PHYSICAL SIMULATION OF METALLURGICAL PROCESSES

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Abstract
The worldwide demand of improving quality and efficiency of metallurgical processes, while simultaneously maintaining low costs of the products, stimulates intensive research to reach these goals. In this respect, any running of full-scale industrial experiments appears to be too expensive and non-acceptable. To cut the R&D costs and speed-up implementation of new technologies, physical and numerical simulations of metallurgical processes become widely used. And the computer simulation can be only correct when exact data of materials behaviour at processing conditions are available. To obtain the data, physical simulation is needed, which must be executed on multi-purpose thermal-mechanical testing devices able to accurately reproduce the real industrial processing conditions. For continuous casting or metal forming, this refers to individual phases of processes or multi-step operations characterized by their time, temperature, and by applied forces, strains and strain rates. Actually the physical simulation allows in a fraction of time for a fraction of cost an improvement of existing technology or development of a new one for modern materials and products. The physical simulation is also effectively used for solving production problems related to solidification phenomena or deformability limits, such like these resulting in hot cracking. In this paper are mentioned methods of physical simulation related to continuous casting and metal forming processes as well as highlighted some recent developments of physical simulators.

1. Introduction

Physical simulation actually finds its place between the computer simulation and industrial process. It deals with real time and energy and its aim is to gain physical data of the processed material. Such data describe the behaviour of material in the specific conditions of the real process or application and are also useful for exact computer calculations.

Historically, welding has been the first metallurgical process successfully studied by the simulation technique, in particular the use of simulated thermal cycles to reproduce the situation occurring in parent plate material affected by heat generated during welding. Further development of this technique led to an introduction of several testing procedures aiming to exactly replicate various situations in the weld metal or between the welded joint and adjacent material, in particular these occurring due to the stress relaxation and plastic accommodation processes during multiple heat cycling characteristic of multi-pass welds. The necessity to apply physical simulation for studying ductility and fracture behaviour of heat-affected zones of welds, occurred just after WW-II and was associated with cracking of the high-strength steels introduced to shipbuilding [1]. In 1949 the first welding thermal cycle simulator was developed and utilized to generate uniform heat-affected zone microstructures through the CVN-sample for impact testing [2]. At that time, using the simulation, the results of impact strength appeared to be often better than on real welds. This discrepancy initiated more detailed studies on physical phenomena standing behind the toughness of weldments, which
study revealed the role of thermal gradients in generating crystallographic lattice defects to plastically accommodate various micro-strains and affecting phase transformations in steels. Accordingly, the thermal-cycle simulator was equipped with a mechanical system capable to deform specimens with adequate speed at exact temperatures. When this was done, the Gleeble thermal-mechanical simulator was born [3]. Since 1957, when the first commercial Gleeble was produced for the purpose of weld heat-affected zone simulation, it has experienced several metamorphoses and the recent dynamic thermal-mechanical simulators allow the use of physical simulation techniques not only for welding but also for other industrial application processes, such as high strain rate multi-step hot forming including all kinds of thermal-mechanical processing, melting and controlled solidification for the purpose of conventional casting and continuous casting and semi-solid processing, checking for susceptibility to hot cracking and embrittling, studying sintering, stress relaxation, accelerated creep, thermal-mechanical fatigue, and others.

The main concept of the thermal-mechanical simulator, however, has not been changed much since the beginning, and the actual Gleeble system comprises: an AC electric resistance heating system as it was originally, a mechanical deformation system which earlier was pneumatic and now is servo-hydraulic, a vacuum and/or controlled atmosphere working chamber, and like in all the most recent testing equipments the computer control plus data acquisition and processing. For specific applications it may comprise various working units and attachments. And like at the beginning, the main aim of the physical simulation is to exactly reproduce the thermal and mechanical situation of the workpiece material as it appears in real processing. In the historical case of welding and its vulnerable to embrittlement and cracking heat-affected zone (HAZ), during the electric arc action a short thermal cycle appeared comprising a rapid heating, followed after reaching peak temperature by a cooling due to heat flow from the hot zone of the weld towards the cooler bulk of the material. The heating and cooling rates result from the balance between the energy input and the heat flow, and are controlled by thermal gradients between the hot zone of the weld and the parent plate. During the thermal cycle the electric current flows through the HAZ and the heat flows from the fusion surface between the weld and the plate to form isothermal planes perpendicular to this main direction of flow. This situation has to be reproduced on a bar-like sample in which a narrow uniformly heated zone is formed in the middle due to the thermal balance between the electric heating and the heat flow, and are controlled by thermal gradients between the hot zone of the weld and the parent plate. During the thermal cycle the electric current flows through the HAZ and the heat flows from the fusion surface between the weld and the plate to form isothermal planes perpendicular to this main direction of flow. This situation has to be reproduced on a bar-like sample in which a narrow uniformly heated zone is formed in the middle due to the thermal balance between the electric heating and the heat flow towards cold copper jaws, producing real temperature gradients, Fig.1. During the thermal cycle, a part of the HAZ material of at first expands on heating and then is compressed being restrained crosswise by the cold portions of the parent material, while in the second portion of this cycle the faster cooling down thermal gradient zones once again compress it. In this second part of the thermal cycle, tensile strains appear in the main heat flow direction, and they may assist embrittlement due to generation of dislocations and interaction of these with interstitials [4], or even initiate cracking by “an internal necking”. The magnitude of this phenomenon can be illustrated in the following test. On samples like drawn in Fig.2, tested for phase transformations by contact-less laser dilatometer, at the cooling rate of 100°C/sec obtained in the central heated gauge zone by heat transfer to cooler mounting portions of the sample and to cold copper jaws of the Gleeble, a permanent shrinkage of diameter occurs after the thermal cycle, Fig.3. At the lower cooling rates of 30°C/sec and below, which cause weaker temperature gradients, such permanent change of sample’s diameter can be negligible, Fig.4.
Another factor contributing to the accuracy of physical simulation is the apparent strengthening of material when its plastic flow is restrained during testing at elevated temperatures. For example, in hot tensile testing, depending on the length and diameter of the uniformly heated zone, different results of hot ductility may be obtained. The following Fig.5 shows sets of pearlitic-ferritic (upper row) and austenitic stainless (lower row) steel samples, hot tensile tested at the same elevated temperature with the same extension rate. Noticeable are differences in reduction of area in the neck portions of these samples. The samples with narrower hot zone deform before fracturing to a lesser extent and at a higher force, Fig.6.

