INFLUENCE OF MICROSTRUCTURAL CHANGE IN AISI 4340 STEEL SPRING MATERIAL HAVING IDENTICAL HARDNESS LEVEL ON THE HYSTERESIS ERROR OF FORCE TRANSDUCER

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ABSTRACT

Different heat treatment processes can be applied on the spring element of a force transducer in order to obtain good and satisfactory performance. The manufacturers are generally focused on the improvement of performance by applying different heat treatments on spring material, and no information is in free circulation regarding the process-performance relationships of transducers due to tight competition in the market. The study covers the attempts of different heat treatments on spring element using AISI 4340, which is regarded as one of the best spring materials for force transducer applications. The steel was quenched and tempered at predetermined temperature, and 45 Rockwell-C hardness values was reached to obtain fine martensite structure. In order to obtain coarse martensite structure having identical hardness from spring material, some specimens were subjected to high temperature during austenite transformation in 1000°C in 4.5 hours priority. In order to produce bainitic structure different heat treatment was applied on the specimens to have identical hardness level. It was observed that different heat treatments influenced the transducer performance, particularly hysteresis behaviour point of view. To minimize the hysteresis error of force transducers has prime concern and best result was obtained in the bainitic-structured specimen. After building the force transducers with differently heat-treated spring materials, their performances were recorded by using a dead weight force standard machine, concentrating on hysteresis characteristics. The results were compared with each other and analysed regarding the structural properties of spring materials and a process path was proposed to obtain the best performance in force transducers.

1. INTRODUCTION

In order to achieve low measurement uncertainty in force measurements, performance characteristics of force transducer must be low as much as possible. The most important characteristics of force transducers are hysteresis and creep response of spring elements [1-4]. At the same time, hysteresis error is known the most influenced factor among the performance specification of the transdcuer [2]. Spring materials may exhibit different hysteresis behaviour and application of heat treatments cause microstructural and hysteresis error changes of force transducers [2-3,6]. In the literature survey it is determined that performances characteristics of force transducers were directly depending on the heat treatment applied to the spring element [2-4]. Different heat treatment processes can be applied on the spring element of a force transducer in order to obtain good and satisfactory performance. The manufacturers are generally do not publish heat treatment process and performance relationships of transducers due to tight competition in the market.

In this study, different heat treatments on spring element using AISI 4340, which is regarded as one of the best spring materials for force transducer applications, were examined to determine influence on the hysteresis characteristic of force transducer. It was determined that heat treatments especially influence the hysteresis error of force transducers.

After application of all heat and mechanical processes, finishing process was applied to get the resulting specimens. Then special strain gages were bonded on the specimen surface. It is essential to select good performance materials, to perform good design, and to apply carefully controlled manufacturing procedures for force transducers. The use of high accuracy electronic instruments in transducer outputs and the use of dead weight force standard machines in determining the performance characteristics of transducers are also very important to get reliable results. Finally, the selection and application practice of strain gages should also be done properly [2]. After completing the strain gage circuits of transducers, all of specimens are calibrated with dead weight UME Force Standard Machine having $2x10^{-5}$ measurement uncertainties in a specified measurement procedure to obtain performance specifications of each specimen.

2. MATERIAL AND HEAT TREATMENT OF SPRING ELEMENT OF TRANSDUCER

Spring element of force transducers in this study is selected as AISI 4340 steel. This steel is known as an excellent material for the force transducer application [1,7]. In order to get different microstructure in AISI 4340 steel specimens, different heat treatments were applied on it. During the heat treatment of spring elements, all specimens placed in the gas-controlled oven with 0.2 % H_2O, 0.5.% CO_2, 0.5% CH_4, 40 % N_2, 22% CO and 36.8 % H_2 atmosphere to protect them decarburising. These are;

- Specimens were austenitised at 845 °C during 30 minute in oven and then quenched in oil for martensite transformation. Then, tempering is applied in 440 °C during 1,5 hour to each specimen to get 45±1 HRC hardness values.
- In order to obtain coarse martensite, specimens were austenitised up to 1000 °C during 4.5 hour, then oil quenched. Then, they are tempered in 440 °C for obtaining 45±1 HRC hardness value,
- Austanitization at 845 °C and quenching in salt bath at 320 °C during 40 minute were applied to some specimens. After this isothermal transformation, bainitic structure having 45±1 HRC hardness values was obtained.

