Steel - a Classic Material with a Large Potential for the Future

B Masek, H Jirkova, D Aisman and S Jenicek
University of West Bohemia
Univerzitni 22, 306 14 Pilsen
bohuslav.masek@mb.tu-chemnitz.de

Abstract. Steel is a traditional material which has been used by mankind for more than five thousand years. We may therefore be tempted to believe that we know practically everything about steel and its forms and variants which offer an extraordinary and broad range of properties. It is this diversity of properties which makes steel such a popular and widely used material. And yet, in recent years new opportunities have emerged for processing steel by unconventional techniques and producing novel, as yet unknown or unusual microstructures. This paper describes several examples of how microstructure evolution can be modified and how new and unconventional processing routes can be developed. These examples present several results of projects carried out in recent years by FORTECH Research Centre of Forming Technology and the University of West Bohemia in collaboration with their research partners.

Keywords. AHSS, UHSS, semi-solid, thixoforming, mini-thixoforming, TRIP, Q-P, ODS

1. Introduction
The fact that steel is one of the most important technical materials – and the most widely used technical metal – is and will probably remain indisputable in the near future. The key element found in steel is iron. Iron’s allotropic transformations are the source of the diverse forms of steel microstructures. The amount of iron in the space is fairly large because iron is the last stable element produced by the nuclear reactions which take place while stars are burning out. This is the reason why Earth is so rich in this raw material. Although a majority of iron is embedded within deep-lying layers of our planet, the Earth’s surface always offered enough iron and iron ore for steel to become the essential material that fuelled the mankind’s evolution and civilization over the millennia.

Since the conventional structures found in steels – ferrite, pearlite, bainite and martensite – are well known, this article focuses on examples of development of unusual mixed microstructures attainable only by means of unconventional routes or by innovative technology chains.

2. Semi-solid treatment and rapid solidification
The first unconventional route involves steel solidifying at a high rate during cooling from the freezing range. This process is known as thixoforming. In high-alloy steels, the resulting structures typically consist of metastable austenite and carbides [1-4]. Most often, the metastable austenite takes the form of polygonal grains embedded in carbide network (Fig. 1). Thanks to being super-saturated with respect to multiple elements, this austenite exhibits relatively high stability and good deformation ability. Nevertheless, the presence of the carbide network means relatively high brittleness and poor toughness. Therefore, efforts were begun to remove these drawbacks. One of the available solutions is
alloying with elements which form carbides with high thermal stability. Such carbides do not dissolve during heating to semi-solid processing temperatures and remain present in the melt. After the material cools rapidly, these act as nuclei for crystallization and, finally, become dispersed particles within a ductile austenitic matrix [5-7]. Consequently, the resulting microstructure is inverted with respect to structures that form during conventional thixoforming (Fig. 2).

**Figure 1.** Structure of X210Cr12 steel after thixoforming; left: overview of the microstructure under light microscope; right: detail scanning electron micrograph of lamellar network

**Figure 2.** Inverted microstructure in CPM15V steel after thixoforming

3. **New oxide dispersion-strengthened steels**

For some applications, namely for operation at high-temperatures, steels must be specially modified to prevent degradation of their mechanical properties. During high-temperature exposure, carbides – which are normally used as the strengthening constituent – become the weak spot. For this reason, ODS steels (Oxide Dispersion-Strengthened Steels) have been developed, in which oxide particles are used to strengthen the matrix, instead of the carbides [8, 9]. As these oxide particles exhibit much better thermal stability than carbides, these steels promise to be usable in high-temperature applications in the future. However, there is a major drawback related to the manufacture of these steels which normally involves embedding the oxide particles in the matrix by mechanical alloying. The procedure is demanding and sometimes fails to produce the desired fine and uniform dispersion of strengthening particles in the matrix. If the required properties are to be guaranteed, this is the major
problem that needs to be solved. An alternative procedure was thus proposed, in which oxides precipitate in the matrix which is super-saturated with respect to oxygen. This produces a good distribution of the strengthening oxide particles and reduces their size to several nanometres (Fig. 3). It is also corrosion resistant to temperatures of 1200°C. Thanks to its extraordinary properties, such steel can be expected to find use in high-temperature and other applications.

