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The effect of low tempering, medium tempering, and high tempering heating temperature variations in the type of medium carbon steel ST 60 on microstructure, hardness, and toughness

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The effect of low tempering, medium tempering, and high tempering heating temperature variations in the type of medium carbon steel ST 60 on microstructure, hardness, and toughness.

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Abstract. To determine the changes in the microstructure, impact strength, and hardness of the carbon steel medium type ST 60 with variations in temperature: quenching, tempering 200^{0}C, tempering 400^{0}C and tempering 600^{0}C, then a heat treatment was given at 850^{0}C for 30 minutes then quenched with brine solution with a salt content of 10% and continued with tempering for 30 minutes with variations in tempering temperature: 200^{0}C, 400^{0}C and 600^{0}C. The chemical composition of the ST 60 steel specimen obtained that the main constituent elements are iron (Fe) = 98.1%, manganese (Mn) = 0.572%, silisium (Si) = 0.246%, and carbon (C) = 0.362%. Meanwhile, the hardness, impact, and microstructure test results show that the quenching specimen has the hardest and softest material properties. This is indicated by the highest hardness value of 772.67 VHN and the smallest impact value of 1.24 J / mm². The martensite phase structure formed causes the material properties to be the hardest. In the 200^{0}C tempering specimen the hardness began to decrease and the ductility increased as indicated by the hardness value of 625 VHN and the impact value of 2.02 J / mm². In this specimen, a tempered martensite phase was formed, which is softer than martensite. In the 400^{0}C tempering specimen, the hardness value was getting smaller, but the ductility increased as indicated by the hardness value of 448.67 VHN and the impact value of 2.56 J / mm². The bainite phase structure with ductile / malleable properties was formed in this specimen. In the 600^{0}C tempering specimen the properties of the resulting material were the most ductile and softest indicated by the lowest hardness value of 295 VHN and the highest impact value of 3.11 J / mm². The structure of the ferrite and fine pearlite phases with very soft properties was formed in this specimen.
Keywords : Quenching, Tempering, Martensite, Ferrite, Bainite, Pearlite

1. Introduction

The heat treatment process aims to obtain a metal that is hard, soft, ductile, and eliminates residual stress. Heat treatment is often referred to as a way to increase the hardness of the material, in fact it can also be used to change the properties of use or with certain interests for user needs, such as: increasing malleability, restoring elasticity after cold work. Even heat treatment not only changes the properties of the material, but is also able to increase the performance of the material by increasing the strength or certain characteristics of the material that has been heat treated (Beumer, 1985).

Through the tempering process, hardness and ductility can be reduced to meet the requirements of use. If the hardness decreases, the tensile strength decreases while the ductility and toughness of the steel increase. The tempering process consists of reheating the hardened steel to below the critical temperature, followed by cooling. Although this process produces a softer steel, it differs from annealing process because here physical properties can be carefully controlled (Amstead, 1995).

Based on the above background, the writer needs to conduct research studies on the effect of tempering temperature variations on ST 60 steel to determine the effects that occur so that the results can be possible in more optimal use in several applications in the field.

2. Study Methods

The study method used is experimental method. The research material referred to in this includes primary and secondary data as well as theory and references which form the basis of this research. The selected experimental design category is ST 60 steel specimen that has undergone heat treatment with temperature variations, namely tempering.

- *Heating Process*

Heating begins with the preparation of materials and heating kitchen. Heating is done using an electric kitchen. The quenching specimens were heated at 850^{0}C while the tempering process was set at 200^{0}C, 400^{0}C, and 600^{0}C, respectively.

- *Quenching Process*

The quenching process is carried out by cooling all specimens that have been heated at 850^{0}C into a brine solution with a salt content of 10%.

- *Tempering Process*

The tempering process is carried out by reheating the tempered specimens at temperatures of 200^{0}C, 400^{0}C, and 600^{0}C respectively into a heating kitchen then cooled naturally in open air.

- *Testing Specimens*

This specimen test was carried out to determine the characteristics of the material from quenching and tempering at temperature variations of 200^{0}C, 400^{0}C, and 600^{0}C, respectively.

