Stainless steel valves with enhanced performance through microstructure optimization

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Abstract. Compressor valves are made of hardened and tempered martensitic steels. The main design criterion for the material selection is the fatigue performance of the material under bending loads. In some cases impact loads and corrosive atmospheres additionally act on the part. For the first time, the microstructure of the most commonly used stainless steel and its influence on the properties relevant for flapper valves is presented and described in this paper. It is demonstrated how the tensile properties of a martensitic stainless steel can be enhanced by tailoring the microstructure. Electron back scatter diffraction method is carried out to explain the changes in monotonic mechanical properties. Through a modified heat treatment the martensite microstructure is refined resulting in an increase of yield and ultimate tensile strength and at the same time a significant increase of elongation.

1. Introduction
Stainless martensitic steels were discovered in the year 1912 by Harry Brearly in Sheffield England and by Elwood Haynes in the USA [1, 2]. These alloys combine high hardness and wear resistance with reasonable toughness and are resistant to corrosion under ambient atmospheric conditions. Since then various alloys have been developed and mainly used for blades in household, medical, industrial and consumer applications. Because of the high strength, corrosion resistance, good toughness, and very good fatigue properties they are used as well in compressors as valves [3-5]. Numerous researchers have reported about the performance and properties of the martensitic stainless steels used in valves [3-8]. Manifold commercial names are available for the stainless chromium steel X38CrMo14 used for the production of valves. It contains approximately 13.5 weight percent of chromium, 0.38 weight percent of carbon, and around 1 weight percent of molybdenum.

However, few reports are found on the correlation between the microstructure of the stainless martensitic steels itself and the mechanical properties. Toro et. al. described the influence of chromium nitrides on the corrosion-erosion resistance of AISI 410S [9]. Yuan has thoroughly investigated a chromium steel with 0.44 weight percent of carbon and demonstrated how through control of the heat treatment parameters the tensile properties of X44Cr13 (1.4034, AISI420) can be tailored (Yuan 2009). The TRIP effect described in the paper is related to reverted austenite. The influence of martensite packet size, lath or needle geometry on mechanical properties remains open for further research. Especially, for flapper valves where fatigue behavior is of utmost importance the morphology of the martensite could play a crucial role for the fatigue behavior. It has been demonstrated for carbon steels that the
toughness and fatigue properties can be controlled by the martensite block size [11, 12]. In the present paper for the first time the influence of the martensite microstructure on tensile properties is investigated for the alloy X38CrMo14 (1.4419, UNS420026, Zapp 1.4028MO) used in flapper valves since decades.

Table 1 - Chemical composition of precision strip used for the investigation (Zapp 1.4028MO, X38CrMo14, 1.4419, UNS420026)

|   | C  | Si | Mn | Cr  | Mo |
|---|----|----|----|-----|----|
|   | 0.38 | 0.30 | 0.46 | 13.46 | 0.93 |

2. Experimental

Precision strip with a thickness of 0.41mm made out of the alloy X38CrMo14 with the composition given in table 1 was austenitized, quenched, and tempered in a continuous hardening line. The continuous hardening line consists of an austenitization furnace, quenching section, and tempering furnace. The heat treatment is schematically shown in figure 1.

In order to obtain various microstructures the heat treatment was modified. The strip selected for the test was divided into two strips. Two set of heat treatment parameters were defined to investigate the influence of the microstructure on the tensile properties. The first set of parameters consists of the standard heat treatment parameters used at Zapp Precision Metals for the production of quenched and tempered Zapp 1.4028MO. The second set of parameters was defined to reduce the size of the martensite units. The austenitization and tempering temperature and time in each process step were kept constant. The sample taken from the first quenched and tempered strip heat treated with the standard set of parameters are designated as modification A. The strip heat treated to obtain a refined martensite microstructure and the samples thereof are called modification B.