As a result of each heat treatment, obtained microstructures are examined with an optical and transmission electron microscope. At the same time hardness values and mechanical specifications were determined for each type of specimens to determine relation between performance and mechanical specifications.

3. TRANSDUCER DESIGN AND STRAIN GAGE APPLICATION

All transducers were designed for 100 kN capacity and produced in tension type and circular bar shape for easy strain gage application. Tension type transducer enables easy and exact centering in force standard machine since it has spherical apparatus, which eliminates the bending effect during loading.

The basic elementary elasticity calculations were employed in the design of cylindrical tension type transducer. In order to eliminate end effect, the diameter to length ratio was taken grater than five.

Diameter of tension bar is calculated as 20 mm for a strain level of 1500 μm/m for 100 kN capacity. First greater diameter was obtained by turning before heat treatment, then all specimens were heat treated and last all specimens were produced as exact diameter by finishing (grinding) processes.

In order to get output signal from transducer spring element, N2A-06-S053P-350 type (Measurement Group Co, USA) strain gages were used and bonded on it in this study. Its STC (Self Temperature Compensation) number is 06 associated with exactly AISI 4340 steel for approximating the thermal expansion coefficients of the transducer material [8].

In order to correct application of strain gage, recommendations of strain gage producer are carefully applied to obtain better performance and quality bonding using M bond-610 adhesive. Final transducer performances are greatly depending on the application of a uniform and repeatable clamping pressure Strain gages are bonded according to manufacturer recommendations using special apparatus, ovens and conditions [8-9]

These strain gages are selected as 90° rosette to eliminate alignment errors. Two rosettes pair is bonded on opposite side with a 180° angle between them to establish a full bridge wheatstone circuit. Another pair of rosettes is bonded on the spring element to obtain another a full bridge circuit. This second bridge enables to determine the installation errors of strain gages.

4. METHOD FOR HYSTERESIS ERROR DETERMINATION

Hysteresis (reversibility) error is determined at each calibration, by carrying out verification with increasing forces then decreasing forces. The difference between the values obtained with increasing force and with decreasing force enables the relative hysteresis error to be calculated by using equation [10].

$$u_{1\text{-}2} = \frac{X'_{1\text{-}2} - X_{1-2}}{X_{N(1\text{-}2)}} \times 100 \qquad (1)$$

$$u_{ave} = \frac{u_1 + u_2}{2} \qquad (2)$$

where u is the relative hysterisis error of force transducer, u_1, u_2, are the hysterisis errors in first and second series of readings, u_{ave} is the average relative hysterisis error, $X'_{1\text{-}2}$ are the readings on the indicator with decreasing test force in first and second series, $X_{1\text{-}2}$ are the readings on the indicator with increasing test force in first and second series and $X_{N(1\text{-}2)}$ is the average reading on the indicator with maximum test force in first and second series [10].

Increasing and decreasing forces in 10 steps with 10 % increment of 100 kN load were applied on the force transducer in a 110 kN dead weight force standard machine in two series. Before beginning the force application three preloading in 100 kN were applied on it. Transducer output were recorded at the end of 60 seconds after application of each force steps using high precision indicating instrument that is DMP 40 S2 located in Force measurement Lab. of UME. Figure 1 shows the force transducers that are under test in dead weight force standard machine.

