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Effect of Hardness on Creep Response of Strain Gage Based Force Transducer Using AISI 4340 Steel as Spring Material

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Abstract

Creep problem of spring materials plays an effective role on the performance of force transducers. Several heat treatments can be applied to spring materials in order to minimize creep response. The effect of heat treatment on creep properties of AISI 4340 steel was investigated in this study. The tensile specimens of AISI 4340 steel were austenitized and oil quenched, and then tempered to 35, 45 and 55 Rockwell-C hardness levels. After proper heat treatment and final machining of column type specimens, the preparation of tensile force transducers was completed by bonding special-class transducer strain-gages onto them and constructing necessary Wheatstone bridge circuits. Then all force transducers were loaded in a dead-weight force standard machine to measure the related creep response. It was observed that heat treatment (and the resulting martensitic structure) of the spring material had a major effect on the performance of the transducer, particularly where creep response was concerned. Since the minimization of creep problem had prime concern, best results could be achieved in transducers consisting the hardest spring material.

1. Introduction

Strain-gage based force transducers are used extensively in different branches of industry. Several applications of force transducers in materials laboratories, manufacturing and control systems, where critical force measurements are strictly needed. When a load is applied to a transducer, dwell time in loading may have influence on obtaining precise results in measurements. The creep response of transducer must be known very well in order to obtain reliable results. If the measurements are made under similar conditions and with identical dwell time under load, the amount of creep response is not so important. When different dwell time range and loading conditions are present, different outputs from transducers can be obtained depending on their creep responses. The user involving precise measurements of force does not prefer this type of transducer and try to use force transducers having minimum creep response. Creep of a force transducer can be defined as the difference between initial response under load and the response after certain period of time under the same load [1]. In order to achieve high accuracies in force transducers, it is essential to select good performance materials, to perform good design, and to apply carefully controlled manufacturing procedures. 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].

Spring materials may exhibit different creep behavior and application of heat and thermo-mechanical treatments cause microstructural changes and creep response of force transducers respectively [3]. The aging heat treatment also improves the creep performance of Be-Cu alloys as spring element [4].

Creep response of a transducer can be adjusted by adjusting the end tabs of strain-gages [2,4]. The most important specifications of force transducers for long-term reliability are the hysteresis and creep response of spring elements [5,6]. Two sources of creep can be pronounced; the first is from the material of spring element, which is due to small scale permanent deformation under load, and the second is related to the transfer of elastic deformation from spring element to the strain gage through the cement and backing of gage [4-6]. Generally, metal spring elements of transducers show positive creep behavior while strain gages and adhesives show negative creep characteristics [7,8]. Creep is time dependent behavior of materials and influences the uncertainty of measurements. Under the influence of elastic and/or thermal stresses, some imperfections in the material and incompatibilities of the elements in transducer are the probable sources of creep errors in force transducers [9]. It is well known that metal spring elements in force transducers and load cells do not behave in a perfectly elastic manner, even they are stressed well below than the elastic limit [10]. Small scale inelasticity causes non linear characteristics in stress-strain plot and the main reason is attributed to the inelastic behaviour of materials due to time dependent creep [11]. It is well established that structural characteristics or mechanical properties have extremely important role in inelastic behaviour of spring materials and creep response respectively [2-4,9,12]. The easiest way to change microstructure and mechanical properties of materials is to apply heat treatments. In this study, AISI 4340 low alloy steel was selected as spring material for a force transducer and the effect of hardness on creep response was investigated. Applying austenitizing, quenching in oil and proper tempering treatment, necessary changes in hardness were maintained in the range between 35-55 Rockwell-C and the change in creep response were determined for different hardness levels of steel.

