sample outside the furnace will briefly be covered in the next section.

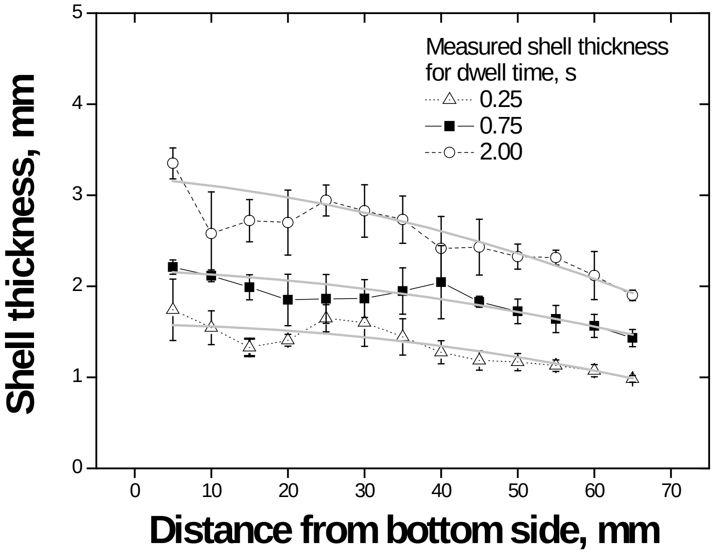


Fig. 4: Measured and calculated shell growth for different dwell times

4. RESULTS

Fig. 5 shows an example for the microstructure of a solidified sample with 0.07 % C, 0.2 % Si, 0.9 %Mn and increased P content of 0.04 %, etched in picric acid. Due to the higher P content, the columnar solidified structure is clearly visible in this example.

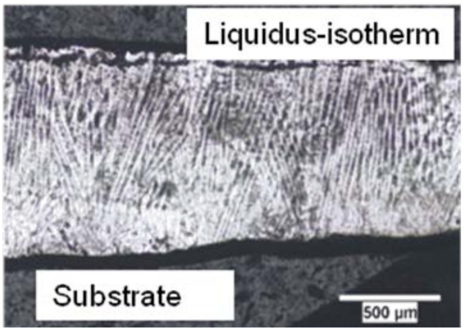


Fig. 5: Micrograph with microstructure of solidified sample (0.07 % C) [20]

Fig. 6 and 7 show results from the microprobe analysis (concentration mapping for Si and Mn) of samples from two different steel grades: one with 0.06 % and the other with 0.3 % percent carbon steel. Comparing conventionally cast products, the enrichment of Mn and Si is less pronounced. Even the columnar structure is not clearly visible. This demonstrates one of the main advantages of solidification processes at higher cooling rate: the higher solidification velocity results in a fine primary structure, favouring the back diffusion during solidification and thus lowering the enrichment of segregation elements.

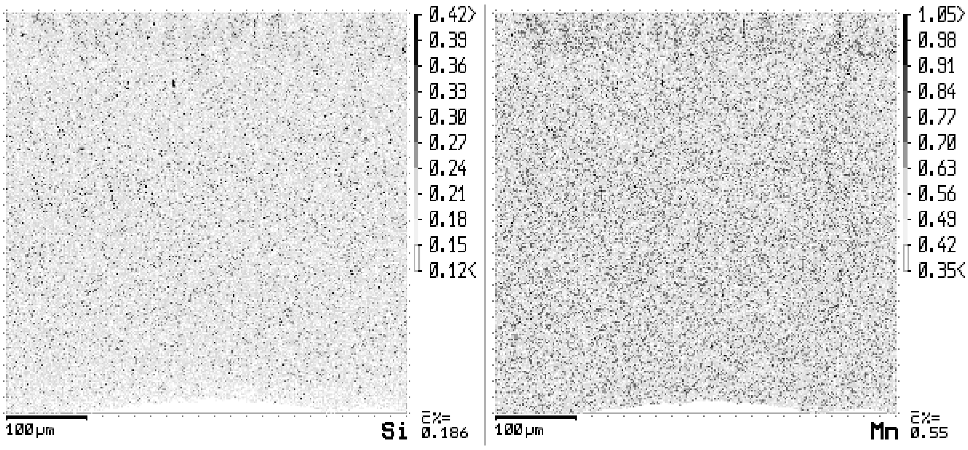


Fig. 6: Concentration mapping for Si and Mn, 500 µm x 500 µm sample from dipping test, 0.06 % C, 0.2 % Si and 0.55 % Mn