These test are performed at very fine controlled laboratory conditions with a temperature of 21±1°C and humidity 45±5 %. The short-term temperature control is better than ±1°C. The temperature variation is measured to be less than ±0.2 °C during full test of transducer. Since the construction of force transducer is not affected changes in barometric pressure, therefore the pressure is not recorded.

5. RESULTS AND DISCUSSION

The hysteresis error of several heat-treated spring materials are presented in Figures 2-4. In these figures, measured data are shown with symbols (♦,∇, •) while corresponding fitted curves are plotted with continuous lines. The dashed horizontal line represents the highest permissible hysterisis error limit in force transducers conforming EN 10002-3 standards according to full scale output (FS) in each figure [10]. As it explained tranducer design section that the three groups of measurement results are obtained from two specimens that are subjected to identical heat treatment The result most deviated from an average value is decided as bonding error and not presented. The difference between three experimental results is attributed to bonding errors.

The bonding error is possibly resulted from the strain gage application even the all conditions are identical.
Average values of these three data are plotted to the graphs for comparison of the results to see effect of heat treatment on the hysteresis error of force transducers. Two type of graph are plotted as fitted curve and bar shape for better representation the comparison results. The hysteresis error of several heat-treated spring materials are presented in Figure 5.

Figures 4-6 show the hysteresis errors of three results from the specimens with martensitic, bainitic and coarse martensitic structures having hardness value of 45±1 HRC and represented with MART 45 HRC, BAIN 45 HRC, COMART 45 HRC respectively.

It is seen that the hysteresis error is strong function of microstructure. These results can be attributed to crystal structure of the specimen forms after heat treatment.

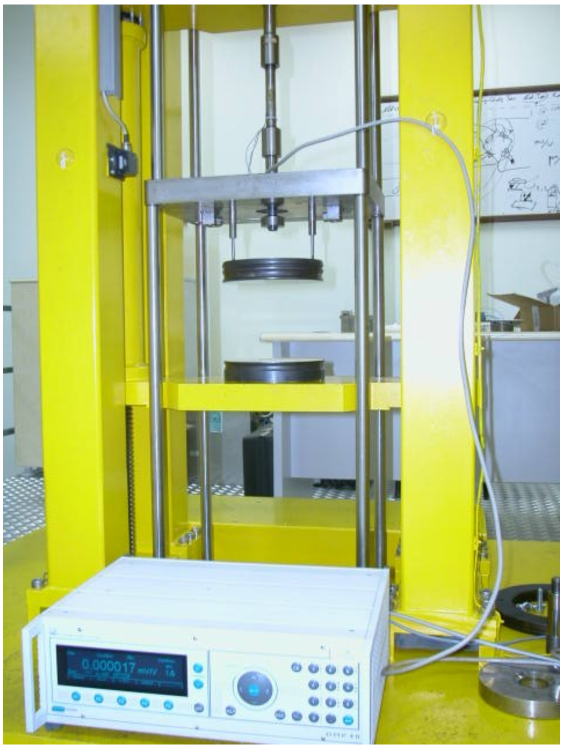

Figure 1. Completed force transducer specimen and measuring amplifier under performance test in 110 kN dead weight force standard machine.

When a comparison is made for hysterisis error performance of specimens containing different structures but having the same hardness (45±1 HRCD) such as tempered martensite (MART 45 HRC), bainite (BAIN 45 HRC) and coarse tempered martensite (COMART 45 HRC), it can easily be concluded that the maximum hysterisis error was obtained in coarse tempered martensite structure and the minimum hysterisis error was obtained in bainite structure. Although all of these structures have the same hardness 45 HRC, the micro structural changes must be responsible for the change in hysterisis error performance. The martensite type, residual austenite, shape, size and distribution of cementite and/or other carbides as well as dislocation density are the principal factors that are causing micro structural changes. Since the main reason of hysterisis error was mainly attributed to the restriction of dislocation motion in the structure, some factors and mechanisms should effectively influence the mobility of dislocations in different microstructures of AISI 4340 steel. The increase of strength in bainitic structure is believed due to fine cementite (Fe_3C) particles distribution in the structure instead of lamella cementite. Finely distributed Fe_3C particles in the ferrite matrix cause a very effective restriction to the movement of dislocations and consequently it results a considerable increase in the strength of material [11-13].

