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A New Opportunity for the Design of Advanced High Strength Steels with Heterogeneous-Phase Microstructures via Rapid Thermal Processing

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Abstract

In the following paper, the developments in Advanced High Strength Steels (AHSS) that are used in automotive industry are summarized. AHSS show good formability while maintaining high strength values. These properties can be achieved via grain refining, mixed ferritic microstructures and by leveraging phenomena such as Transformation Induced Plasticity and Twinning Induced Plasticity (TWIP). However, time and energy consuming thermal processes as well as expensive alloying additions should be employed in order to achieve these properties. The new era of AHSS requires combinations of greater strength – ductility via ultra-grain – refined ferrite, martensite, bainite and austenite at a cost significantly less than the previous grades. It is envisaged that microstructural evolution under the effect of ultra-fast heating and the subsequent quenching or air cooling may result to a new outlook for alloy design. The key aspect in this technological possibility is the effect of chemical heterogeneity in the initial microstructure. The inhomogeneous microstructure remains unchanged due to the rapid reheating as a result of the restriction of the time available for solid state diffusion. A promising example of such technology is the single-stepped reheating of steel which, although unconventional, has been observed to lead to complex microstructures of chemical heterogeneity.

Keywords: Ultra-fast heating, Phase transformations, Rapid reheating, Ultra-fast annealing, TEM, Undissolved carbides, Martensite, Bainite, Phase diagrams, 42CrMo4, Automotive, Austenization, Kinetics, TRIP, TWIP, Complex Phase, TRIP-effect, Multi-phase, Mixed bainitic-martensitic microstructure, Advanced high strength steels.

Overview of the evolution of 1st and 2nd Generation of Advanced High Strength Steels

Within the last five decades steel was and still remains the most important material for a variety of applications ranging from construction, automotive, special engineering applications, naval, nuclear and various other purposes. The industrial application was based on high strength steels (HSS) such as high strength low alloy (HSLA), interstitial free (IF) steels that were developed during the 1970-1980. Especially, the advanced high strength steels (AHSS) of the first generation i.e. dual phase (DP), transformation induced plasticity (TRIP) and complex phase (CP) that were industrially released during the years 1990-2000 were fully exploited by the automotive industry contributing to safer and more light weighted automobiles that consumed less fuel resulting in lower emissions. After 2005 and until 2010 the second generation of these steel grades (AHSS 2.G), i.e. the twinning induced plasticity steels (TWIP) was introduced driving the production cost in the sky as a result of their high alloying element content (e.g. high manganese – Mn). Still TWIP steels could not make it to mass production. Nowadays efforts to reduce cost drives the alloy design in reducing the Mn content of TWIP steels and to fully exploit the potential of TRIP and TWIP effect [1-3].

The volume fraction, morphology and distribution of retained austenite and/or martensite strongly affect mechanical properties of AHSS [4-6]. In these materials (TRIP, TWIP, CP, PM) necking and fracture are subdued and pushed to large strains due to continuous work hardening, the latter determined by the heterogeneous distribution of dislocations 6. The increase in overall interface density -induced by the additional phases- could also improve mechanical properties [7-10]. On the other hand, TWIP and Quenching & Partitioning (Q&P), which should, in principle, enhance the TRIP steels, have, on the whole, not been achieved. For example, TWIP steels exhibit delayed fracture and are considered unsafe for structural implementations, while Q&P steels involve complex heat-treatments which are forbidding for large scale applications [4,11,12].

Overall, the main strengthening mechanisms, i.e. solid solution, carbide strengthening, TPIP and TWIP effects, are well established concepts accompanied by streamlined technologies [2,4,11-16]. Invariably, the design of steel alloys adheres to the central principle that co-existence of soft and hard phases leads to favorable combinations of strength and ductility via optimal stress/strain partitioning [2,4,17-18]. However, structural design might also pivot on the improvement of the ductility of multiphase systems, in which optimization of the fractions of the various phases will inevitably become essential [4]. Current research on the design of steel alloys focuses on the use of ultrafine grained phases as well as on phase hardening by ferritic and bainiticnano-precipitates. However, there is still ample potential for the utilization of new ways to enhance hardening, which are not purely based on ferrite grain refinement [2,4,8,19-21].