3. Results And Discussion

Chemical Composition Test Results

This test aims to determine the percentage content of the elements in the steel contained in the test object, in particular the carbon content (C). Testing the chemical composition using the WAS Spectrometer by firing argon gas at the test specimen then giving the reading results automatically in the form of the average chemical composition content of the specimen or test object.

Figure 1. Spectrometer Testing Equipment and Test Specimens

From the test results, the chemical composition of the specimen contains the main constituent elements iron (Fe) = 98.1%, manganese (Mn) = 0.572% which is useful for increasing hardness, strength, and can be hardened in steel. Silisium (Si) = 0.246% which is influential in increasing the overall hardening ability, wear resistance, resistance to heat and rust. While other elements obtained are: copper (Cu) = 0.0125%, carbon (C) = 0.362%, aluminum (Al) = 0.0117%, chromium (Cr) = 0.369%, phosphorus (P) = 0.0654%, sulfur (S) = 0.0094%, nickel (Ni) = 0.0135.

Based on the carbon content (C) in the test specimen of 0.369%, the test material is included in the content of medium carbon steel, which is the main requirement for medium carbon steel to contain carbon (C) between 0, 30% - 0.60%.

Testing of Micrographic Structures

The new micro structure will be clearly visible when the surface of the test object is completely flat, smooth and shiny without scratches, and has undergone proper embracing. Observations were carried out under an Olympus Metallurgical Microscope with optimal magnification, while for shooting, the Olympus Photomicrographic System was added.

Microstructure testing is carried out to observe and physically compare the microstructure of each part of the specimen, observe the microstructure of the specimen without, and by experiencing heat treatment followed by a varied cooling process. The main location for taking photos is specimens with quenching treatment and for tempering specimens with temperature variations: 200^{o}C, 400^{o}C and 600^{o}C.

Shooting will be done after the appearance is completely clear or in focus. The number of objects photographed for their micro structure is the same as the number of test objects (tested for hardness) because the hardness test is carried out on objects that have already been photographed for their microstructure. The steps for testing the microstructure are as follows:

1. Inserting the film into the Olympus Photomicrographic System camera that is available.
2. Turn on the appliance by pressing the power button.
3. Prepare test specimens.
4. Place the specimen on the test plane or table.
5. Ensure that the specimen is not skewed.
6. Select the desired magnification.
7. Determine the shooting point so that it can be seen clearly.
8. Carry out the shooting process with the desired magnification

a. *Micro Quenching Photo*

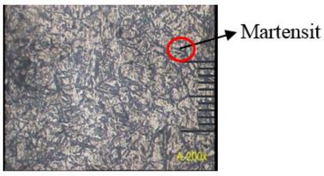

Figure 2. Photo of Micro Structure of Medium Carbon Steel Quenching with Magnification 200x.

This specimen has the highest hardness value, this is due to the presence of a martensite phase (black color with a hardness value> 500 VHN) which is shaped like larger needles that are evenly distributed due to rapid cooling (Quenching) with salt water, causing the properties of the material. hardest and brittle which is one of the main properties of the martensite structure. Although, the hardest and most ductile properties make the specimen tough or malleable or easy to break if the excess energy is applied to it.

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b. Photo Micro Tempering 200 ℃

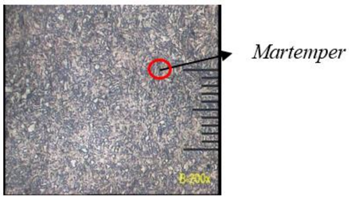

Figure 3. Photo of Medium Carbon Steel Tempering 200^{0}C Micro Structure with 200x Magnification.

At the lowest tempering temperature with a temperature of 200^{0}C, the martensite temper (martemper) phase is obtained which can prove the occurrence of a very fast cooling rate followed by reheating. The structure of tempered martensite (martemper) is formed more tightly and evenly. The fast cooling rate then with the lowest heat input of 200^{0}C produces tempered martensite whose structure is shaped like needles that are evenly distributed (black color and hardness value> 500 VHN) and smaller than the martensite structure, causing a decrease in the hardness value of the test material. The nature of the tempered martensite structure is softer than the quenched martensite structure, because the quenched masrtensite structure has undergone improvement / transformation of the phase structure.

c. Photo Micro Tempering 400 ℃

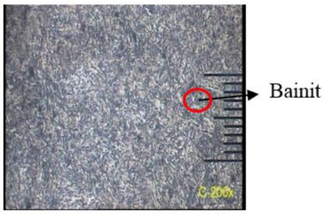

Figure 4. Photo of 400 C Tempering Medium Carbon Steel Micro Structure with 200x Magnification.