Dislocation density is one of the most important factors dictating the hysterisis error characteristics of materials. Although they have the same hardness, tempered martensite and bainite contain different dislocation densities [14]. The dislocation density is about 15 x 10^{11} per cm^2 for martensite while the dislocation density is about 6.3 x 10^{11} per cm^2 for bainite at the same hardness level near to 45 HRC [14]. In other words, dislocation density of martensite is approximately two times greater than of bainite for the same hardness level. Since the bainite structure has lower dislocation density than the tempered martensite, fine cementite and/or carbide particles most probably increase the resistance to dislocation motion with respect to tempered martensite structure. The existing carbide particle barriers to movements of dislocations are playing a strong role in bowing and piling up dislocations effectively and this will cause decrease in hysterisis error for bainite structures in steels.

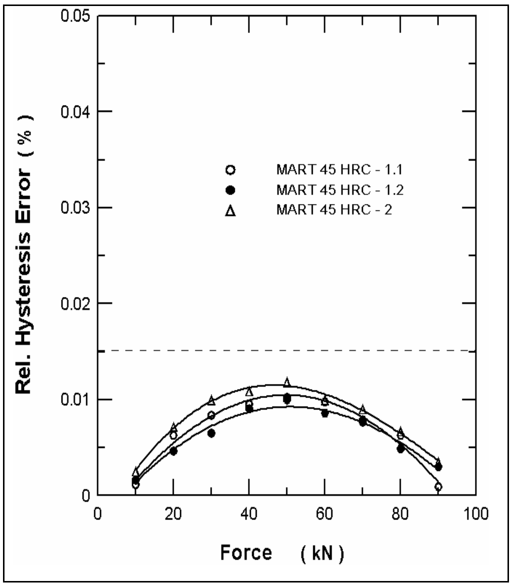

Figure 2. Hysterisis graph for martensitic structure specimens having 45 HRC hardness.

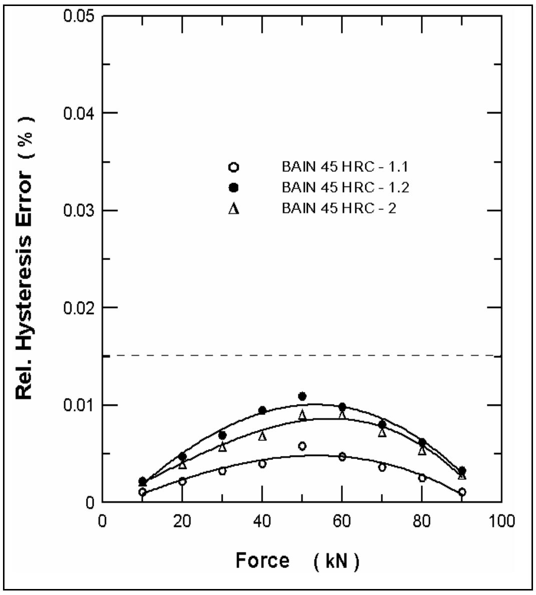

Figure 3. Hysterisis graph for bainitic structure specimens having 45 HRC hardness.