2. Transducer Design

All transducers were 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. The strain gage producer advised such strain level to obtain better performance and longer fatigue life limits [8]. Using the selected strain level, output signal that is ratio of output voltage, V, and excitation voltage, U, in wheatstone bridge circuit, is calculated as 2 mV/V which is a desired value for the transducer [3]. In order to complete the wheatstone bridge circuit, two strain gages are bonded in axial (longitudinal) direction (ε_1 and ε_3) and two of them in radial (lateral) direction (ε_2 and ε_4). A relation between output signal and measured strain values can be expressed as[13];

$$\frac{V}{U} = \frac{k}{4}(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4) \qquad (1)$$

When the column type design shown in Fig.1 used in force transducer application, Poisson ratio, ν, influences the Eq.(1). Using the definition of Poisson ratio ($\nu=-\varepsilon_2/\varepsilon_1$) and its value for the steel ($\nu\cong0.3$), the output signal equation can be written as;

$$\frac{V}{U} = \frac{k}{4}\left[\varepsilon_1 - (-0.3\cdot\varepsilon_1) + \varepsilon_1 - (-0.3\cdot\varepsilon_1)\right]$$

$$= \frac{k}{4}\cdot 2.6\cdot\varepsilon_1 \qquad (2)$$

In order to obtain output signal from transducer spring element, mechanical strain should be converted to for electrical signal. For this purposes, strain gages are used in applications. N2A-06-S053P-350, model strain gages were used in this study. This model strain gages are specially produced for column type transducers by Measurement Group Co, USA and its resistance value, gage factor (k) are 350 Ω and 2.09 respectively. 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].

These strain gages are produced 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.

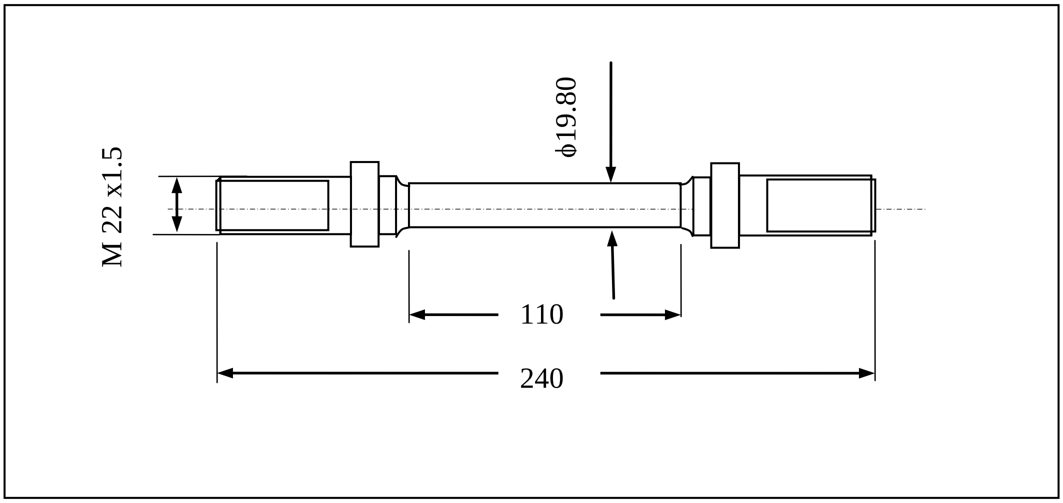

Figure 1. Geometry of column type spring element

3. Material and Heat Treatment Details

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 [3,14]. During the heat

treatment of from spring elements, all specimens placed in the gas-controlled oven to protect them decarburising. Austenitising is performed in 845° C [15] for 30 minutes in 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. Total six specimens were oil quenched from 845° C to room temperature to obtain martensitic structure.

Table.1. Mechanical properties of AISI 4340 steel used in the study.