Figure 3. The new generation of ODS steels developed in collaboration with Dr. Svoboda from IPM Brno in 2016

4. AHSS and UHSS – low-alloy steels for the future

Intensive development can be seen recently in the fields of AHSS (Advanced High Strength Steel) and UHSS (Ultra High Strength Steel) [10-12]. Both groups comprise a majority of low-alloy steels or steels with cost-effective chemistries whose final properties are obtained by sophisticated treatment. In order to produce the desired structures, and therefore the required properties, the compatibility of the requirements of manufacturing processes and the limits of microstructural evolution should be taken into account for developing the manufacturing processes. Thanks to high-quality monitoring instruments and accurate manufacturing process control tools being available today, the extent of the potential of advanced multiphase steels which can be actually exploited is much greater.

Three main process types are mentioned with respect to producing AHSS-type structures. These include: intercritical processing used for TRIP steels (Transformation Induced Plasticity) [10], Q-P processing (Quenching and Partitioning) [12] and long-time austempering. As the last-named process still involves too long annealing times, it is not suitable for industrial use yet. Hence, only the first two processes were chosen for this demonstration and obtaining AHSS structures in TRIP and Q-P types.

5. Warm-formed and cold-formed TRIP steel

The following technology chain [13, 14] (Fig. 4) was developed for manufacturing products of TRIP steels with simple chemistries involving 0.2 % carbon and various amounts of manganese and silicon.

Rolled bar feedstock is heated to a warm-forming temperature and incrementally formed by rotary spin extrusion into a hollow semi-finished product with a deep axial blind hole. This formed part is then annealed in the intercritical range between the AC1 and AC3 temperatures, held at a bainitic transformation temperature, and finally cooled down to ambient temperature. This produces a TRIP microstructure with ferrite, bainite and metastable retained austenite (Fig. 5).
This mixed microstructure generally offers high plasticity characterized by a value of approx. 30%. The material is therefore very suitable for cold forming. Originally, steels of this kind were developed for the automotive industry for absorbing large amounts of energy in a crash. This ability to undergo plastic deformation can be used for achieving the prescribed deformation in cold forming. This was the case in the present technology chain, where hollow feedstock with a TRIP microstructure was formed by cross rolling to produce multiple steps. This profound deformation causes deformation hardening of the material and transformation of retained austenite to martensite. Furthermore carbides are fragmentated (Fig. 4). The resulting stepped hollow semi-finished product which received no further heat treatment showed a strength of about 1000 MPa and an elongation of approximately 10%
(Fig. 6). By this process, a hollow, thin-walled and very lightweight product was obtained just by plastic deformation without any machining operation.

**Figure 6.** Stepped hollow semi-finished product of TRIP steel

### 6. Q-P process integrated into an internal high-pressure forming (IHP) route

Another example of new processes which have been specially developed for AHSS and UHSS steels is the process chain for making ultra-high-strength complex-shaped hollow semi-finished products (Fig. 7). It combines several high-tech aspects, most importantly the Q-P process and IHP forming. The entire process sequence is as follows [15-17].

**Figure 7.** Technology chain combining internal high pressure forming, hot stamping and Q-P process

The feedstock material is 0.42 % carbon steel with a cost-effective chemistry containing manganese, silicon and chromium. The feedstock is a thin walled tube which is heated to the forming temperature of 1000 °C. It is then placed into a split die and inflated using nitrogen gas at high pressure until it comes into contact with the die walls (Fig. 8).
This leads to partial quenching as the die is pre-heated to 200 °C. Martensite forms in the microstructure but some austenite remains untransformed due to incomplete quenching. To prevent the retained austenite from transforming during further cooling, the semi-finished product is placed into a furnace at 250 °C for several minutes. At this temperature, carbon diffuses from martensite into retained austenite. The internal stress in the martensite is relieved and the austenite becomes stabilized by this chemical process. The resulting mixed microstructure consists of martensite whose brittleness has been suppressed and retained austenite with good plasticity (Fig. 9). It offers high strength in excess of 2000 MPa and adequate elongation for the service use of approx. 10 %.

Figure 9. UHSS-type mixed martensitic structure with low fractions of bainite, ferrite and retained austenite produced in 42SiCr steel using a manufacturing route with integrated Q-P process

7. Summary
Steel – and its treatment – continues to demonstrate its broad innovation potential. Under the pressure from a number of sectors, such as automotive and transport engineering, power generation and manufacture of machines, equipment and tools, research is pursued continuously, yielding new ways of using steels. New types of steels with their sophisticated structures and excellent properties can compete with other alloys, such as non-ferrous and light metals in various applications. In addition, steel is fully recyclable and can be produced using an acceptable amount of energy. Therefore, it will remain a significant material in the future, offering a broad range of options in both traditional and novel applications.
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