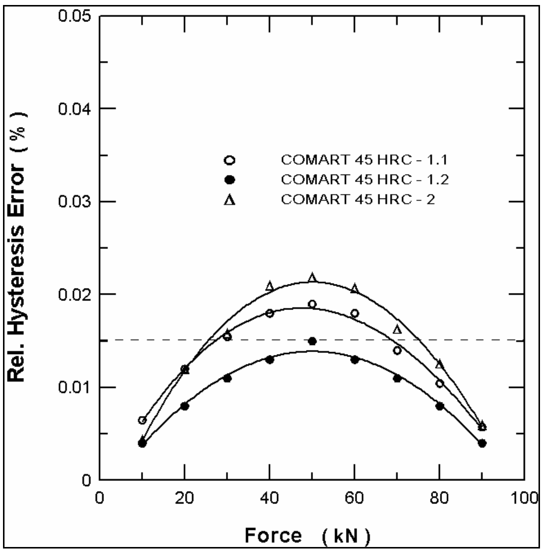

Figure 4. Hysterisis graph for coarse martensitic structure specimens having 45 HRC hardness.

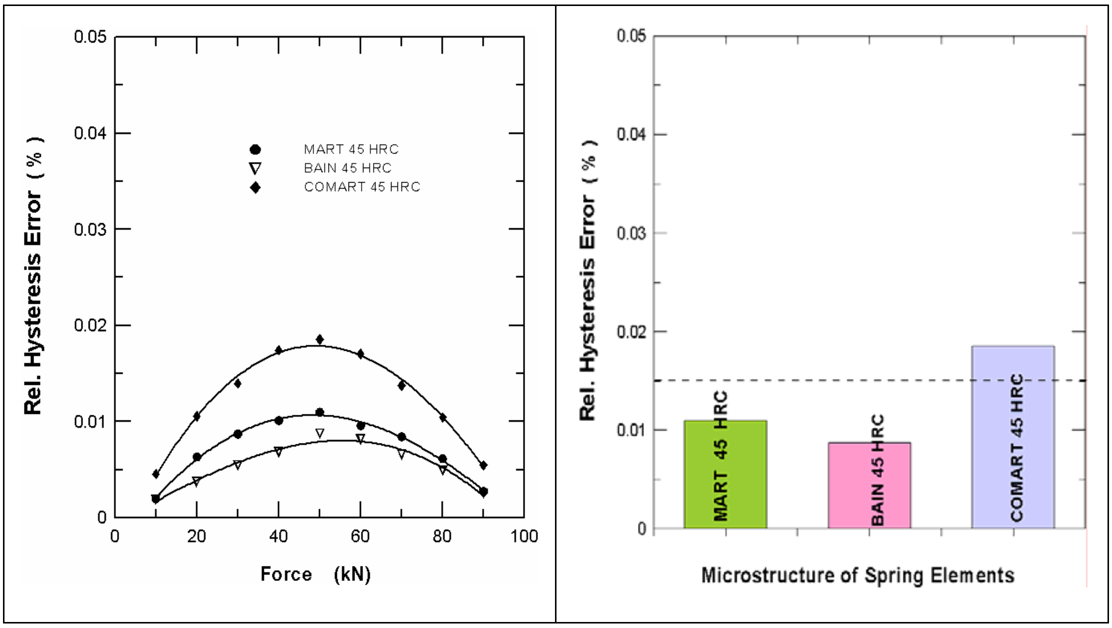

Figure 5. Comparison graph for the hysterisis errors of specimens with martensitic, bainitic and coarse martensitic structures having hardness value of 45 HRC.

Prior austenite grain size of coarse tempered martensite is approximately 50 percent greater than pf fine tempered martensite structure due to the prolonged waiting at the austenitizing temperature of 1273 K. It is known that the increase of strength of material may also be related to the increase of grain or crystal surface area and block boundaries area in martensite. Since coarse tempered martensite has less grain or block boundary surface area than of fine tempered martensite, the dislocations can move more easily and consequently hysterisis error will be increased in coarse tempered martensite structure [15].

6. CONCLUSIONS

The conclusions of the study can be outlined as follows:

a. AISI 4340 steel spring element containing bainite structure exhibits better hysterisis error performance than of the same steel spring element containing tempered martensite structure at the same hardness level,
b. Coarse tempered martensite structure has harmful effects on hysterisis error performance of steel spring elements of force transducers with respect to fine tempered martensitic structure at the same hardness level.

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