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Lath martensite in 1.4%C ultra-high carbon steel and its grain size effect

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Abstract

1.4%C ultra high carbon steel (UHCS) was prepared in order to study the substructure of martensite transformation. Because of ultra-fine spherical carbide, the growth of austenite grain, whose average size was 2.5 μm, was prohibited. After quenching, there was a great deal of lath martensite. The sub-structure was composed of a large quantity of dislocations and twins. Through calculation, it was determined that twin shear stress increases faster than that of slip due to the reduction of austenite grain sizes. A model based on twin and slip shear stresses has been proposed, which yields critical grain size ranges from 1–4 μm. The result is in agreement with measured results.
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Keywords: Martensitic phase transformation; Slip; Twin

The carbon content of ultrahigh carbon steels (UHCS) is in the range of 1.0–2.1% [1,2]. Traditional heat treatments used for normal steels will cause the microstructure of UHCS to be coarse and do not produce optimal properties. With controlled rolling and special heat treatment, UHCS can be in ferrite, pearlite, bainnite or martensite structures, which all have different mechanical properties. The yield stress of a 1.8%C, 1.6%Al ferrite UHCS can reach 1500 MPa, which is much higher than that of high strength and plain alloy steels [3]. The tensile strength of a 1.25%C–1.5%Cr pearlite UHCS can reach 1810 MPa and its elongation can be 18%. When it is treated into martensite, its compression strength reached to 4690 MPa and compression strain reached to 26% [1,4], which is comparable to WC-12Co. Such good mechanical properties can be ascribed to the ultra fine grain sizes because of the undissolved carbide particles which resist austenite grain growth during heating. Another reason could be the lath martensite structures. Sherby and co-workers [4] had reported that there was a lot of lath martensite in quenched UHCS. In general, it occurs only in low and middle carbon steels while twin martensite occurs in high carbon steels. Lath martensite has advantages of toughness and strength while twin martensite displays high strength but is brittle. Up to now, there has been no systemic study to explain why lath martensite occurs in very high carbon steels. The present paper studies this problem through experimentation and theoretical analysis.

1. Experimental

The UHCS was melted in a 120 kg middle frequency inductive furnace. The ingot was purified by re-melting it using inductive heating outside the furnace with residue protection. The final chemical composition of the steel was: $C_{1.37}$, $Cr_{1.6}$, $Al_{1.5}$, $Si_{0.35}$, $Mn_{0.42}$, $S_{0.01}$, $P_{0.02}$ (wt.%), where the additions of: (1) aluminum was to prevent eutectic network carbide, stabilize the ferrite and raise the transformation temperature of A_1. (2) Mn was to reduce the harmful effects of the S and P. (3) Cr was to raise the hardening ability and its resistance to graphite and thus stabilize carbides. (4) Si was to promote super plasticity [6,7].

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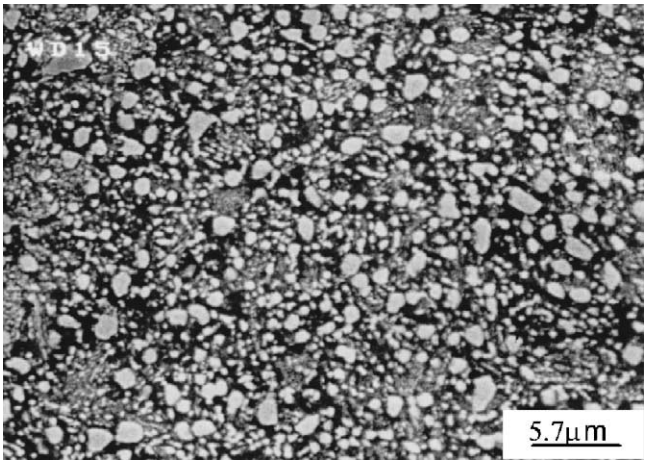


Fig. 1. SEM photograph for UHCS quenched from 950 °C and tempered at 700 °C (ferrite and carbide particles).