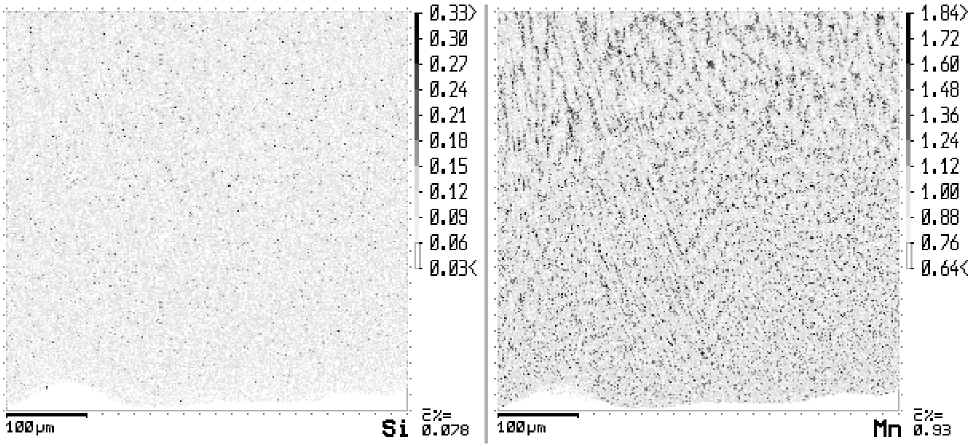


Fig. 7: Concentration mapping for Si and Mn, 500 µm x 500 µm sample from dipping test, 0.3 % C, 0.08 % Si and 0.9 % Mn

The arising tensile stress inside the sample results in the formation of micro cracks, Fig. 8. The number and length of these cracks are quantified in a subsequent metallographic examination and are finally correlated with the experimental parameters, as – for example – the steel composition, shrouding gas composition and characteristics of the substrate (coating, roughness etc.).

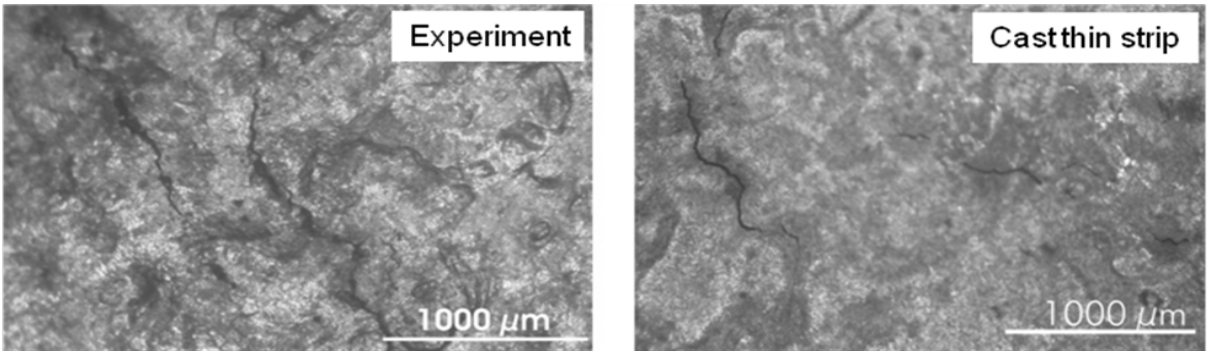
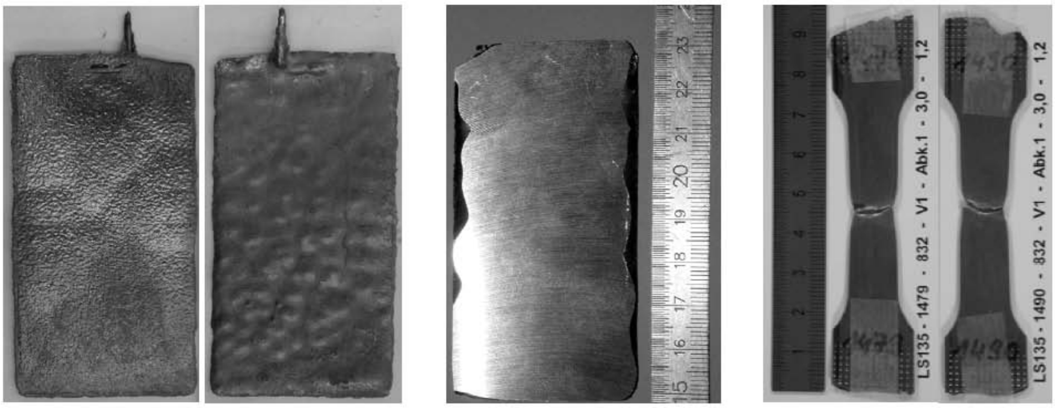


