Capabilities of Unconventional Processing of Multiphase AHSS Steels

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Abstract. Today, new types of materials and procedures are sought continuously in order to achieve lower manufacturing costs, reduced energy consumption, shorter production times and other savings. In terms of the materials, TRIP steels are an attractive choice, as they provide an excellent combination of strength and ductility. They also offer good energy absorption in crash scenarios. Their main use is in the production of automotive body parts. One can expect that well-chosen processing parameters and unconventional forming routes would enable a wider range of thin-walled products to be made of these steels. Those could include thin-walled hollow products with excellent mechanical properties imparted by effective manufacturing routes at relatively low costs. If these materials are to be employed in real-world forming processes, an appropriate forming route must be chosen, integrated into an appropriate production chain and then optimized in terms of its parameters. This article describes a study of a rotary spin extrusion process. In the first stage, the impact of strain magnitude on microstructural evolution was studied in CMnSi steel using physical modelling of thermomechanical treatment. Subsequently, trials of a real-life technology chain, which efficiently combined incremental forming and heat treatment, were carried out on low-alloy CMnSi and CMnSiNb steels. The resulting products were stepped hollow parts of various diameters. Their strength was close to 1000 MPa and their elongation level exceeded 20 %.

Keywords. TRIP, spin extrusion, incremental forming, hollow parts, AHSS

1. Introduction

One of the available ways of improving the efficiency of engineering production involves using low-alloy steels, i.e. low-cost materials, and processing them by innovative techniques to obtain very complex shapes of products with excellent mechanical properties. The aim of this experiment was to conduct trials of rotary spin extrusion and reduction rolling on low-alloy multiphase TRIP steels, and thus produce stepped hollow products from solid bar stock without drilling axial holes by metal cutting methods.

TRIP steels possess multiphase microstructures which consist of ferrite, bainite and retained austenite. Their great asset is an excellent combination of high strength and good ductility [1]. Today, they are mostly used for making sheet components in automotive industry. However, recent research efforts have been focused on several novel combinations of multiple processes based on thermomechanical treatment or heat treatment and incremental warm and cold forming of bulk stock [2, 3].
2. Experimental programme

The above reasons inspired the authors of this study to use multiphase TRIP steel stock for trials of unconventional production of rotation-symmetric hollow products by forming. The technology chain comprised warm rotary spin extrusion, in-process annealing in the intercritical range, and reduction rolling. Stepped hollow thin-walled demonstration products were obtained, with outer diameters ranging from 37 to 40 mm and with a wall thickness of approximately 4 mm.

The experimental programme was divided into two stages. The first one comprised physical modelling of thermomechanical treatment in a thermomechanical simulator. Its purpose was to optimize the process variables. These findings were then used for the actual production of thin-walled products.

The fraction of retained austenite in the material was determined by either X-ray diffraction analysis or image analysis. The latter was also used for finding the fraction of ferrite and the ferrite grain size on metallographic sections which had been prepared by two-step etching with 3 % nital and 10 % aqueous solution of Na$_2$S$_2$O$_3$.

2.1. Experimental materials

Two TRIP steels were employed: C-Mn-Si and C-Mn-Si-Nb (Tab. 1). The conventional chemistry of the C-Mn-Si steel is suitable for obtaining the desired final microstructure. The other steel only differs in having niobium as a microalloying addition, which contributes to its slightly higher strength.

|        | C   | Mn  | Si  | P   | S   | Cr  | Ni  | Cu  | Al  | Nb  | Mo  | W   |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| T1     | 0.206 | 1.418 | 1.849 | 0.007 | 0.005 | 0.007 | 0.071 | 0.059 | 0.006 | 0.002 | 0.02 | 0.02 |
| T2     | 0.21  | 1.449 | 1.797 | 0.008 | 0.005 | 0.008 | 0.072 | 0.058 | 0.006 | 0.059 | 0.02 | 0.02 |

2.2. Physical modelling of thermomechanical sequence

Physical modelling of the thermomechanical sequence was carried out in a thermomechanical simulator with high frequency resistance heating. The samples for the experiment had 8 mm diameter and active length of 16 mm. The crucial aspects are the temperature profile and the strain intensity. At this stage, the focus was on the latter. Besides its role in imparting the required shape to the workpiece, deformation has a substantial impact on grain refinement. In TRIP steels, deformation also promotes the formation of ferrite. Deformation in the intercritical range between 730 and 800 °C increases the volume fraction of ferrite by accelerating its nucleation process [4, 5]. It also accelerates the nucleation of bainite but retards the subsequent bainite growth, thus reducing the size of bainitic regions and the resulting volume fraction of bainite [4, 5]. At the same time, it leads to larger fractions of retained austenite which thus exhibits finer grain and contains higher carbon levels. This austenite is typically found in granular form which facilitates the TRIP effect better than the acicular retained austenite. Deformation applied in the intercritical region therefore stabilizes retained austenite both chemically and mechanically [5].