To prepare the UHCS for the final heat treatments the steel was first heating to 950 °C, quenched to water, and then tempered at 700 °C. The microstructure was mainly composed of ferrite with large amount of undissolved fine carbides, seen in Fig. 1. The final heat treatment process can be seen in Table 1. The purpose of heating at 900 °C for different length of times for treatment process A_1 and A_2 was to see the coarsening tendency of the carbides during heating and to see their effect on the microstructure after quenching. By comparing treatment A and B, the effects of temperature on the microstructure could be observed. The microstructures were observed using (JEM 200-CX) TEM.

2. Experimental results

From the experiments we found a large amount of lath martensite. For treatment A_1, the grain size of prior austenite is around 2 μm and there is estimated around 50% of volume fraction of lath martensite and 9% of undissolved carbides. The remains are twins and retained austenite, see Figs. 2 and 3. The width of the lath grain is around 0.3 μm. As the heating time was increased by 30 min intervals, both the martensitic and carbide grain sizes (regime A_2) increased slightly, see Fig. 4. Comparing with Fig. 2, we see that the

Table 1
Heat treatment and microstructure of 1.4%C UHCS

Treatment process	Parameters of heat treatment	Microstructures
A_1	Heating at 900 °C for 30 min and quenching to water	Figs. 2 and 3(M + C)
A_2	Heating at 900 °C for 60 min and quenching to water	Figs. 4–6(M + C)
B_1	Heating at 950 °C for 20 min and transferred to 860 °C for 30 min and quenching to water	Figs. 7 and 8(M + C)

M, martensite; C, carbide.

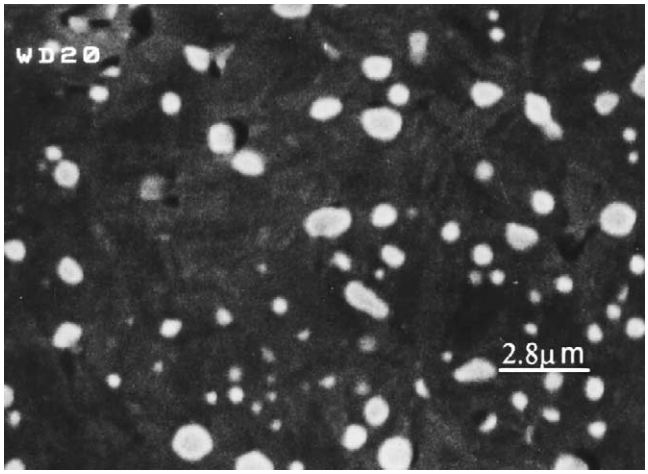


Fig. 2. SEM photograph for sample group A_1, heated at 900 °C for 30 min and then quenched in water (martensite and carbides).

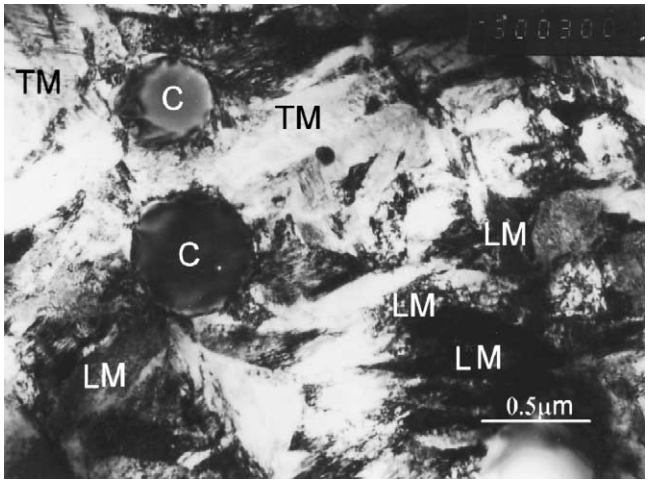


Fig. 3. TEM picture for sample of group A_1, heated at 900 °C for 30 min and then quenched to water (LM is lath martensite, TM is twin martensite and C is carbides).