Ultra – Fast Heat Treatments – Advanced Ultra High Strength Steels

One alternative promising approach is to apply rapid thermal cycles. The application of ultrafast heat treatments limits macro-diffusion, can affect phase transformations and contributes to grain refinement. Rapid thermal cycles can be used as a tool to design and produce high strength complex phase which will be responsible for very high mechanical properties. With the aid of experiments (ultra-fast cycles applied using dilatometry and Gleeble) and modeling (Thermocalc and Dictra) we try to shed light to the following points:

1. What is the nature of ferrite to austenite transformation during ultrafast heating (UFH)?
2. What is the effect of the stored energy in austenite grain growth, when residual stresses are being massively released due to the rapid re-heating?
3. What is the role of chemical heterogeneity introduced by rapid reheating (UFH) in the subsequent austenite decomposition?
4. How can an alloy be designed to best exploit the rapid thermal cycles and to stabilize the austenite to be retained at room temperature (in order to stimulate a TRIP-effect)?
5. Novel design ideas for advanced ultra-high strength steel (AUHSS) grades: The phenomena related to ultrafast heat treatment are complex to conceive, understand and analyse. Can the fundamental understanding and later control of these phase transformations change the steel design?

By modifying and refining the martensitic morphology via novel processing routes, the material's tensile strength (TS) is pushed to higher levels. In fact it has been suggested [8,17,22] that both toughness and ductility could be increased through the formation of mixed bainitic/martensitic microstructures produced with austempering treatments at 125-350 °C for up to 240 h. One such promising route is via the application of rapid thermal cycling. When rapid thermal cycles are applied in common quenched and tempered steel grades, multiphase microstructures can be obtained in a single step. This approach has been utilized for years to achieve surface hardening, while the exploitation of properties arising as a result of the application in bulk steel was first introduced by G. Cola [5,15] in his so called "flash process"; in that, a very short-time heat treatment process involving flame heating and water quenching managed to produce when applied to an AISI4140 steel a yield strength (YS) of 1.4-1.5 GPa, a tensile strength (TS) of 1.8-2.0 GPa and 7-8% for total elongation (TEL), surpassing those of advanced high strength steels. By using a common low-alloyed medium carbon steel grade, Cola's work produced a very fine, multiphase microstructure with properties equivalent to the ones obtained by other well established AHSS heat treatments. Coupled with that advancement, there is a recent trend to reduce the number of the extra-long austempering steps. Examples of such work are the research of Belde et al. [20] who tried to develop a complex multiphase system and that of Zhang et al [4] who demonstrated the effect of dispersoids acting as containers of specific alloying elements ("vessel phases"). Such chemical gradients within the microstructure could enable the control of the transformation behavior of multiphase metals and alloys. Again, multiple day-long heat treatments (e.g. 2 h at 1200 °C followed by 47 h at 750 °C under Argon atmosphere) are always necessary to create an enhanced microstructure.