Specimen Code	**Tempering Temperature**	**Ultimate Tensile Strength**	**Yield Strength**	**Elongation**	**Hardness**
	°C	**Mpa**	**Mpa**	**%**	**R_C**
MARTEN 35 R_C	600	1001	919	18	35±1
MARTEN 45 R_C	440	1471	1372	12	45±1
MARTEN 55 R_C	205	1918	1707	11	55±1

In order to obtain different hardness level, a pair of specimens was tempered at different temperatures. Each pair of specimens were tempered 600° C, 440° C and 205° C sequentially to obtain different hardness levels [15-18]. The pairs of specimens have the hardness levels of 35 ±1 R_C (Hardness Rockwell C), 45 ±1 R_C and 55 ±1 R_C respectively. All of them are held in oven for 90 minutes during tempering process then cooled in air. This study was focused to examine, how the hardness really affect the creep responses of the identical martensitic structure.

The mechanical properties of different hardness level in martensitic structure were obtained in tension test results are shown in Table.1

4. Strain Gage Application

Correct application of strain gages is very important to obtain repeatable performance from the force transducers. Recommendations of strain gage producer are carefully applied to obtain better performance and quality bonding. Final transducer performances are greatly depending on the application of a uniform and repeatable clamping pressure Schematic sketch of a typical strain gage installation is shown in Fig.2. Clamping pressure controls glue line thickness and state of stress in the installed gage-both major factors in performance [19]. Manufacturer recommends the clamping pressure to be 300-400 kPa (3-4 bar). Special spring clamps are used during bonding of strain gages.

Strain gages are bonded according to manufacturer recommendations. M bond-610 is used as an adhesive for strain gage application. This adhesive produces the thin and almost creep free glue line. . After clamping of the strain gage, adhesive glue line temperature is raised at a rate approximately 5 C/min. This is done to protect the adhesive from failure causing uneven thickness and bubble formation.

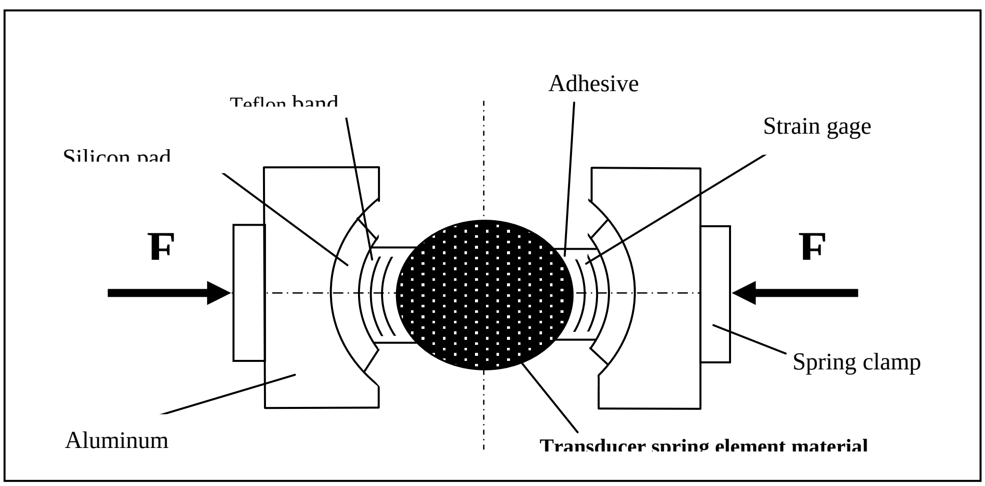

Figure 2. Installation of strain gages for bonding and under clamping conditions.

Transducer is placed together with clamps for curing of adhesive in 175 C temperature for 1 hour. After curing of adhesive the elements allowed to cool down to at least 55 C before clamps are removed. Then transducers are then placed in an oven to raise their temperature to 205 C and left for 2 hours in this temperature for post curing of adhesive. Post curing of strain gage installations is an essential step in assuring stable transducer performance during initial cure. The adhesive will polymerise at elevated temperature. Due to the high forces applied to the gage during clamping, residual stresses will be locked-in to the gage when polymerisation occurs. Proper post curing steps (with clamps removed) will greatly reduce these residuals and their pronounced effects on the backing and adhesive stability [19].