The thermomechanical treatment involved heating to 900 °C and soaking for 20 seconds. After soaking, several different schedules were applied which involved various numbers of deformation steps and various levels of total strain (Fig. 1). High number of deformation steps is characteristic of the rotary spin extrusion process. In this process, three rollers introduce strain into the workpiece, change its shape and dictate the microstructure evolution. The workpiece was held at the temperature of bainitic transformation of 425 °C for 600 s and then cooled in air. In the real-world process, this holding step takes place in a furnace.

The deformation schedules took place in 900-720 °C range. The first schedule involved twenty deformation steps. In the subsequent 40-step schedules, two different deformation step magnitudes were used (Tab. 2). Thus, two different true strain levels were applied. The same deformation step magnitude was used in the 60-step deformation schedule. (Tab. 2).
The true logarithmic strain $\varphi$ imparted in the twenty-step schedule was 2.8. The resulting ferritic-bainitic microstructure contained fine ferrite grains and consisted of more than 50 % ferrite and about 10 % retained austenite. The size of bainite particles was under 10 $\mu$m.

The true strain imparted in the 40-step schedule with smaller deformation steps was 5.8. This is more than twice as much as in the 20-step deformation schedule. It led to very fine ferritic-bainitic microstructure with 55 % ferrite and 9 % retained austenite (Fig. 2). The ferrite grain size of $2.1\pm0.9$ $\mu$m is close to the known physical limit of grain refinement by means of thermomechanical treatment.

The next 40-step schedule comprised deformation steps which were twice as large as in the previous case. The true strain was 10.4, almost double the value in the previous schedule. The microstructure configuration was very similar to the previous case. The deformation promoted the formation of ferrite whose fraction was up to 60 % (Fig. 3).

**Figure 1.** Example of thermomechanical treatment – 900 $^\circ$C/20 s - 40-step incremental deformation – 425 $^\circ$C/600 s

**Figure 2.** Micrograph of TRIP steel after 40-step incremental deformation with small deformation steps applied during continuous cooling from 900 to 720 $^\circ$C. Two-step etch
Figure 3. Micrograph of a TRIP steel after 40-step incremental deformation with larger deformation steps applied during continuous cooling from 900 to 720 °C. The total strain level was 10.4. Nital etch

Figure 4. Detail of bainite sheaf, nital etch

The detail in the scanning electron micrograph shows a bainite sheaf with very fine laths free of any notable carbide precipitates, with polyhedral proeutectoid ferrite grains, and distinct retained austenite regions located between ferrite grains, as well as between bainitic ferrite laths (Fig. 4).

Carbide precipitation during bainitic transformation was suppressed and ferrite formation promoted by the additions of silicon and manganese. Silicon, an element insoluble in cementite, prevents or at least retards carbide precipitation during bainitic transformation, and promotes the diffusion of carbon into retained austenite. Manganese, an austenite stabilizer, increases the solubility of carbon in austenite and expands the region available for cooling because it delays the formation of pearlite. [1]

After the 60-step schedule with the total strain level of 13.4, the microstructure was similar to those obtained in the previous cases. The fraction of ferrite has not increased and its grain has not become finer than before. In the next schedule, the total strain level was increased further and the workpiece temperature was decreased but the material’s ability to undergo plastic deformation proved insufficient and the specimen failed.

In one of the thermomechanical treatment variants which may prove viable in practice, first deformation steps are applied even before the end of the austenitizing hold, i.e. before the temperature starts to decrease. This was tried in a schedule which therefore comprised both isothermal and non-isothermal forming. The first 10 deformation steps were applied isothermally at 900 °C. They were immediately followed by another non-isothermal 10 steps, with the deformation sequence ending at 720 °C. The resulting fine ferritic-bainitic structure was almost identical to that obtained after the non-isothermal 20-step schedule in the 950-720 °C range.
| Temperature interval of deformation [$^{\circ}$C] | Number of deformation steps | $\varphi$ [-] | Microstructure | Ferrite grain size [\mu m] | Ferrite fraction [%] | Retained austenite fraction [%] |
|-----------------------------------------------|----------------------------|---------------|----------------|--------------------------|-------------------|-----------------------------|
| 900 – 720                                    | 20*                        | 2.8           | ferrite        | 2.3±1                    | 51                | 11                          |
|                                              | 20                         | 2.8           | + bainite      | 2.3±1.2                  | 56                | 11                          |
|                                              | 40                         | 5.8           | + retained     | 2.1±0.9                  | 55                | 9                           |
|                                              | 40                         | 10.4          | austenite      | 2.1±0.9                  | 60                | 10                          |
|                                              | 60                         | 13.4          | retained       | 2.1±1.1                  | 59                | 10                          |
|                                              | 60                         | 15.8          |                | Specimen failure         |                   |                              |