There is a predominance of the bainite phase structure (hardness values between 300-400 VHN). The process of forming the bainite structure begins with heating the steel until it reaches the austenite phase with a high temperature of 850^{0}C for 30 minutes which is then followed by rapid immersion / cooling in salt water with a salt content of 10% and then reheated (tempering) at a temperature above the formation Martensite start (Ms) with a temperature of 400^{0}C, held for a while (30 minutes) and continued with normal cooling in the air. So that the austenite phase structure can be transformed into a bainite phase structure. This process causes the hardness value of the test specimen to decrease, but the ductility or toughness increases.

d. Photo Micro Tempering 600 ℃

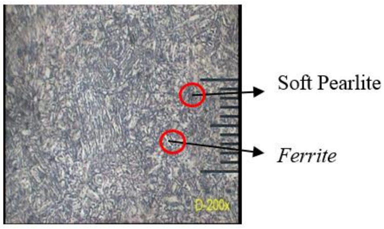

Figure 5. Photo of Micro Structure Medium Carbon Steel Tempering 600^{0}C with 200x Magnification.

It can be seen that the structural forms of the ferrite and fine pearlite phases (hardness between 180-300 VHN) with small and fine grains (fine pearlite). The form of the ferrite structure appears white and soft. While the form of fine pearlite structure is small dark / black granules. The structure of the ferrite and pearlite phases is formed from the transformation of the austenization process (heating the material to a temperature of 850^{0}C) due to slow cooling (re-heating after the quenching treatment until the ferrite and pearlite phases are formed), causing the specimen to be very tough, ductile, and softest which is a common characteristic. both of these phase structures.

a. Impact Test

This test aims to determine the value of resistance, toughness and visibility of the test object against dynamic loads. The impact test is carried out in one stroke for one specimen and 3 specimens for each variation, including specimen A (quenching), specimen B (tempering 200^{0}C), specimen C (tempering 400^{0}C), and specimen D (tempering 600^{0}C).

Things that must be considered when carrying out an impact test are the energy / energy absorbed by the test object or energy to break the test object which can be written in the form of a formula :

$$E = m.g\,(h1-h2) \quad (1)$$

So,

$$\text{Impact Value} = \frac{\text{energi terserap (j)}}{\text{luas penampang payahan benda uji (mm}^2\text{)}} \quad (2)$$

Figure 6. Impact testing process

Table 1. Impact Test Results using the Charpy method

No	Speciment	Wide (mm)	High (mm)	Energy (J)	Impact Value (J/mm²)
A1	*Quenching*	10.32	7.60	88.00	1.12
A2		9.98	7.56	96.00	1.27
A3		10.06	7.10	98.00	1.37
B1	*Quench-Tempering* 200^0C	10.28	7.40	202.00	2.66
B2		10.10	7.26	134.00	1.83
B3		10.14	7.58	198.00	2.58
C1	*Quench-Tempering* 400^0C	10.14	7.24	198.00	2.70
C2		10.10	6.80	184.00	2.68
C3		10.12	7.36	172.00	2.31
D1	*Quench-Tempering* 600^0C	10.30	7.38	226.00	2.97
D2		10.10	7.28	238.00	3.24
D3		10.06	6.98	220.00	3.13