Preliminary Results

The goal of our own research is to fully comprehend and control the microstructure evolution in steel grades with different alloying contents during heat treating processes of a few seconds, which trigger phase transformations responsible for the onset of an advanced set of properties. The conditions which would trigger, control and drive selective phase transformations and which would lead to a specific mixture of bainite/martensite with retained austenite are not well defined, while they are neither controlled nor explained appropriately. The prior austenite grain size (PAGS) and the local chemical composition are expected to be the most influencing parameters. The PAGS is critical, because it affects the kinetics of the martensite transformation. In the case of UF heat treatment, a very fine austenite (4-5μm) is obtained, which retards the martensitic transformation, especially at the intermediate and final stages. If we assume that bainite transformation also occurs, the effect of PAGS is exactly the opposite due to the difference in the nucleation mechanism between bainite and martensite [21]. The heterogeneous bainite nucleation on the prior austenite grain boundaries (PAGBs) is favored when grain boundary area increases, which happens when PAGS reduces. Bainite formation kinetics is also increased in the case where pre-existing martensite has formed. In the case of an UF heat treatment, bainite could form after martensite during the UFQ (below martensite start-M_s) being favored by the small PAGS and the additional nucleation points found on martensite laths. Local chemical heterogeneity can play an important role, because it affects transformation temperatures. In the carbon rich areas austenite is more stable; so M_s is lower, and bainite can grow. If the enrichment of austenite in carbon is large enough, the austenite could be retained at room temperature. Accordingly, it has been our aim to conduct fundamental research on phase transformations which require time for diffusion when this time is not available. The scope of this effort includes:

a) The definition of the nature of ferrite to austenite transformation during UFH,

b) The examination of the role of chemical heterogeneity in austenite decomposition and

c) The design alloys which best exploit UF cycles and stabilize the austenite to be retained at room temperature.

Our initial studies conducted by applying ultrafast processing (UFP) to different steel grades have led to encouraging results [5,12-14,23]. More precisely, it was realized that the process is sensitive to the initial microstructure, the reheating speed (heating rates higher than 250 °C/s are needed), the peak temperature (T_p) and the time (t_p) spent at the peak temperature [6,12-14,23]. Altogether, we believe that the use of UF cycles may allow mixtures of bainite-martensite to be experimentally obtained. Both the research by Lolla et al. [24-26] and our own work [21] have indicated that in the case of UF treatment, a mixed bainitic-martensitic microstructure is obtained (see Figure 1).

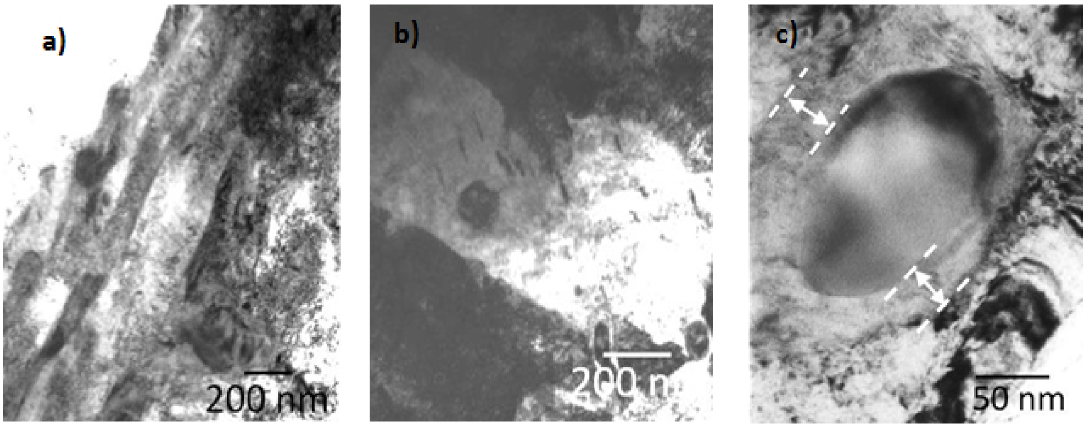

Figure 1: Transmission Electron Microscopy (TEM) micrographs showing: **a)** Martensite, **b)** Bainite, **c)** Partially dissolved carbide [21]

Conclusions

In conclusion, our current research results and the theoretic approach discussed here point out a great potential for ultra-fast (rapid) thermal cycles applied in bulk steel products. For a full exploitation of the effect of UFH, a new alloy design is mandatory. Its starting point will be an artificial but yet fully controlled inhomogeneous microstructure, which due to a focused alloying and the rapid thermal cycles applied will lead to advanced mechanical properties in one-step and with a low cost. For this reason modeling of the UFH is mandatory and our research on this field continues.

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