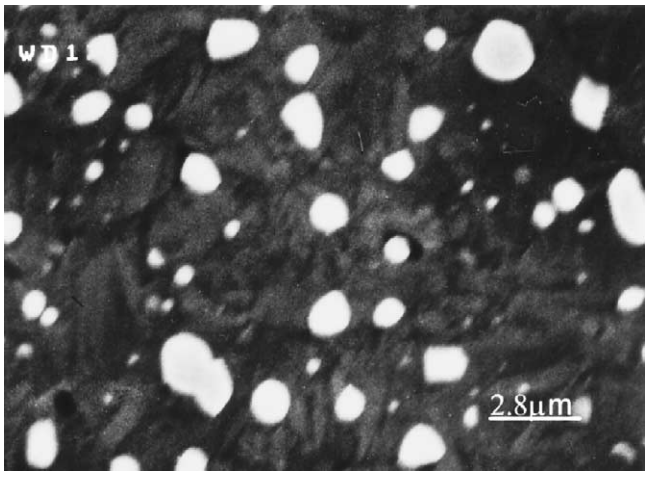


Fig. 4. SEM photograph for sample of group A_2, heated at 900 °C for 60 min and then quenched in water (martensite and carbides).

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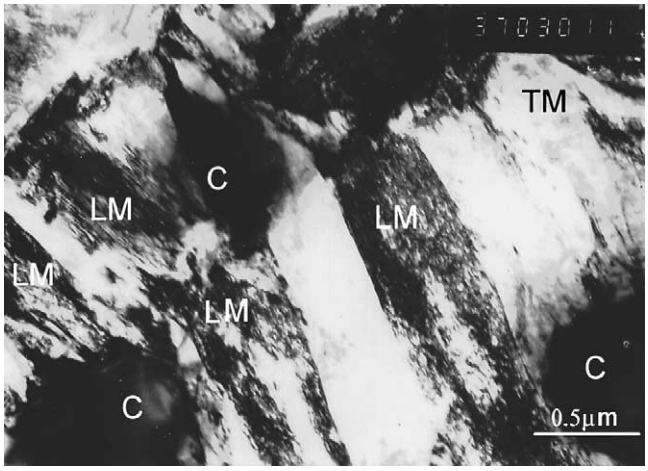


Fig. 5. TEM picture for sample of group A_2, heated at 900 °C for 60 min and then quenched to water (LM is lath martensite, TM is twin martensite and C is carbides).

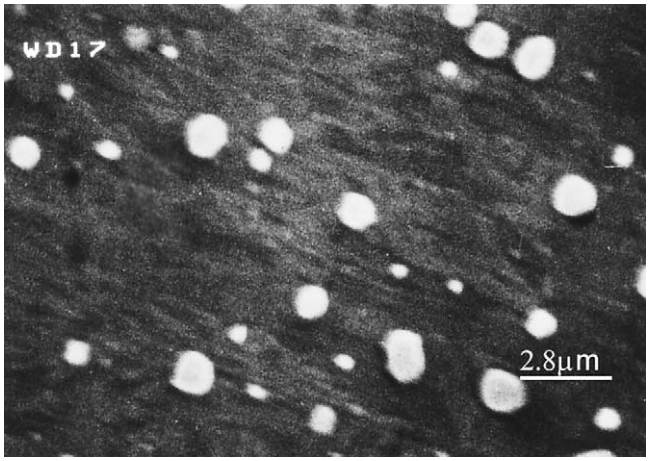


Fig. 7. SEM photograph for sample of group B_2, heating at 950 °C for 20 min, and cooling to 860 °C and then quenching in water (martensite and carbides).

carbides are still very fine. The microstructure of UHCS is still composed of a large amount of lath martensite with dislocations as sub-structure and the presence of some twins located between, see Figs. 5 and 6. Although the heating time was increased from 30 to 60 min for treatment A_2, austenite grains and carbide growth was limited. This restriction on the growth of austenite grain is ascribed to the distribution and presence of fine and undissolved carbides. For the heat treatment of B, the samples were heated to 950 °C for 20 min and then transferred to 860 °C for 30 min before quenching. There was no substantial change of microstructures, It is still composted of lath martensite and twin martensite. There was, however, a slightly increase in grain sizes and twin content, see Figs. 7 and 8.