* 10 deformation steps at the austenitizing temperature of 900 $^{\circ}$C and 10 deformation steps during cooling from 900 to 720 $^{\circ}$C

2.3. **Manufacturing process**

In the preceding experiment, it was found that the material can sustain severe plastic deformation. A manufacturing route was therefore proposed for making thin-walled hollow products by incremental forming, and its trials were carried out on C-Mn-Si and C-Mn-Si-Nb steels. In the first step, bar stock of 58 mm diameter was converted by warm rotary spin extrusion to semi-finished products of 51 mm diameter with approx. 9 mm wall thickness (Fig. 5). The products were annealed in an intercritical temperature range. Their ferritic-pearlitic microstructure then transformed to multiphase ferrite-bainite-retained austenite microstructure with a good plasticity and a potential for the TRIP effect. The semi-finished products were then cold reduction-rolled. This operation produced two steps on the outer diameter of the product. The first stepped-down diameter produced was 42 or 44 mm and the second one was 37 mm.

Figure 5. Hollow product after rotary spin extrusion at 680-700 $^{\circ}$C. The hollow portion is on the left, the middle part is the input stock and the right portion of the workpiece is the grip hold

2.3.1. **Rotary spin extrusion.** Both experimental materials were extruded after heating in a furnace to 750 $^{\circ}$C. The forming operation was monitored with a thermal imaging camera. By analyzing the temperature field within the stock, it was found that the extrusion process started at 680-700 $^{\circ}$C. Just after the end of the forming operation, the temperature within the semi-finished product was still relatively uniform: approximately 650 $^{\circ}$C.

In the semi-finished products of both materials, the microstructures consisted of ferrite and pearlite (Fig. 6). The microstructure was studied in a region between the point of entry of the mandrel and a depth of approximately 40 mm. Down to the depth of 5-10 mm, ferrite grains and regular pearlite colonies were found. In the extrusion direction, this continuously changed into a deformed microstructure. The ferrite grains were heavily distorted and the pearlite colonies disintegrated.

2.3.2. **Intercritical annealing.** The temperature of the subsequent intercritical annealing (austenitizing) was 810 $^{\circ}$C and the annealing times were either 15 or 30 minutes. The products were then cooled to 420 $^{\circ}$C to prepare for bainitic transformation which was to take place in a salt bath. The
salt bath was used instead of a furnace. The holding time was 8 minutes and was followed by water cooling.

In the C-Mn-Si steel, the microstructure upon intercritical annealing consisted of retained austenite islands in a ferritic matrix (Fig. 7). Only a very small volume fraction of bainite was found. Martensite-austenite (M-A) constituent was detected in several retained austenite islands in carbon extraction replicas. No differences between the experimental steels or between the outcomes of 15-minute and 30-minute austenitizing holds were found. This was confirmed by observation of carbon extraction replicas (Fig. 3). Several cementite lamellae were found which, given their amount, should not have any substantial impact on mechanical properties of the material. The difference between the holding times had no impact on the amount of retained austenite. In the niobium-free steel, the fraction of retained austenite was 15 % after the 15-minute hold and 17 % after the 30-minute hold. In the niobium-alloyed steel, the amounts of retained austenite were 16 % and 15 % (Table 3).

Mechanical properties were measured using miniature tension test (Table 3). The samples were located in the wall of the hollow product with the longitudinal axis in the same direction. The samples were taken from the part with uniform structure and its size was 2 x 1.5 x 5 mm. Test pieces of the niobium-free steel upon 15-minute holding showed an elongation of 30 % and an ultimate strength of 904 MPa. Test pieces which had been austenitized for 30 minutes showed an elongation of 32 % and an ultimate strength of 927 MPa. The holding times had only a minor impact on mechanical properties. The difference between the ultimate strength levels was a mere 23 MPa. Higher strength of the niobium-free steel may be due to the slightly larger fractions of hardening structure and retained austenite.

The niobium-containing steel which had been held at temperature for 30 minutes had an ultimate strength of 994 MPa. After the austenitizing time was extended from 15 to 30 minutes, the ultimate strength increased by 40 MPa but elongation levels remained unchanged: 28 % in both cases. The strength of the C-Mn-Si-Nb steel was higher than that of the niobium-free steel upon both schedules. High elongation level of the C-Mn-Si-Nb steel remained unchanged. The higher strength was caused by niobium carbides which greatly affect solid solution strengthening.