The microstructure was observed by light microscopy using various etchants to reveal the different phases and microstructural features. Electron backscatter diffraction technique was used to characterize the microstructure of the two modifications. EBSD samples in rolling direction were prepared using standard grinding and polishing procedures. An area of 80 micrometer by 80 micrometer was mapped with a step size of 50nm.

The tensile properties were determined in the longitudinal direction according to standard practice on 10 samples taken from start and end of the heat treated strips.
3. Results

The samples were examined by light microscopy. Significant differences with respect to carbide dispersion and carbide size distribution could not be identified using various etchants with a magnification up to 1000 times.

The fraction of retained austenite was determined using the EBSD results. Both modifications exhibit approximately one percent of retained austenite.

Figure 2 presents grain boundary maps of the two modifications. Low angle grain boundaries with a rotation angle between 3 and 15 degrees are shown as blue lines, high angle grain boundaries with rotation above 15 degrees are shown as black lines. The coherent twin boundaries (Sigma 3) are presented as red lines. The comparison of maps shows that the microstructure of sample B is much finer. Because areas enclosed by high angle grain boundaries and their size influences the mechanical properties, both the strength and ductility, an effective grain size was defined to be an area enclosed by a boundary with at least 15 degrees misorientation to the adjacent area and having at least 10 measuring points. The effective grain size area was determined for both modifications and an average diameter was derived assuming the area is circle. The average diameter defined in such a way was reduced from 0.74 (sample A) to 0.54 (sample B) micrometer. Acknowledging the fact the martensite block and lath are elongated and more elliptical the width of the blocks constrained by a high angle grain boundary was determined. The result is presented in figure 3. It is seen that 75 percent of the blocks of modification B have a smaller width than 0.5 micrometer and hence the median of modification A.
Figure 2 - Grain boundary maps of the two modifications A and B. Black line: high angle grain boundary (15 to 62.8°); blue line: low angle grain boundaries (3 to 15°); red line: sigma 3 grain boundary with a tolerance of 8.7°.

Figure 3 - Width distribution of martensite blocks limited by high angle grain boundaries for modifications A and B.

Modification B exhibits higher yield and ultimate tensile strength than modification A (figure 4). While the yield strength is approximately 50 MPa higher, the ultimate tensile strength is almost 150 MPa higher. At the same time the elongation is significantly increased (figure 4).

4. Discussion
The present work demonstrates that the microstructure of stainless martensitic steel X38CrMo14 can be modified to be finer resulting in higher tensile yield and ultimate strength and at the same time higher
elongation. The structural unit responsible for the improved mechanical properties is the area enclosed by high angle grain boundaries. Due to the shape of martensitic blocks the width of these units has been extracted as proposed by Naylor [11]. A finer microstructure including high angle grain boundaries increases the yield strength and as well the elongation [11, 12]. It is as well beneficial for dynamic properties like fracture toughness or fatigue limit.

![Graph](image)

**Figure 4** – Average tensile properties in rolling direction of the two treatment, i.e. standard treatment (modification A) and treatment for finer martensite (modification B)

However, the effect of the improved tensile properties can not only be correlated to the structural refinement only. The finer martensite morphology is corresponding at the same time to an increased grain boundary area. As reported earlier for carbon steels an increase of grain boundary area can lead as well to finer carbides [12].

5. Conclusion
The present study shows that the performance of flapper valve could be improved by making the martensite finer. It is known that an increase of the tensile strength values and the elongation at the same time is connected to a higher fatigue life. The microstructure of the stainless martensitic steel X38CrMo14 (Zapp 1.4028MO) is refined by modification of the heat treatment resulting in finer martensite microstructure with smaller blocks. The refinement leads to higher 0.2 percent offset yield strength and ultimate tensile strength while increasing the elongation. The concept of the effective grain size and the effective width of martensitic units are validated for the first time for martensitic stainless steels. The improvement of the reported mechanical values enables the compressor designers to consider a higher fatigue limit or higher loads for the valves without comprising on other attributes.

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