3. Analysis and discussions

Above results indicate that the austenite grains of UHCS can remain ultra fine even after heating at different temperatures and for different times because of the large amount of undissolved carbides. Not only do we get fine martensite grains but their morphology is also different from traditional/previous results, which did not have a lot of lath martensite in high carbon steel. Sherby and co-workers [4] reported a similar phenomenon. These results are in disagreement with the traditional concept of metallurgy. The published work reported that when the carbon content of austenite is higher than 0.8%, the martensite consists of 100% twin substructures [5]. The carbon content of this experiment is as high as 1.4% and the heating temperatures were 900 °C and 860 °C. Under these conditions, the theoretical carbon content of austenite should be higher than 1.0% and the martensite should be 100% twin substructure. In addition

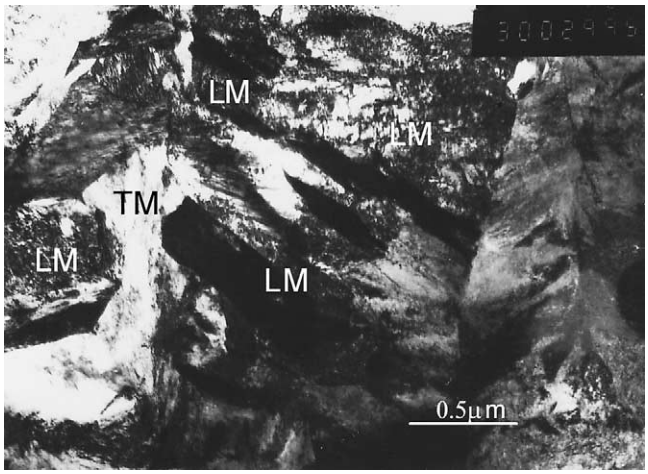


Fig. 6. TEM picture for sample of group A_2, heated at 900 °C for 60 min and quenched in water (LM is lath martensite, TM is twin martensite and C is carbides).

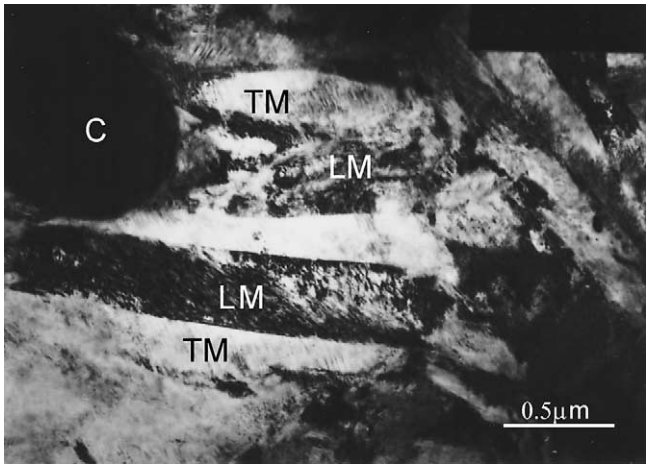


Fig. 8. TEM photograph for sample of group B_2, heating at 950 °C for 20 min, and cooling to 860 °C and then quenching in water (LM is lath martensite, TM is twin martensite and C is carbides).

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to the effect of carbon content, grain size also has an effect on the substructure of martensite transformation, a fact which has never been considered before and could be the cause of the discrepancy between theory and experiment here. In this experiment, the grain sizes of the UHCS were in 1–3 μm on average, which is one order of magnitude lower than that of typical grain sizes. The following calculations will examine the influence of ultra-fine grain sizes on martensite transformation. For a lens like martensite plate, suppose r is the radius and c is the thickness. The non-chemical enthalpy should be [5]:

$$\Delta g_{\mathrm{N}} = (2\pi r^2 \gamma_{M/\gamma}) + \left(\frac{4}{3}\pi r^2 c\right)\left(\frac{c}{r}A\right) \tag{1}$$

where A is the strain energy of an unit volume and $\gamma_{M/\gamma}$ is the interface energy. For an unit volume of martensite:

$$\Delta G_{\mathrm{N}} = \frac{\Delta g_{\mathrm{N}}}{4/3\pi r^2 c} = \frac{3\gamma_{M/\gamma}}{2c} + \frac{Ac}{r} \tag{2}$$

