

Production of high strength hollow shafts using tool hardening and Q-P process

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Abstract. Innovation opens new opportunities in the field of processing hollow semi-products, as it offers the potential for manufacturing complex-shaped structural parts with enhanced properties.

This introduces a manufacturing route comprising the following steps: internal high pressure forming, hot stamping and thermomechanical Q&P processing.

In this manufacturing route, the demonstration product, a tube-shaped stock, is first austenitized. It is then expanded in a closed die by internal pressure of nitrogen until the material touches the die wall. As a result, it cools down quickly and martensite begins to form. At a temperature above the M_f , the cooling is interrupted and the workpiece is transferred to a furnace and tempered. The furnace temperature is below the M_s temperature. Within several minutes, a mixed microstructure forms, consisting of martensite and stabilized retained austenite. Thanks to this microstructure, the material exhibits a favourable combination of high strength and adequate ductility. Martensite imparts sufficient strength to the material whereas the retained austenite provides ductility. At a carbon level of approximately 0.4 % and with a simple Si-Mn-Cr-based chemistry, strengths of 2000 MPa and $A_{5\text{mm}}$ elongations of 15% can be achieved.

1. Introduction

Today's demand for engineering components brings continuously increasing requirements for their quality and excellent mechanical properties. As the same time, the manufacture of complex-shaped components should comprise as few operations as possible at the lowest achievable production cost. In order to meet such criteria, it is imperative to use advanced forming techniques, heat treatment and thermomechanical processing. One example of such techniques is a novel forming sequence for hollow products of high-strength low-alloy steels comprising internal high-pressure forming, tool hardening and integrated Q&P process (Quenching and Partitioning) [1]. As this sequence leads to excellent mechanical properties, it can be used for making structural parts with substantially lower weight than formerly. The purpose of the present experiment was to propose an integrated manufacturing technology for making hollow shafts which, once the manufacturing process is optimized, becomes suitable for making commercially successful products.

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Figure 1. Final product of internal high pressure forming and subsequent Q&P processing.

2. Internal high pressure forming

If the potential of AHS steels is to be fully utilized, the manufacturing route in which they are processed must involve advanced technological elements. One of such routes is the sequence of internal high pressure forming, tool hardening and Q&P processing, which can be used for making complex-shaped thin-walled products.

A thin-walled seamless tube was chosen as the input stock. It was heated to the hot forming temperature. Then it was placed into the die cavity and formed by internal pressure exerted by gas. Unlike conventional manufacturing techniques for hollow shafts, internal high pressure forming can produce non-symmetric and complex shapes (Fig. 1). Despite its non-uniform shape, the product has adequate wall thickness along its entire length. The mechanical properties and microstructure of the final product can be controlled by varying the period of time for which the workpiece remains enclosed in the die. During this time, the material is cooled in a controlled manner to the desired temperature of interrupted quenching. Once this temperature is achieved, the workpiece is removed from the tool. The microstructure evolution continues by partitioning, which is part of the Q&P process. It is decisive for obtaining a good ductility and high strength [2].

3. Q&P process

This heat treatment procedure was carried out immediately after the hot internal high pressure forming. The Q&P process relies on interrupted quenching and on processes that take place in steel between the M_s and M_f temperatures. In the region between these temperatures, the migrating carbon stabilizes retained austenite which remained in the microstructure due to the interrupted quenching carried out in a tool kept at a controlled temperature [3].

In the standard Q&P process, the feedstock is heated to austenitizing temperature. After that, it is rapidly cooled to a temperature between the M_s and M_f – the so-called quenching temperature (QT). A two-phase microstructure of martensite and retained austenite forms. The resulting proportion between these phases can be controlled by the choice of the quenching temperature. The workpiece is then reheated and held at the partitioning temperature (PT). This low-temperature isothermal annealing stabilizes retained austenite, as carbon migrates from the super-saturated martensite to austenite. To