5. Testing Procedure

A constant force is applied on the force transducer in a 110 kN dead weight force standard machine. Creep response is recorded using high precision indicating instrument that is DMP 40 S2 located in Force Laboratory in the National Metrology Institute of Turkey. Figure 3 shows the the force transducers which is under test in dead weight force standard machine.

The test load applied by this machine is 100 kN and corresponding times required to apply and remove the test load is 20 minutes.

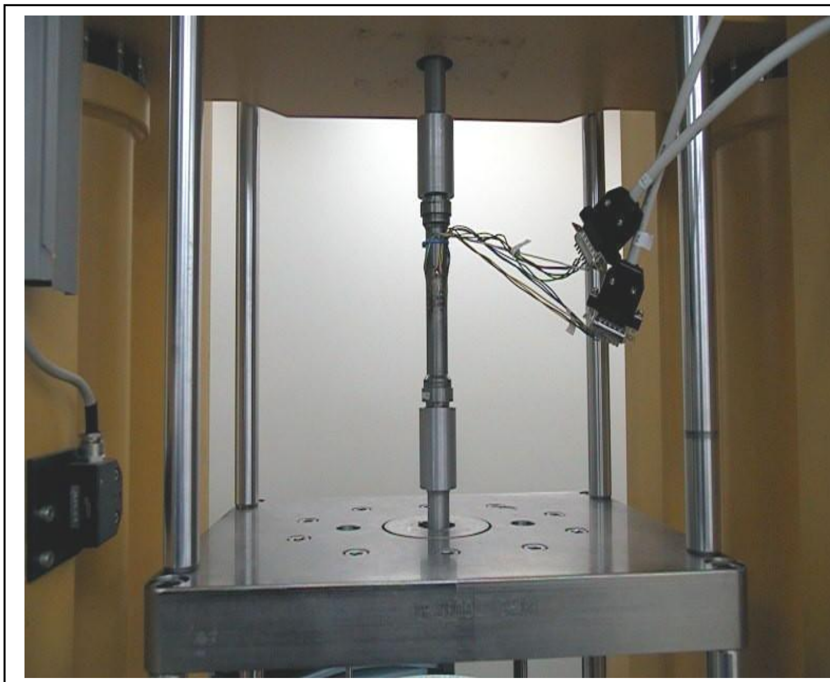

Figure 3. Tension type force transducer in 100 kN dead weight machine at UME

The output of transducers was recorded a minute interval during the measurements.The loading rate is identical for each test since the dead weight machine automatically applies load.

The creep response is calculated from following relation using the data measured during 20 minutes in test period [1];

$$s = \frac{r_n - r_{ref}}{r_{ref} - r_0} \times 100 \quad (3)$$

s : % creep response (error)

r_n : *n* th reading following the reference reading

r_{20sn} : 20 seconds reference reading

r_0 : initial unloaded reading

These tests are performed in very finely controlled laboratory conditions with a temperature of 21±1 C and humidity of 45 ± 5 %. The short-term temperature control is much better than ±1 °C. The temperature variation is measured to be ±0.2 °C in two hour and better than ±0.1 C during creep tests lasting 20 minutes. Since the construction of force transducer is not affected by changes in barometric pressure, the pressure is not recorded.

6. Results and Discussion

The creep responses of several heat treated spring materials are presented in Figures 4-6. In these figures, measured data are shown with symbols (♦,∇, •) while corresponding fitted curves are plotted with continuous lines. Figure 4 shows the creep responses of three results from two specimens with martensitic structure having hardness value of 35±1 R_C and represented with MARTEN 35 R_C. As it explained in previous (tranducer design) section that the four groups of measurement results are obtained from two specimens that are subjected to identical heat treatment. Only three of closest results are presented on the figures. 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.