Differentiating Eq. (2) with respect to r and c, we get the minimum enthalpy $(\Delta G_{\mathrm{N}})_{\min}$ for the transformation:

$$(\Delta G_{\mathrm{N}})_{\min} = 2\left(\frac{Ac}{r}\right) \tag{3}$$

$(\Delta G_{\mathrm{N}})_{\min}$ is the lowest resistance for martensite transformation. Usually, the size of martensite grains is restricted by austenite grain size, the two types of grains sizes are usually on the same order of magnitude [5]. Therefore, as the austenite grain size reduces, the martensite grain r should also reduce. From Eq. (3), when as r decreases, $(\Delta G_{\mathrm{N}})_{\min}$ increases and the transformation resistance increases, too. To maintain the minimum of $(\Delta G_{\mathrm{N}})_{\min}$, the thickness of the martensite plates c, should also decrease. The optimum ratio between the thickness and diameter of a martensite grain is [5]:

$$\frac{c^*}{r^*} = \frac{1}{40} \tag{4}$$

Dislocations and twins are two kinds of substructures for martensite grains. They correspond to slip and twin deformations, respectively. Suppose τ_{s} is a slip critical shear stress and τ_{t} is a twin critical shear stress, γ_{t} is the twin shear strain. When twin and slip shear stress are equal:

$$\tau_{\mathrm{s}} = \tau_{\mathrm{t}} \tag{5}$$

Because twin is a kind of elastic deformation:

$$\tau_{\mathrm{t}} = G\gamma_{\mathrm{t}} \tag{6}$$

where G is the shear Young's modulus. Twin arises from uniform shear deformation of atoms in a region of the metal. Here we only consider the situation assuming elasticity and omit the elastic strain field outside the twin due to twinning deformation. From a schematic figure of twin deformation, Fig. 9 , the twin shear strain and the thickness c should be related by:

$$\gamma_{\mathrm{t}} = \frac{na}{c} \tag{7}$$

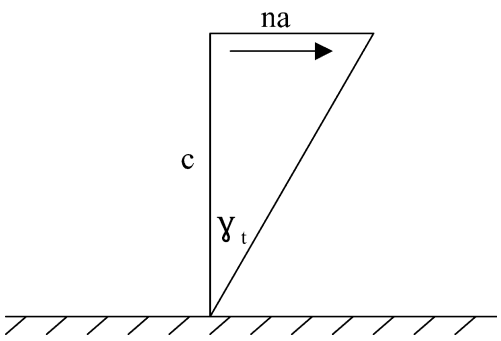


Fig. 9. Schematic diagram showing the shear deformation for twin.

where a is the distance between two neighboring atoms and n is the atomic numbers, which respects the distance of displacement, measured in atoms/using atoms as units, during twin deformation. For iron a = 0.25 nm and take n = 1 for the minimum stress, for iron single crystal G = 60 GPa [8], and for austenite single crystal τ_{s} = 200 MPa and $\gamma_{\mathrm{t}} = 3.3 \times 10^{-3}$, Now from Eqs. (5)–(7), c = 75 nm. Because n and a are constants, if the thickness of a martensite grain is smaller than 75 nm, the twin strain γ_{t} will increase, which will result in twin shear stress being larger than slip shear stress. The slip will become the main deformation mechanism and dislocation will become the main substructure.

Substitute c = 75 nm into Eq. (4), r = 3000 nm. That is, when the grain size is smaller than 3 μm, the slip will become the main deformation mechanism. This is in agreement with the previous [4] and our result. In above calculation, 200 MPa was used as the austenite strength. If the carbon content is higher, the austenite strength will be higher than 200 MPa, causing a decrease in grain size. From this analysis we can infer that when austenite grain size reduces to a certain value, twin shear stress will increase rapidly and this will make the

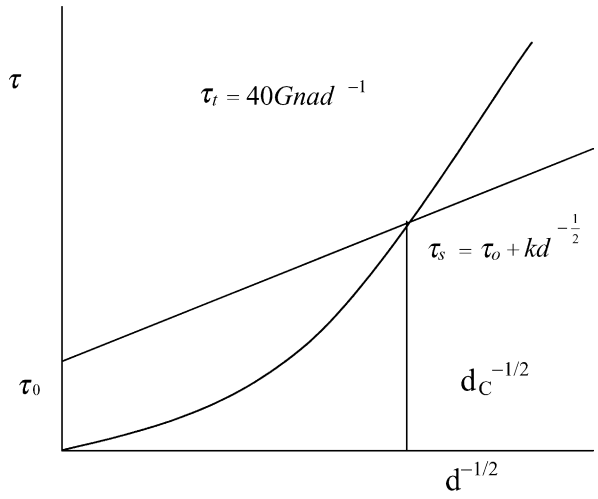


Fig. 10. Schematic diagram showing the relationship of slip shear stress and twin shear stress with grain size.