### Table 3. Intercritical annealing schedules and mechanical properties

| Steel       | Schedule                   | RA [%] | R_m [MPa] | R_e [MPa] | A_5mm [%] |
|-------------|----------------------------|--------|-----------|-----------|-----------|
| Mn-Si (T1)  | Furnace 810 °C/15 min.  - salt bath | 15     | 914       | 904       | 460       | 29        | 31        | 30    |
|             | 420 °C/8 min - water        |        | 893       | 397       | 429       | 29        | 31        | 30    |
|             | Furnace 810 °C/30 min.  - salt bath | 17     | 924       | 927       | 454       | 451       | 33        | 32    |
Based on the above-described results, semi-finished test products were heat treated using intercritical annealing with a 15-minute hold at 810 °C and subsequent bainitic transformation in a salt bath at 420 °C for 8 minutes.

2.3.3. Reduction rolling. The semi-finished products were reduction-rolled to obtain hollow products with a wall thickness of 4 mm. The reduction was 6%. Two steps were formed on the product. The first was a step from 50 mm to 42 mm diameter, and the second had the smaller diameter of 37 mm. Samples for mechanical testing and metallographic observation were taken from both stepped-down areas.

The resulting microstructure consisted of deformed ferritic matrix with disintegrated particles of MA-constituent (Fig. 8). Final material properties and fatigue behaviour will be the topics of future research.

![Figure 8](image-url)

**Figure 8.** Three-dimensional representation of an etched metallographic section through C-Mn-Si steel (T1) upon cold reduction rolling, nital etch

With regard to the very good results obtained thus far, another schedule with twice as large reduction was undertaken. Instead of using the 6% reduction, stepping down to the diameter of 44 mm was carried out using 12% reduction. Another step to 37 mm was formed in the same fashion. (Fig. 9).
Figure 9. Example of twice stepped-down product from TRIP C-Mn-Si-Nb steel upon cold reduction rolling

Mechanical properties were measured by tension testing. The geometry of samples was 2 x 1.5 x 2 mm. Following the reduction to 42 mm, the C-Mn-Si steel (T1) had a strength of 891 MPa and $A_{5\text{mm}}$ elongation of 19 % (Tab. 4). Subsequent reductions to the diameter of 37.3 mm did not cause any substantial increase in ultimate strength. The elongation level remained about 20 %.

Upon the smaller reduction of diameter, the C-Mn-Si-Nb steel (T2) had a strength around 950 MPa and a similar $A_{5\text{mm}}$ elongation of approx. 20 %. The subsequent reduction to the final diameter of 37 mm led to an increase in ultimate strength to 965 MPa.

| Steel              | Diameter reduction [%] | $R_m$ [MPa] | $A_{5\text{mm}}$ [%] | Z [%] |
|--------------------|------------------------|-------------|----------------------|-------|
| C-Mn-Si (T1)       | 14.4                   | 891         | 19                   | 57    |
|                    | 25.4                   | 947         | 18                   | 48    |
| C-Mn-Si-Nb (T2)    | 16                     | 953         | 21                   | 45    |
|                    | 26                     | 965         | 21                   | 54    |

3. Conclusion

Based on previous experience and results of material-technological modelling of incremental thermomechanical processing, a manufacturing route for making hollow stepped products was proposed and tested successfully. A flexible production chain was used which comprised a sequence of warm rotary spin extrusion, intercritical annealing and cold reduction rolling to the final shape. The unconventional combination of warm forming, intercritical annealing and cold forming produced an appropriate combination of technological properties in low-alloy TRIP steels of CMnSi and CMnSiNb types. The process of microstructure evolution was designed to meet the requirements for technological properties of the materials throughout the manufacturing sequence and to enable the desired shapes and final properties to be obtained with as low energy consumption as possible and without the need for the final heat treatment operation. Thanks to a new material-technological strategy, a zero-waste manufacturing route for making stepped hollow thin-walled products was tested successfully.

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References

[1] Bleck W 2002 International Conference on TRIP – Aided High Strength Ferrous Alloys Using the TRIP effect – the down of a promising group of cold formable steels Prof. Bruno C. De Cooman Aachen

[2] Jirkova H, Rezek M, Meyer L W and Masek B 2009 Influence of austenitization temperature and number of incremental steps on structure development of TRIP-steel, Proceedings of the 20th International DAAAM Symposium Intelligent Manufacturing & Automation: Theory, Practice & Education 20 1461-2

[3] Masek B, Stankova H, Novy Z, Meyer L W and Kracik A 2009 The Influence of thermomechanical treatment of TRIP steel on its final microstructure Journal of Materials Engineering and Performance 18

[4] Basuki A and Aernoudt E 1999 Influence of rolling of TRIP steel in the intercritical region on the stability of retained austenite Journal of Materials Processing Technology 89 – 90 37 – 43
[5] Godet S and Jacques P J 2004 2nd International Conference on Thermomechanical Processing of Steels Thermomechanical processing of TRIP-assisted multiphase steels Belgium