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Cold heading quality low-carbon ultra-high-strength bainitic steels (Coheadbain)

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The chemical composition and wire-rod production process of low-carbon, precipitation-strengthened bainitic steels were specially designed for the production of cold-headed products without heat-treating operations. The chemical composition of the bainitic steel was developed using high Ti content, in the range of 0.1–0.2 %. The experimental steel contained 0.06–0.08 % C, ~ 1.9 % Mn, ~ 0.3 % Ni + Cu, ~ 0.002 % B and ~ 0.1 % Ti. The low-carbon cementite-free granular bainite, in which the precipitation of brittle cementite is replaced by the finely dispersed MX-type carbides and a ductile second phase, is the most suitable microstructure, which fulfils the cold headability requirements. The investigation has shown that the exceptional workability of wire rod, as well as the high strength and ductility of the final products, can be achieved by developing in the wire rod during TMCP either non-recrystallised (pancaked) or, alternatively, dynamically recrystallised austenite grains with an average size of less than 15μm, followed by accelerated cooling at rates in the range 3–6 ° C/s to 500–400 °C. After accelerated cooling, the wire rod is slowly cooled in coil, which allows for intense precipitation of TiC.

Industrial trials of wire rod rolling were successfully performed. Industrial trials of cold forging of the rod and wire rod produced from the Ti steel were also conducted. The cold-headed fasteners and machinery components were thoroughly investigated. The trials finished with the production of cold-headed fasteners fulfilling the 8.8 class property requirements without the Q & T treatment.

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European Commission

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Final report

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Final summary

WP1: Selection of the appropriate steel chemistry and production of experimental material

The main result of WP1 was the design of chemical composition of precipitation strengthened bainitic steel for cold heading applications. The selection of chemical composition was conducted based on the literature review concerning bainitic steels and laboratory experiments comprising phase transformation study with deformation dilatometer and physical simulation of wire rod rolling with Gleeble 3800 simulator. The best mechanical properties were obtained in the steels with high titanium content (0.10-0.15%) and carbon content less than 0.08%. The bainite promoting elements include manganese (~ 1.9%), boron (~ 0.002%), and Ni+Cu (~ 0.4%). Within the WP1, a number of heats were produced for the physical simulation experiments on laboratory rolling mills.

WP2: TMCP processing of high strength low carbon bainitic bar and wire rod

Physical simulation experiments of wire rod rolling were conducted with Gleeble 3800 thermomechanical simulator. The purpose of the investigation was to characterize the effect of deformation parameters and cooling conditions after the last deformation, reproducing real industrial conditions, on microstructure and properties of bainitic steels. The microstructure of the deformed samples was characterized by means of light and scanning microscopy. The mechanical properties of the samples were also measured.

The rolling experiments were conducted on the reversing laboratory three–high mill at TUBA to investigate the effect of process parameters on the microstructure and mechanical properties of bars of bainitic steels. Soaking temperature prior to rolling, rolling start and finish temperature and cooling rate in the transformation temperature range were changed to characterise the effect of these parameters on microstructure and mechanical properties of the bars. The microstructure of the bars was investigated by light and scanning microscopy, and mechanical properties were measured using standard procedures.

The investigation has shown that the thermal-mechanical–microstructural response of the bainitic steel is strongly influenced by the precipitation of TiC. For most applications, austenite grain size in the range 20-30μm should be developed in rod and wire rod during rolling to obtain a very good cold headability of this semi-products and required mechanical properties of the ultimate products. However for more demanding applications, requiring high impact toughness at low temperatures, low temperature TMCP methods should be used to produce either very small–recrystallized grain size (below 15 μm) or non–recrystallized (pancaked) austenite. The finish rolling temperature in such a case should be around approximately 850°C. High strength and ductility of the wire rod can be obtained using accelerated cooling in the Stelmor line with cooling rate in the range 3 to 6°C/s. Application of accelerated cooling to the very fine or pancaked austenite in the wire rod produces very fine and uniformly distributed second phase of the granular bainite which favours high strength and ductility.

WP3: Cold heading limits map for bainitic microstructures

Two aspects related to the workability limits determination of the samples characterised by different bainitic morphologies were considered, namely: (i) the conditions for the formation of the external cracks due to the exhaustion of the material workability, and (ii) internal cracks occurrence caused by the adiabatic shear bands development during forming or the presence of brittle phase constituents. The workability limits due to the external cracks formation were determined by measuring the maximum axial and circumferential strain achievable without generating a crack. The geometries of the samples used for the cold headibility investigation comprise: solid cylindrical, ring, tapered and flanged. Using these samples allows different strain paths, in terms of proportions between axial and circumferential strain, to be followed prior to crack initiation. The investigation clearly indicated that the cold formability of the new steels is in general better than that of the standard C-Mn steels, as for example grade 1018 or 1020.

The phenomena occurring in the adiabatic shear bands (*ASB*) were investigated by the formation of rivets out of the rod samples, at high strain rates, using the die for the simulation of cold heading developed at IMZ. An ultra-fine and well developed substructure was observed in all heavy deformed

grains. The coarse grains developed coarse substructure and the fine grains were extremely elongated and were divided into a sequence of ultra-fine subgrains. The dislocation density inside the heavily deformed grains was relatively low, indicating that a significant recovery occurred during cold heading.

All tests showed a very good performance of the cold heading dedicated granular bainite microstructures in terms of defects formation at the surface and within *ASB*, which is comparable to that of *DP* steels used for the fasteners production. The best cold headability was observed for the granular bainite microstructure composed of very fine grains, both, of bainitic ferrite and uniformly distributed and stable second phase. On the contrary, the presence of the stringers of high-carbon autotempered martensite islands eases the crack initiation. The cracks were also initiated on elongated non-metallic inclusions.