Finally, the size and performance of the mechanical / deformation system is also going to play its role. The actually most popular dynamic servo-hydraulic systems do not allow directly any instantaneous acceleration and deceleration and their performance is much dependent on the size of masses which have to be moved as well as on the strength and related response of the tested sample of material, in this last case including internal changes which occur in the material during the simulation processing. So, the largest and strongest machines very often “hide” numerous effects related to the material behaviour during the simulation while too weak machines working on too small samples miss various important factors of the deformation like e.g. crosswise strains induced by thermal gradients, or generate false microstructures resulting from inadequate volume of the transforming material.

Fig. 1 Weld HAZ simulation in Gleeble on 10mm round-bar sample mounted in “cold” copper jaws.

Fig. 2 Schematic drawing of Gleeble sample for laser dilatometer studies of phase transformations in steels with cooling rates up to 200°C/sec.

Fig. 3 Laser dilatometer curve of HSLA steel heated up in Gleeble to 1020°C and cooled by heat flow with rate of 100°C/sec

Fig. 4 Laser dilatometer curve of HSLA steel heated up in Gleeble to 1020°C and cooled by heat flow with rate of 30°C/sec
3. Physical simulation in metallurgy

The physical simulation actually plays an important role in the design and application of the most efficient industrial manufacturing process, which is the continuous casting and the following hot rolling. As shown in Fig. 7, in different stages of process may occur flaws such as shrinkage cavity, centre-line porosity, facial and corner cracks. Physical simulation can be used to determine flawless processing parameters, without interrupting of production.

3.1 Continuous casting

In the first phase of process like schematically shown above, the liquid metal is poured into a crystallizer chambre in which its outer shell has to solidify to the extent securing the liquid core inside. When a vertically cast slab or billet has to be bent into horizontal position, the ductility of outer shell must allow this. Gaining physical data for such operation includes melting and solidifying of a sample in Gleeble, such as a 25mm diameter bar, and deforming it by compression after a partial solidification. The heating-cooling balance of Gleeble causes
in the sample thermal gradient to occur keeping molten core inside when outer shell solidifies. The test called Strain Induced Crack Opening (SICO) gives critical strain to fracture, strain rate and temperature, and in the case of incomplete solidification reveals thickness of outer shell on crashed sample, Fig.8. Distribution of strains in the SICO sample can be determined by numerical simulation [6]. Having known the strain distribution and temperature gradient as well, valuable information can be gained from cross section of the sample like given in Fig.9: cracks at maximum perimeter occurred at temp of 1385\(^\circ\)C and 0.35 strain with 0.5/sec strain rate, then no-crack zone at ~0.5 of radius appeared representative to temperature ~1400\(^\circ\)C and strain of 0.2, and once again cracks in the middle of the sample were formed representative to strain ~0.05 at temperature of ~1425\(^\circ\)C, the last is the nil ductility temperature of tested steel.