Fig. 8: Surface cracks in samples from dipping experiments (left side) and from a thin strip caster (right side), 0.07 % C [20]

The previously described procedure permits detailed studies of the effects of the listed parameters on the surface quality of samples from all kind of steel grades. The vacuum furnace allows the simulation of most secondary metallurgical processes and also the accurate adjustment of the composition of non-metallic inclusions in the steel melt.

A further important step in the development of the method was the installation of a pyrometer in order to measure the temperature of the sample after emerging. The temperature differences over the cross section of the sample are not only important indicators for the existence of microcracks. The temperature control during the cooling of the sample allows by now also the heat treatment of the sample. Once the temperature of the sample equals a given certain temperature, the solidified sample is removed out of the cooling chamber and either moved to a heat treatment furnace and/or quenched in a cooling medium. This allows the simulation of the secondary cooling zone in a TSCR plant as well as the cooling of the strip in the TSC process.

After cooling down to room temperature the samples are ground, polished and prepared for a tensile test, Fig. 9. Fig. 10 shows an example from tensile tests on a 0.07 % C steel after unaffected cooling to room temperature. The tensile strength amounts to 720 MPa and the strain at failure amounts to appr. 17 %. Both values are remarkable.



Solidified sample

Sample after grinding and polishing

Tensile specimen

Fig. 9: Preparation of the tensile specimen from the solidified samples

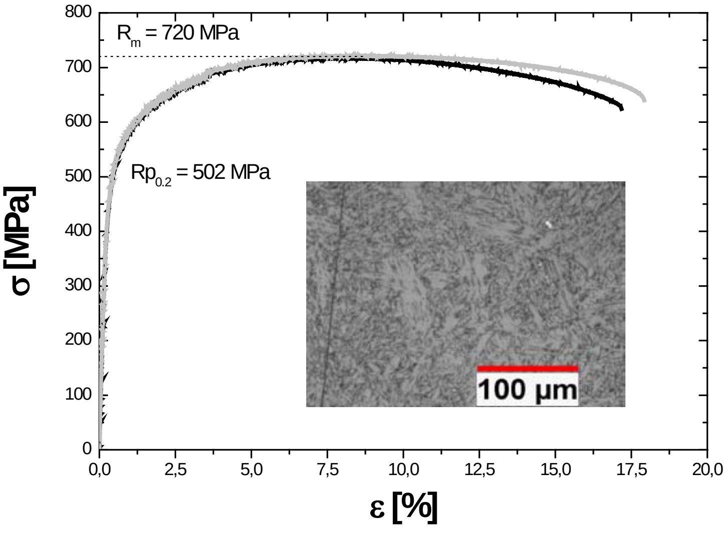


Fig. 10: Results from tensile tests on 0.07 % C steel, unaffected cooling.

5. SUMMARY

Casting processes at higher cooling rate comprise mainly the TSCR and the TSC process. The former is characterized by an average heat flux in the mold of 2.3 - 3.2 MW/m², the latter by an average heat flux of more than 6 MW/m². In both cases the average heat flux depends on the dwell time in the mold and thus on the casting velocity.

The present work describes a laboratory experiment for the simulation of solidification and subsequent heat treatment in these processes. The experiment was both used to characterize the interaction between the main casting parameters and the quality of the solidified sample as to characterize the mechanical properties of the solidified sample with or without heat treatment. Both possible applications are exemplified.

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