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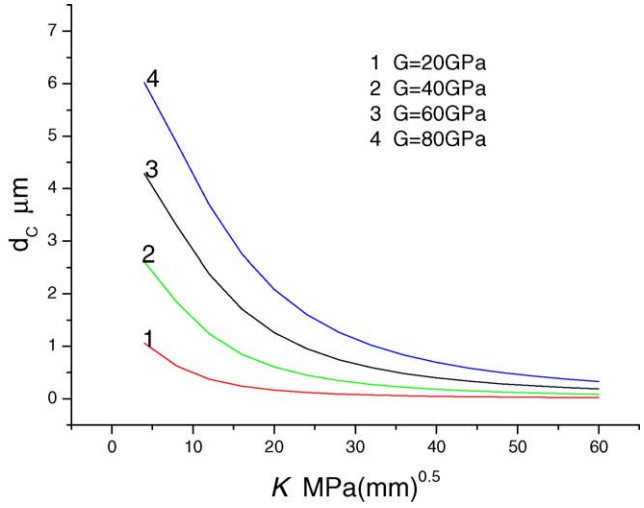


Fig. 11. The relationship of the Hall–Petch constant k with grain size d_c for several of shear modulus.

change in the substructure of martensite from twin to dislocation. This phenomenon has rarely been reported. The main reason is that it is not easy to obtain such fine austenite grain sizes using conventional carbon content, alloy compositions and conventional heat treatment technology. When grain size reduces, the austenite yield stress will increase, which makes the slip critical shear stress increase also. Generally, yield stress is related to grain size by:

$$\tau_s = \tau_0 + kd^{-1/2} \tag{8}$$

Substituting Eqs. (4) and (7) into Eq. (6) and letting $r = d$ [5,9] we have:

$$\tau_t = 40Gnad^{-1} \tag{9}$$

Fig. 10 shows the relationship between slip shear stress and twin shear stress with grain size. As the grain size reduces, both stresses increase, but the rates are different. It is clear that the twin shear stress increases faster than that of the slip shear stress. There should be a critical grain size at which both shear stresses are equal to each other. Over this critical size, there is a transition of the deformation mechanism from twin to slip. From Eqs. (5), (8) and (9), we get:

$$\tau_0 + kd^{-1/2} = 40Gnad^{-1} \tag{10}$$

which gives:

$$d_c = \frac{(80Gna)^2}{2k^2 + 160Gna\tau_0 + 2k(k^2 + 160Gna\tau_0)^{1/2}} \tag{11}$$

In Eq. (11), k is the Hall–Petch constant and is only undetermined. Through a regression with some published data [10], k can be obtained and it gives values from 16 to 22 MPa mm$^{1/2}$ for low carbon steels. When we take $n = 1$, $a = 0.25$ nm and $\tau_0 = 100$ MPa, the calculated d_c for several elastic shear modulus is shown in Fig. 11. The k value is generally four times smaller for austenite than for ferrite [10]. When we take k to be around 5 in Fig. 11, the calculated d_c is around 1–4 μm, which is just in the range of austenite grain sizes measured in this experiment/paper. This model indicates that grain size determines the deformation mechanism for martensite transformation. When grain size reduces to a certain value, twin stress is higher and the deformation is dominated by slip, which explains our experimental observation well.

4. Conclusion

1. It is found that there is a great deal of lath martensite in 1.4%C UHCS. The substructure of the martensite is composed of dislocations.
2. When austenite grain size reduces, the twin shear stress increases faster than that of slip. There exists a critical dimension, over which twin shear stress is higher than that of slip and the martensite substructure becomes dislocations. A critical grain size at which the dominant transformation mechanism changes has been obtained which agrees with experimental observation well.

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