3.2 Hot cracking

The SICO and hot tensile tests are effectively used for studying phenomena related to continuous casting and conventional casting processes, in which susceptibility to hot cracking occurs. This refers also to hot cracking of welds [7]. For the most recent developments in continuous casting processes, such as direct thin strip casting, dedicated physical simulators have been built, like HDS-V40 [8], allowing after melting and solidification with controlled dendrite size and growth direction to perform multi-step high rate deformations representative to multi-stand rolling. Nevertheless, the conventional multi-functional physical simulators are always useful to provide complimentary information, as for example at corner cracking of hot rolled billets. The corner or near-corner cracks may occur when the flow of material to the corner of billet is hampered by thermal gradient – lower temperature of the corner, Fig.10a. This situation schematically given in Fig.10b, shows that normal force exerted by rolls causes material flow in the rolling direction as well as towards the corners, while the plasticity of the material along the cooler corners is limited.

To physically reproduce this situation a two-step SICO test may be used. After forming a bulge in the first compression deformation, an air (or inert gas) blow is locally applied to produce the thermal gradient like in the real situation, and when this gradient is achieved the second compression is applied, with adequate strain rate, till the cracks appear. This procedure gives the amount of strain to fracture at certain strain rate, at controlled temperature and real temperature gradient – it is not easy to gain all these data simultaneously in any other simple and continuous test.
3.3 Hot rolling: Gleeble–Hydrawedge system

An exact simulation of multi-step hot rolling by plane strain compression test requires constant strain rates to be maintained in each step with an instantaneous stop at the end of deformation. To achieve such characteristic of Gleeble’s servo-hydraulic system, a special deformation-assisting device called Hydrawedge was designed and implemented by DSI [9]. The Hydrawedge, synchronized with the main / primary deforming system, is acting as a flexible mechanical stop that allows the primary hydraulic ram to be stopped by running into an immovable object. In order to perform exact multiple compressions sequentially, for which the specimen must be moved since the main hydraulic ram will stop at the same point in space each time, the Hydrawedge is used to program the displacements. This allows to exactly control the amount of strain, while simultaneously and separately controlling the strain rate at which the sample is being deformed. Without such device, all fast servo-hydraulic machines or give substantial over-travel or must slow down before stopping at the right sample’s height. In the first instance other than programmed strains are generated while in the last case final microstructures are generated characteristic of slower than programmed strain rates.

In Fig.12 the schematic of Hydrawedge is given and its operation explained. In the system consisting of main power piston (M), punch with stop (P), yoke (Y), sample (S) and Hydrawedge piston (H), before deformation the system is in position like drawn in Fig.12(a). Preparation to deformation includes pulling off the main piston (M) to form a gap “g” between it and punch (P). Simultaneously the Hydrawedge piston (H) pushes the sample (S) and punch (P) to set-up the amount of required deformation between the punch’s stop ring and the yoke (Y), Fig.12(b). Finally in the deformation step, Fig.12(c), the main piston accelerates through the gap “g” reaching the required top speed, then during the deformation decelerates in a programmed manner to maintain constant strain rate, and when the stop of the punch (P) hits the yoke (Y), the deformation is finished with high accuracy. Such steps can be then repeated several times.
An application example, which follows, shows how the physical simulation can be used to generate various as-hot-rolled microstructures. A HSLA steel, used for manufacturing of hot rolled plates in a 7-step continuous process, after such procedure achieves an acicular ferrite / upper bainite microstructure, with very uniform grain size across the plate thickness, like given in Fig.13. On this steel an attempt was made by physical simulation on Gleeble, to refine grains, separate the phases, achieve a dual-phase microstructure, and to reduce amount of deformation steps. For this a five-step procedure was programmed with three initial steps in austenite phase, maintaining strains, strain rates, as well as interpass times adequate to preserve and/or to additionally stimulate precipitation of fine carbides. The last two steps were executed in the austenite-ferrite two-phase region. In these final steps an attention was given to dynamic and static recovery / recrystallisation of ferrite. The last deformation was followed by a short hold and then rapid cooling, i.e. quenching by water spray. The resulting fine-grained microstructure, which formed mainly in shear-bands, is shown in Fig.14.

Light microscopy was not able to resolve its details; for describing these the scanning electron microscopy as well as transmission electron microscopy appeared more informative. In the following Figs 15 and 16, well recrystallised ferrite grains can be seen and the second phase - martensite islands between the ferrite grains. In this microstructure high dislocation density appears near to the martensite islands, as an evidence of the high strength.
Conclusions

1. Up-to-date physical simulation procedures allow studying materials behaviour at conditions very close to real industrial processing or applications.
2. The process parameters such like temperature, sense and amount of strain, strain rate as well as thermal gradients can be adequately reproduced and their values accurately recorded.
3. By means of physical simulation a large variety of microstructures and associated mechanical properties can be obtained and studied in a short time and for a tiny fraction of full-scale industrial experiments.
4. The materials behaviour data gained from physical simulation experiments can be further used in computer modeling and control of the industrial manufacturing processes.

References


Fig. 15 Elongated recrystallised ferrite grains in deformation bands of HSLA steel after the 5-step physical simulation of rolling

Fig. 16 Dual-phase microstructure of HSLA steel comprising ferrite with high dislocation density surrounded by martensite islands