The constitutive model was developed for the *Finite Element Method* (*FEM*) simulation of the cold heading process. Numerical simulations of cold heading process were performed showing good capability of the model to predict the material's flow, and specifically, the flow localization phenomena.

WP4: Hot rolling and phase transformation model for optimization of microstructure and properties of high strength bainitic wire rod and bar steel for cold heading

Gleeble and dilatometric tests were conducted on Ti–steel to provide the data that were used for the development of microstructure evolution and phase transformation models. The deformation tests were designed to generate the data necessary to develop the sub–models for dynamic, metadynamic and static recrystallization, and also for grain growth after the recrystallization completion. The uniaxial upsetting tests were also conducted to determine the flow curves for *FEM* modelling of the rolling processes.

The phase transformations in the bainitic steels were simulated using Suehiro and Donnay at al. models. Due to the inaccuracy of the results generated in the isothermal test, the inverse module was developed to identify the coefficients of kinetics equations using the results of dilatometric tests conducted under continuous cooling conditions realized at constant cooling rate.

The following microstructure evolution/rheological sub-models were developed for Ti–steel (Ni+Cu≈0.3%):

- Constitutive equation (Sellars–Tegart model) relating flow stress to austenite grain size, strain, strain rate and temperature.
- Model for dynamic recrystallization.
- Model for metadynamic recrystallization.
- Model for static recrystallization.
- Model for grain growth after recrystallization.

A complete model predicts the onset of the dynamic recrystallization, static recrystallization and grain growth kinetics with a reasonable accuracy. The experimental data gathered in the course of deformations experiments conducted using the Gleeble simulator confirmed the strong retarding effect of strain–induced precipitation of TiC on static recrystallization and to the lesser extend on dynamic recrystallization.

The austenite evolution model was implemented into the Forge 2D/3D commercial code and was validated with respect to the simple hot working processes, e.g. uniaxial upsetting. After validation, it was implemented in FEM-based computer programmes to simulate the bar and wire rod rolling process with the aim of investigating the effect of processing parameters and plastic flow inhomogeneities on the austenite microstructure evolution during wire rod and bar rolling.

WP5: Development and validation of the process control system for bainitic bar and wire rod steels – laboratory hot rolling trials

The core components of the wire rod production process control system were prepared for use by industrial partners including:

- Set of general rules concerning the chemical composition design, steel making practice, and finally, rolling and cooling parameters adjustment to meet diversified customers requirements.

- Qualitative and quantitative relationships relating mechanical properties to microstructure of wire rod.
- Database comprising flow curves and phase transformation characteristics.
- CCT diagrams of Ti- and Ti-V bainitic steels.
- The initial design of Excel sheet allowing the calculation of microstructure evolution in the rolling process.

The wire rod rolling experiments on the continuous rolling line were conducted at TUBA to validate the main technological and theoretical bases of the system. A positive effect of TMCP with low finish rolling temperature effect on impact toughness of the wire rod was confirmed.

The rolling trials at Swiss Steel AG, ArcelorMittal Hamburg and ArcelorMittal Poland were administered based upon the knowledge gained in the initial stage of the project. All industrial trials focussed mainly on the adjustment of the cooling conditions in the Stelmor line to obtain required type of bainitic structure.

WP6: Industrial implementation of the bar and wire rod rolling technology

Industrial partners conducted measurements and calculations of the cooling conditions in their Stelmor lines. Based upon the measurements, the preliminary industrial trials were conducted with the currently available bainitic steels to confirm the capability of the processes to obtain the cementite–free granular bainite morphology in the wire rod. The results obtained by all the partners have demonstrated the correctness of the assumption that the desirable morphology of granular bainite can be developed in the industrial semi–products using available production facilities.

The preliminary rolling trials have demonstrated that the desired cementite–free granular bainite morphology can relatively easily be developed in the wire rod of the bainitic steel provided that some critical cooling rate (approximately 3°C/s) can be achieved in the Stelmor line when the temperature of the wire rod is in the phase transformation range. Although application of high cooling rates in the bainitic transformation range increases the ductility of the semi–products, a precise control of the cooling conditions is not necessary in the bainitic transformation temperature range to obtain a good cold headability of the resulting microstructure. This observation means that good cold headability of a bar or wire rod produced from the bainitic steel can be achieved without necessity of application of complex cooling conditions.

WP6 was completed with Swiss Steel AG wire rod rolling experiments of Ti-V bainitic steel. The following mechanical properties were obtained in the wire rod ϕ10 mm: $R_{p0.2}$=590 MPa, R_m=730 MPa, A_5=20%, Z=61%. The industrial trials provided the material for cold forging trials of ball stud that were successfully performed. In the case of bolts, mechanical properties for grade 8.8 fasteners were achieved.

WP7: Product characterisation

The cold headed products manufactured in industrial conditions from the bainitic steels include: bolts, screws, spindles, ball studs. The strength properties achieved for the fasteners meet 8.8, 9.9 and even 10.9 (ISO 898-1) strength class requirements. The microstructure of the cold headed products was characterized in detail with LOM and FEM SEM. Main focus of the investigation was the deformation substructure developed in the deformation bands. Main component of such a structure include subgrains having approximately 1-3 µm in diameter. A substantial hardness increase was observed in the heavily deformed areas of heads. Despite this, no cracking occurrence was found in these areas. Therefore, the substructure development may be used in the future to increase locally the strength of the components for special applications.

In all cases, high strength properties were achieved in the products. A detailed characterisation of the microstructure, mechanical properties was made. The potential applications, including fasteners, ball studs, spindles, were indicated.

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