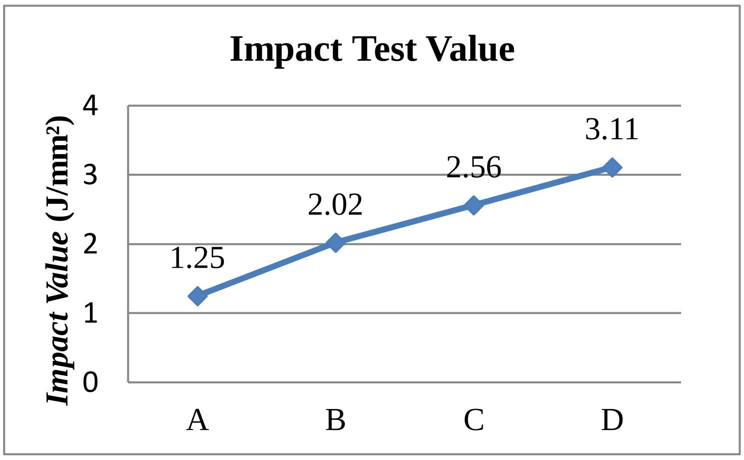

Figure 7. Graph of Mean Value of Impact Test

From the results of the impact test, the highest average toughness value (toughest and most ductile) was the specimen with a tempering treatment of 600^0C of 3.11 J / mm² and respectively to the lowest position, namely: the specimen of 400^0C tempering treatment of 2, 56 J / mm², the 200 perlakuanC tempering treatment specimen was 2.02 J / mm² and the lowest (most brittle / soft) specimen was quenched with an impact value of 1.25 J / mm².

Impact Specimen Quenching
It was the most brittle and softest specimen with the lowest mean impact value (1.25 J / mm²). This is due to rapid cooling after heating to a temperature of 850 ^{0}C, so that it forms large / coarse metal crystals (martensite), the bonds between the grains are weak and brittle breaks easily. The brittle type fracture can be seen in the following figure with the smallest deformation characteristic (shown by a flat surface fracture).

Figure 8. Quenching Specimen Fault

Impact Specimen Tempering 200 ^{0}C

In the 200^{0}C (2.02 J / mm²) tempering specimen, the tempered martensite phase was stronger, although the hardness decreased because the metal grains were slightly smaller causing the metal bond to be stronger. Brittle-type fractures were seen in this specimen.

Figure 9. Fault of Tempering Specimen 200 ^{0}C

Impact Specimen Tempering 400 C

The impact strength of the 400^{0}C tempering specimen of 2.56 J / mm² is greater than that of the 200^{0}C tempering specimen because the bainite phase with a fine carbide dispersion in ferrite makes the metal crystalline grains finer which leads to increased toughness and visible test specimens. The clay type fracture shows high plastic deformation (the fracture surface looks rough and tapered).

Figure 10. Fault of the 400 C Tempering Specimen

Impact Specimen Tempering 600 ^{0}C

The 600^{0}C tempering specimen had the greatest average impact value, at 3.11 J / mm². Due to the slowest cooling (with a maximum heat input of 600^{0}C) it produces the finest grains of ferrite and pearlite crystals that make this specimen the toughest and most resilient. The fracture that occurs is a clay fracture, seen from the more sharp and sharp fractures that show higher plastic deformation and greater energy absorption.

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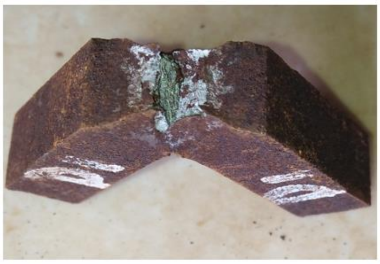

Figure 11. Tempering Specimen Fault 600 ^{0}C

b. Hardness Test

Hardness testing is carried out to determine the level of hardness and resistance of a material to deformation in the local area and material surface. In this case, the hardness test for ST 60 steel uses the Vickers method. The data from the test results are grouped into 4 groups of specimens, namely specimen A (Quenching), specimen B (tempering 200^{0}C), specimen C (tempering 400^{0}C), and specimen D (tempering 600^{0}C) with 3 test points on each specimen.

The hardness testing procedure is by pressing a hardened steel ball or forming a diamond pyramid on its surface. Then the size of the scrap is measured based on the pressure load and the size of the ball or pyramid, so the area of the mark gives a ratio of hardness values. Steel balls are used in the Brinell hardness test and the diamond point in the Vickers pyramid hardness test, which are more suitable for harder metals. In this test, the Vickers method is used with a load of 40 kg. The Vickers hardness test uses a diamond pyramid indenter which is basically a square shape. The angle between the faces of the diamond pyramid facing each other is 136. This value was chosen because it is close to most of the desired ratio values between the indentation diameter and the diameter of the impact ball in the brinell hardness test. The vickers hardness number is defined as the load divided by the surface area of the indentation. Practically. This area is calculated from microscopic measurements of the diagonal length of the trace. VHN can be determined from the following equation :

$$\mathrm{VHN} = \frac{2P\sin(\frac{\Theta}{2})}{d^2} = \frac{(1{,}854)P}{d^2} \tag{3}$$

with :
P = load used (kg)
d = the average diagonal length (mm)
ϴ = the angle between the facing diamond faces = 136^0

The Vickers hardness test is mostly done in research work because the method gives results in the form of a continuous hardness scale. The shape of the trampling marks that meet the Vickers principle is shown in Figure 12.