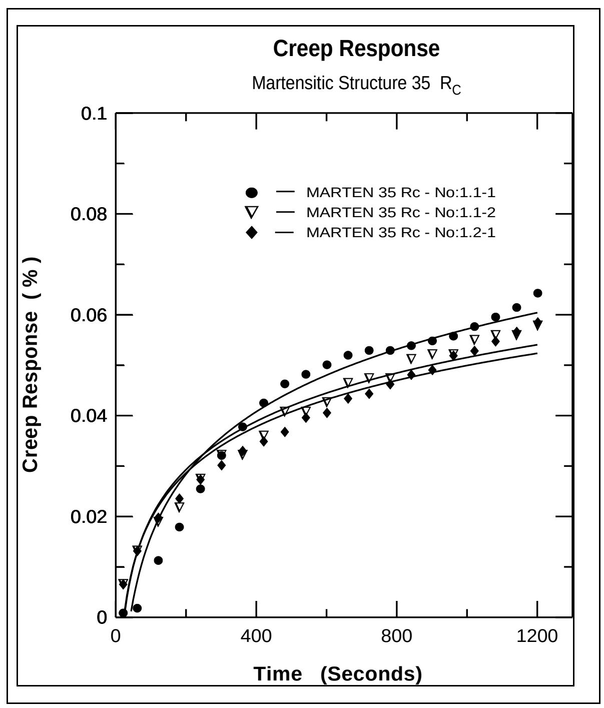

Figure 4. Creep response of specimens with 35±1 R_C hardness

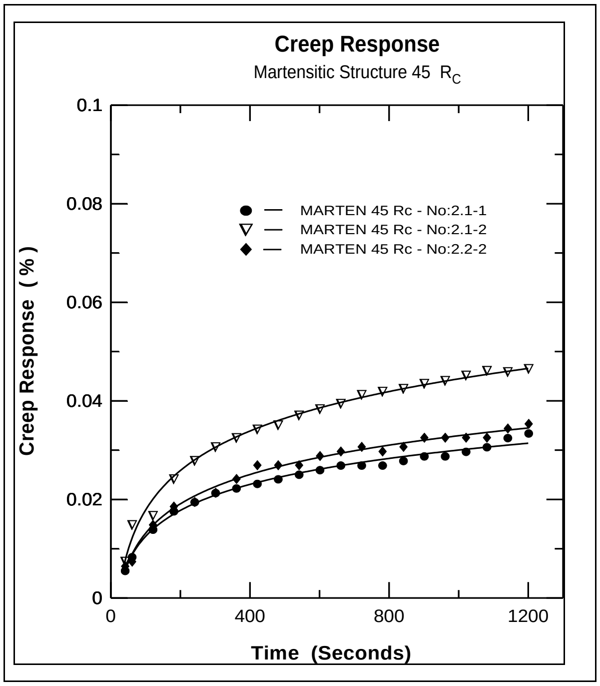

Figure 5. Creep response of specimens with 45±1 R_C hardness

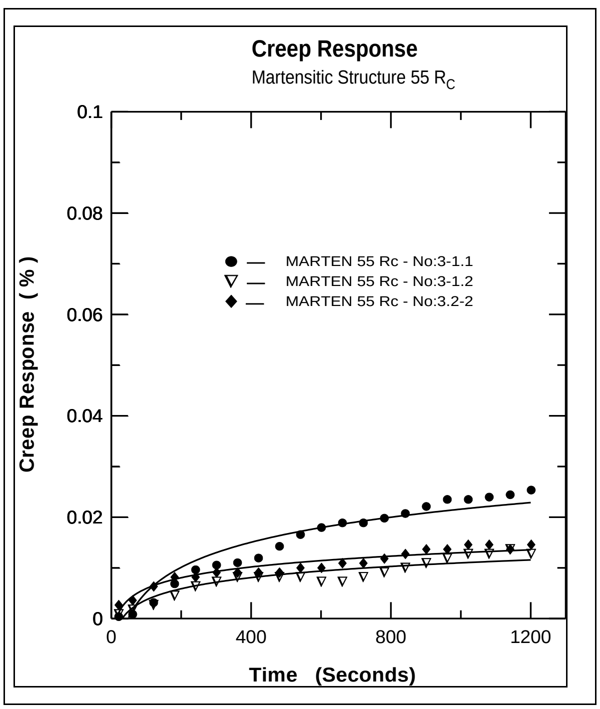

Figure 6. Creep response of specimens with 55± 1 R_C hardness

Similarly, Fig.5 and Fig.6 show the creep responses of two group specimens with martensitic structure having hardness values of 45±1 R_C and 55±1 R_C respectively. These are represented in the figures as MARTEN 45 R_C and MARTEN 55 R_C.

7. Comparison of Creep Responses

Fig. 7 compares the creep responses for three different specimen group having the hardness values of 35, 45, and 55 R_C with martensitic structure. Each plot shows the average value of three measurement presented in Fig.4, Fig.5 and Fig.6. In this figure, three average measurement results are plotted and shown with symbols (♦,∇, •) and the fitted curve also presented with continuous line.

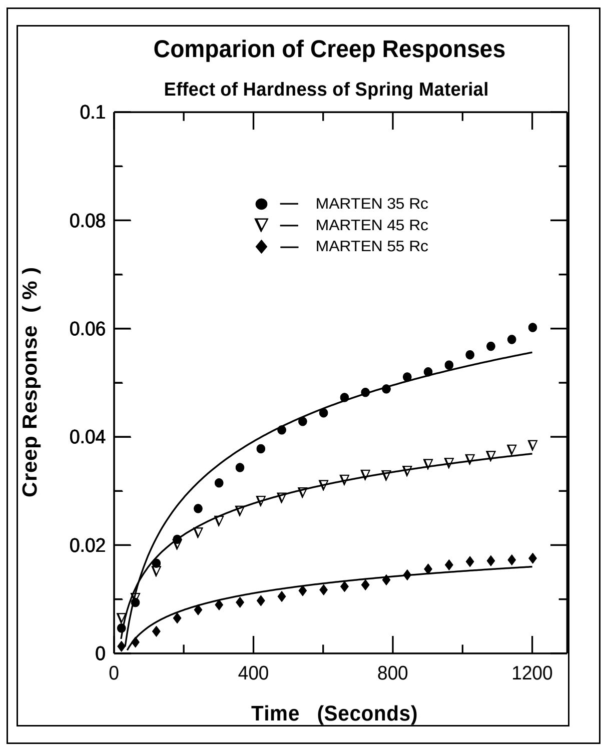

Figure 7. Creep response of specimens with 45±1 R_C hardness

It is seen that the creep response is strong function of the hardness. Even though all the specimens have martensitic structure, they exhibit different creep responses. The creep response is lower at high hardness values. This result can be attributed to crystal structure of the specimen forms after heat treatment.

8. Conclusion

In this study, the creep response of materials having martensitic structure with a range of hardness is experimentally measured. It is found that heat treatment applied on the spring element influence the creep response of force transducer. It is possible to control hardness of martensite structure with the heat treatment.

It is found that the creep response decreases at high hardness and increases as materials soften. The hardest specimens, which is MARTEN 55 R_C, show the best behaviour among materials tested or shows the smallest creep response. This behaviour may be attributed to dislocation density. These specimens have the highest dislocation density and this high density causes the dislocation locking and resist to dislocation movement in the grains [20-22]. As a result of this resistance, the dislocation motion cause to decrease creep response and small elastic change under load. The average creep response of the test materials also compared and shown in Fig.7 the hardest material has the best creep response.

In this study, all of strain gages have the identical characteristics and creep code. For this reason, the results only reflect only the effects of heat treatment. After determination of best hardness or heat treatment on the transducer spring material, resulting creep code can be adjusted by strain gage manufacturer for mass production of force transducers.

9. References

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