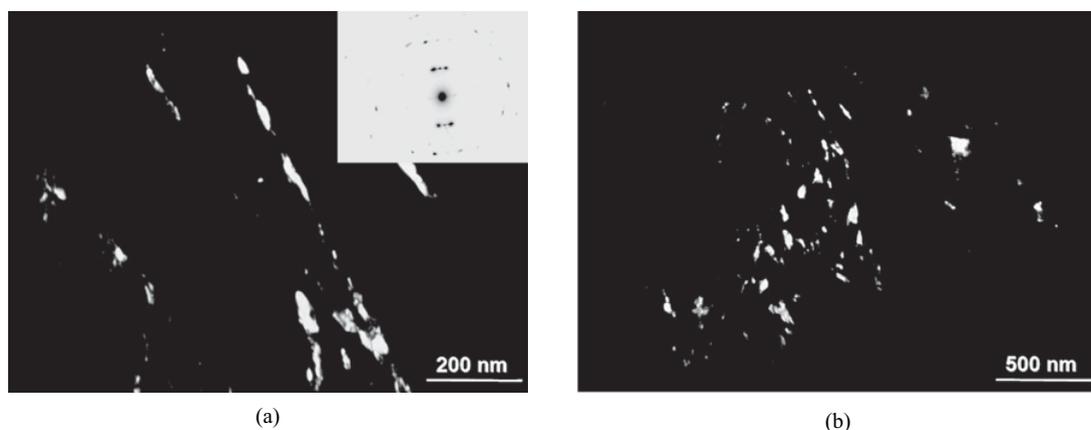


Figure 2. a) 42SiCr – Detail of retained austenite in martensite matrix (dark field), b) 42SiCr – Detail of retained austenite dispersed in a volume of the structure (dark field).

Table 1. Chemical composition of the 42SiCr steel [wt.%].

C	Si	Mn	Cr	Mo	Nb	P	S	M_s [°C]	M_f [°C]
0.42	2.6	0.59	1.33	0.03	0.03	0.01	0.01	289	178

keep the austenite stable, carbon must not precipitate in the form of carbides at the PT. It is therefore desirable to use appropriate alloying elements, such as aluminium and silicon which retard carbide formation and promote austenite stabilization. Chromium acts as a carbide former in steel but at the same time strengthens the solid solution [4, 5].

Internal high pressure forming, tool hardening and the Q&P process can be combined to form a single technology chain which delivers products with microstructures consisting of martensite and retained austenite (Fig 2a), 2b)). Austenite exists predominantly in the form of thin foils between martensite particles and provides a better combination of high strength and adequate ductility than that found in quenched and tempered materials. In the steel with 0.42% carbon, it is possible to achieve an ultimate strength of approximately 2000 MPa combined with the $A_{5\text{mm}}$ elongation level up to 15%.

4. Experimental programme

The purpose of the present experiment was to develop a novel technology for forming hollow products by directly incorporating the heat treatment procedure known as the Q&P process.

4.1 Feedstock choice

The chosen feedstock for the experimental programme was a seamless tube of 42SiCr steel (Table 1) with a diameter of 43 mm, 380-mm length and a wall thickness of 4 mm. The main alloying elements in this steel are manganese, silicon and chromium. Approximate values of the M_s and M_f temperatures for the first step of the process design were calculated using the JMatPro software.

4.2 Process design

The first step in the process of making final products from the tubular stock consisted of heating in a furnace to 950 °C for 25 minutes in order to obtain a fully austenitic microstructure. After that, the feedstock was removed from the furnace and immediately transferred to the die cavity. In the die,

the workpiece was formed by internal high pressure of gas. Due to the contact with the die walls and the cooling effect of the gas, the workpiece then cooled rapidly to a temperature between the M_s and M_f . The gas pressure required for forming such thin-walled hollow workpieces was between 700 and 800 bar. This step was immediately followed by the second part of the process which focused on stabilizing retained austenite through carbon partitioning by diffusion. This took 25 minutes in a furnace at 260 °C [6, 7].

5. Microstructure and mechanical properties

The microstructure of the product made using this newly-designed process was examined by means of optical and electron microscopy. It was found that the microstructure is uniform throughout the product. The two-phase structure of martensite and retained austenite is present along the entire length of the product. A small fraction of free ferrite can be found in some locations where the contact between the workpiece and the die wall was not perfect.

The mechanical properties of the product were examined from many different perspectives. The focus was on determining variations in local mechanical properties. The ultimate tensile strength did not decrease below 1950 MPa in any location. The elongation level was between 17 and 21%.

Despite the variation in the cross-section and the complex shape of the product, the forming process did not lead to any apparent defects or discontinuities. In order to gain better insight into the potential for developing forming processes for non-symmetric and complex-shaped hollow shafts, the final wall thickness was measured along the entire length of the product. The initial wall thickness was 4 mm. The final thickness did not decrease below 2.4 mm in any location.

Since products of this kind are expected to operate under long-term cyclic loading, fatigue strength is an important aspect. To find the fatigue strength of the product, three-point bending fatigue testing was used.

Twenty fatigue test specimens were taken from identical locations of the products. Fatigue strength was measured in three-point bending under steady cyclic loading with $R = 0.1$. The test was carried out using Resonant POWER SWING NewLineMAG 20 kN machine (Fig. 3). The length of the test was set at 2×10^6 cycles. The loading frequency was 36 Hz with a deviation of $\Delta f = \pm 1$ Hz.