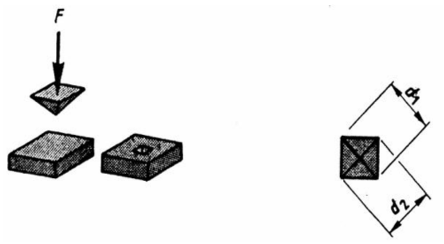

Figure 12. The Principle of the Hardness Testing Process Using the Vickers Method with a load of 1 to 120 kg.

Figure 13. Hardness Testing Process Using the Vickers Method with a Load used of 40 kg

Table 2. Hardness Test Results

No	Specimens	d1 (mm)	d2 (mm)	Average of d (mm)	Hardness Value (VHN)
A1		0.30	0.31	0.305	797
A2	*Quenching*	0.32	0.32	0.320	724
A3		0.31	0.30	0.305	797
B1	*Quench-*	0.37	0.35	0.360	572
B2	*Tempering*	0.34	0.33	0.335	661
B3	200^0C	0.34	0.34	0.340	642
C1	*Quench-*	0.40	0.40	0.400	464
C2	*Tempering*	0.42	0.40	0.410	441
C3	400^0C	0.42	0.40	0.410	441
D1	*Quench-*	0.50	0.50	0.500	297
D2	*Tempering*	0.50	0.49	0.495	303
D3	600^0C	0.51	0.51	0.510	285

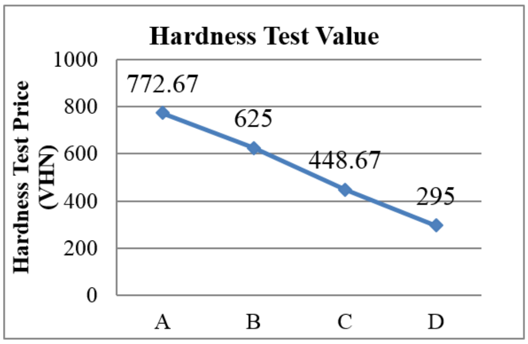

Figure 14. Graph of Average Hardness Test Value

From the results of the hardness test, the highest average hardness price was found in the quenching specimen of 772.67 VHN and respectively to the lowest position, namely: 200^0C tempering specimen at 625 VHN, 400^0C tempering specimen at 448.67 VHN and the lowest tempering 600^0C specimen. amounting to 295 VHN.

Quenching Specimen Hardness
Specimens with treatment, only on quenching without tempering and obtained the highest average hardness price of 772.67 VHN because the quenching treatment has a martensite phase and due to the fastest cooling rate by immersing the test object into a salt solution so that the phase transformation of the austenite runs more very quickly into the martensite phase. And this is evidenced by the highest price of hardness (the smallest diameter of the hole test results).

Tempering Specimen Hardness 200 ℃
The 200 SpesC tempering specimen with an average hardness value of 625 VHN is due to the fastest cooling rate by immersing the test object into a salt solution and then reheating (tempering) with the lowest temperature (200^0C) so that the phase transformation goes up to the martensite finish (Mf) until a tempered martensite phase was formed (below 220^0C). The nature of this specimen is still classified as hard, indicated by the diameter of the test result hole which is still of little value.

Tempering Specimen Hardness 400 ℃
The average hardness price of 400^0C tempering specimen is 448.67 VHN due to the temperature condition of the specimen passing through the martensite start area (Ms) and the temperature getting hotter (400^0C) so that the phase transformation from temper martensite enters the bainite phase area ($250\text{-}550^0$C) which indicated by a decrease in the hardness value of the test specimen or the softness of the specimen (indicated by the larger value of the hole in the test results).