The test specimens had the dimensions of $40 \times 6 \times 2.5$ mm and a surface roughness of $R_a = 1.6$. In order to find the fatigue strength level, specimens were tested under loads varied in steps of 20 MPa. Using the fatigue strength testing method for small specimens according to Dixon and Mood, the three-point bending fatigue strength was determined at 1355 ± 129 MPa. No less than 50% of the tested specimens reached this value (Fig. 4).

6. Conclusion

Hot internal high pressure forming, integrated tool hardening and subsequent heat treatment by the Q&P process were used to manufacture complex-shaped thin-walled products. Despite the complex and non-rotation-symmetric shape, the quality analysis revealed no defects or discontinuities. The wall thickness in the product upon forming was adequate along its entire length. The three-point bending fatigue strength of 1355 MPa indicates that the product is suitable for operation under cyclic loading. It was found that incorporating the Q&P process into the manufacturing route provides $A_{5\text{mm}}$ elongation level of more than 15% at the ultimate strength of 2000 MPa. An analysis of local mechanical properties carried out with respect to the position in the die cavity revealed no substantial variation. Equally, the microstructure is very uniform and free from any notable variations along the entire length of the product. This microstructure consists of martensite and the desired fine and uniformly distributed chemically stabilized austenite with the volume fraction between 10 and 20%.

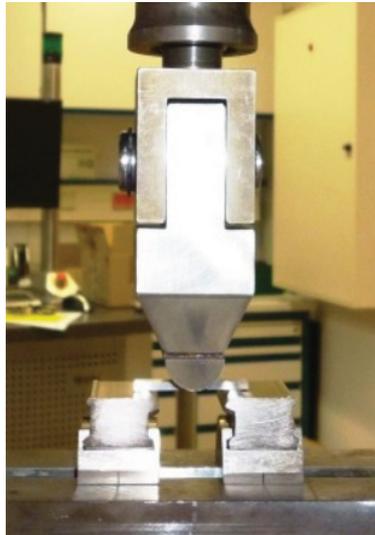


Figure 3. Equipment for experimental measurement of the flexural fatigue strength.

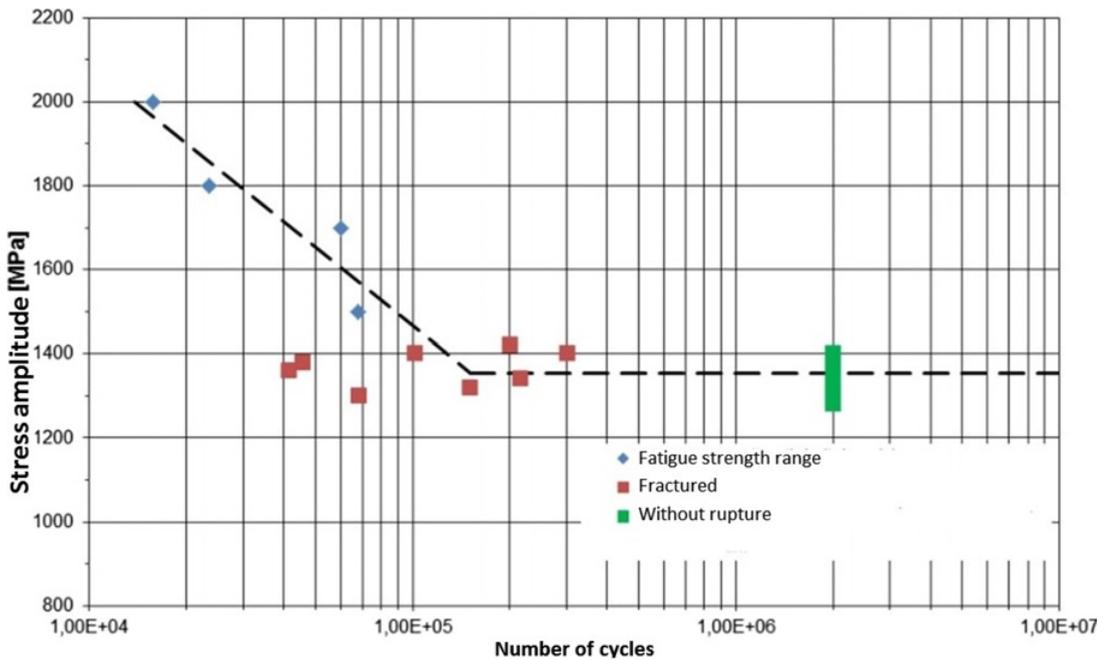


Figure 4. S-N curve for the 42SiCr steel upon final processing.

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