Tempering Specimen Hardness 600 ℃
The average hardness price of 600^0C tempering specimen was 295 VHN. Because at a temperature of 600^0C, there is a transformation of austenite to pearlite and ferrite ($550\text{-}723^0$C) or from tempered martensite to bainite and then transformed into pearlite. Due to the very high heating temperature (slow cooling) so that the resulting metal grains become fine, small which causes the smallest hardness value (the softest, indicated by the diameter of the test results with the largest value).

Combining Test Results Graphs and Tempering Test Graph Correlation Using Time Transformation Temperature (TTT) Diagrams.

The following is the result of combining the test graph and the correlation of the tempering test graph using the Time Transformation Temperature (TTT) diagram :

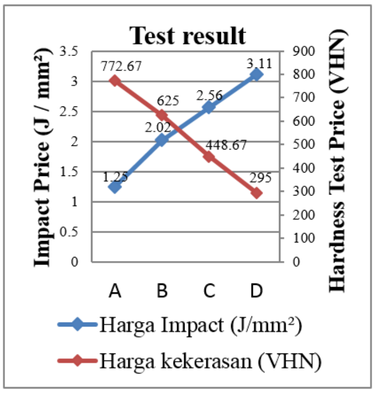

Figure 15. Graph of Hardness and Impact Test Results for St 60 Steel with Tempering Temperature Variations

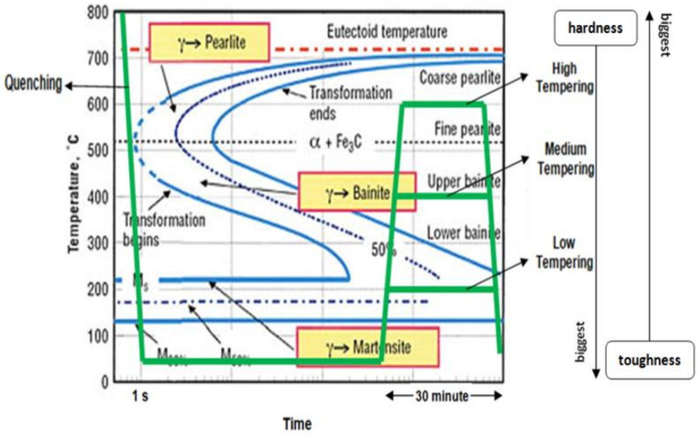

Figure 16. Graph of Tempering Treatment Diagram

The Martensite phase (the hardest character) is formed due to the rapid cooling / immersion process in a brine solution which was previously heated to a temperature of austenite (850^{0}C). Then 200^{0}C tempering by reheating the quenched specimen for 30 minutes to reduce the hardness value by forming a mild temper / martemper martenst phase.Tempering at 400^{0}C enters the formation of the bainite phase. By reheating the quenched test specimen at 400^{0}C for 30 minutes. The formation of the bainite phase gives the material properties to be tougher than the 200^{0}C test specimen, thereby reducing the hardness value and increasing the toughness value of the test specimen. High tempering with the highest temperature, which is 600^{0}C, produces the toughest test specimens with the formation of fine pearlite and ferrite phases, which have soft properties.

4. Conclusions

Based on the research data and the discussion in this study, it can be concluded that the quenching specimen has the hardest and softest material properties, indicated by the highest hardness value of 772.67 VHN and an impact value of 1.24 J / mm². The martensite phase structure formed causes the material properties to be the hardest.

In the 200^{0}C tempering specimen, hardness began to decrease and the toughness / ductility increased, as indicated by the hardness value of 625 VHN and the impact value of 2.02 J / mm². In this specimen a martemper phase (tempered martensite) is formed, which is softer than martensite.

In the 400^{0}C tempering specimen, the hardness value was getting smaller, but the toughness increased. This is indicated by a hardness value of 448.67 VHN and an impact value of 2.56 J / mm². The bainite phase structure with ductile / malleable properties was formed in this specimen.

In the 600^{0}C tempering specimen, the properties of the resulting material were the toughest / ductile and softest, indicated by the lowest hardness value of 295 VHN and the highest impact value of 3.11 J / mm². The structure of the ferrite and fine pearlite phases with very soft properties was formed in this specimen.

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