Secondary-hardened bainite

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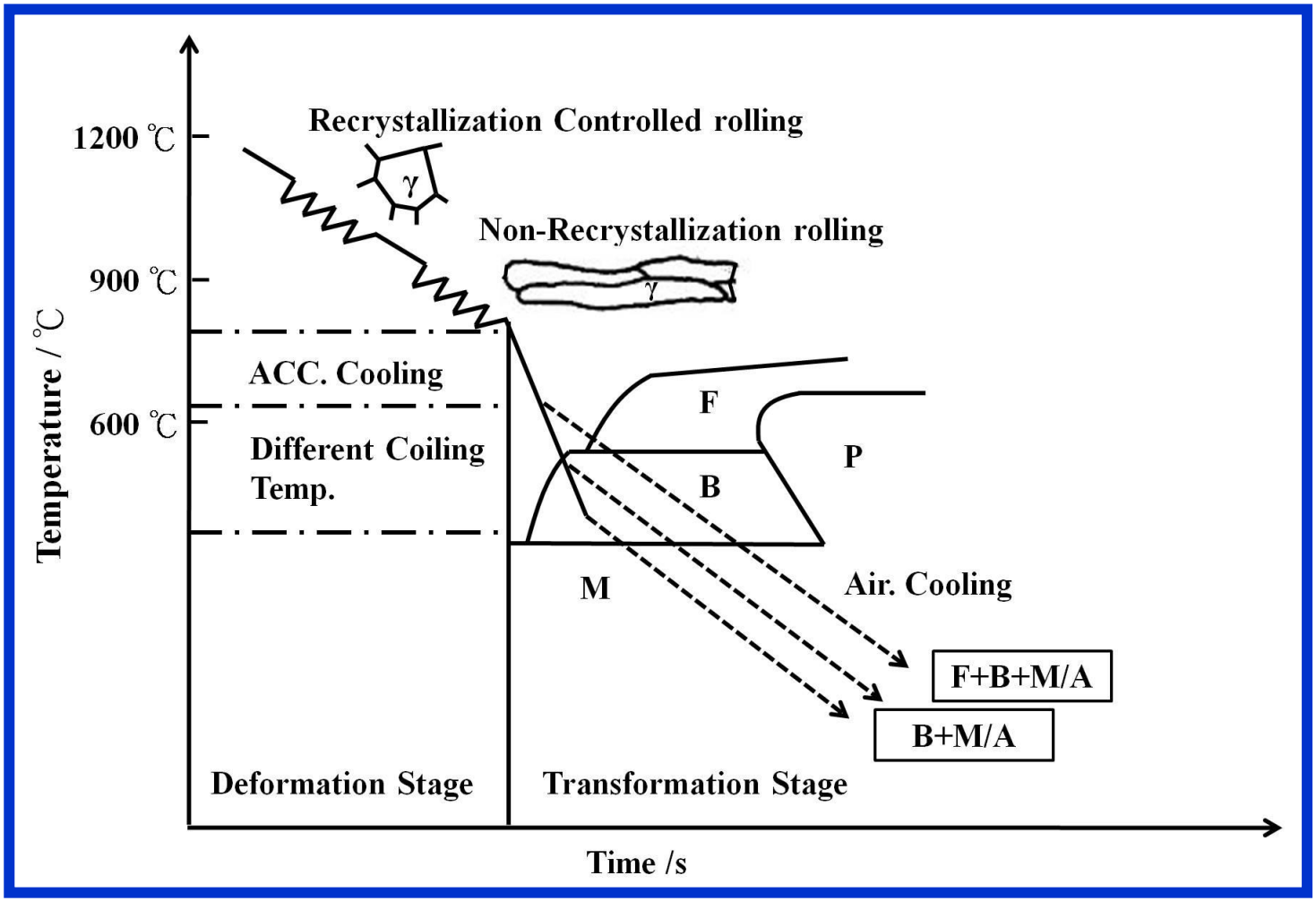
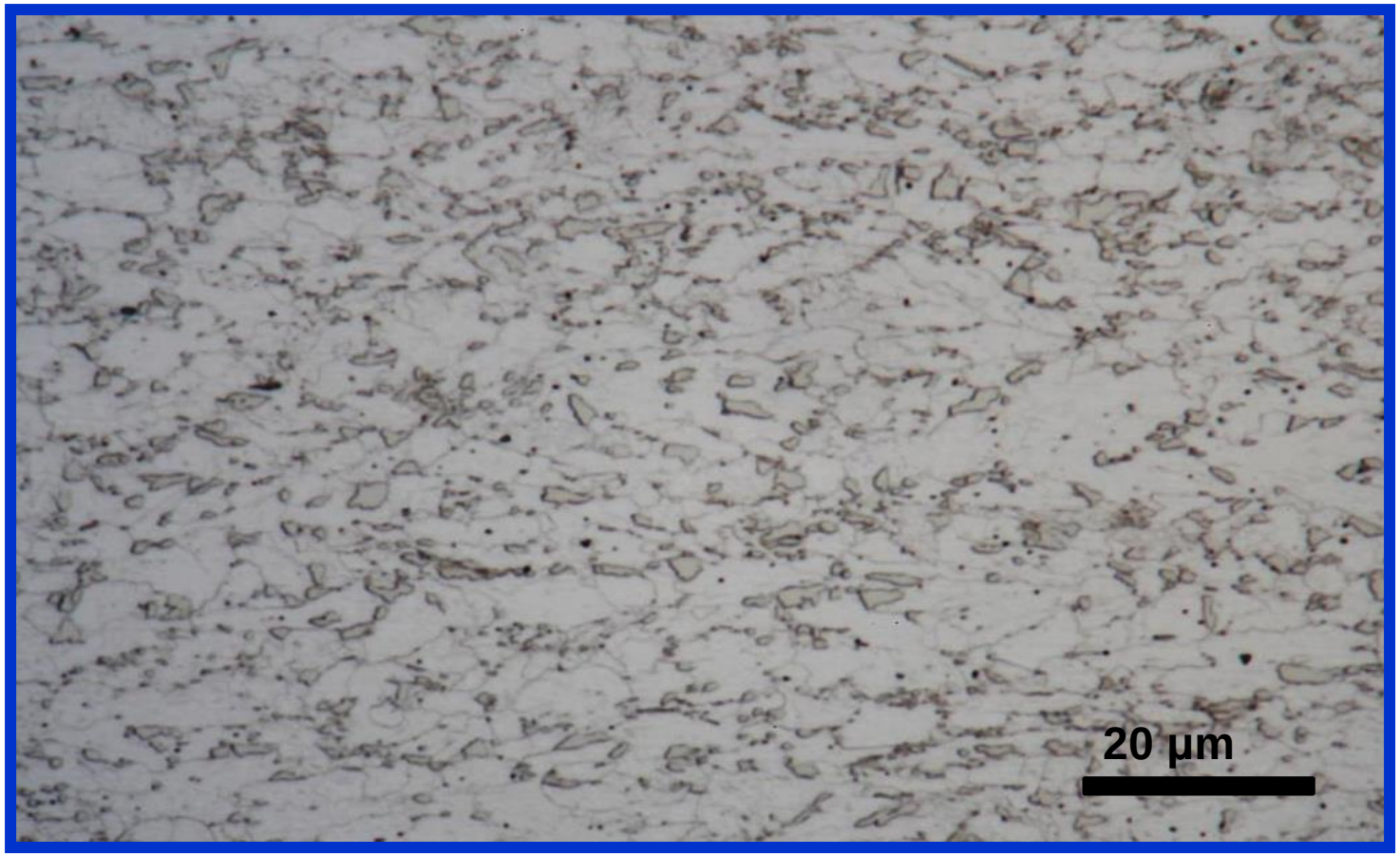


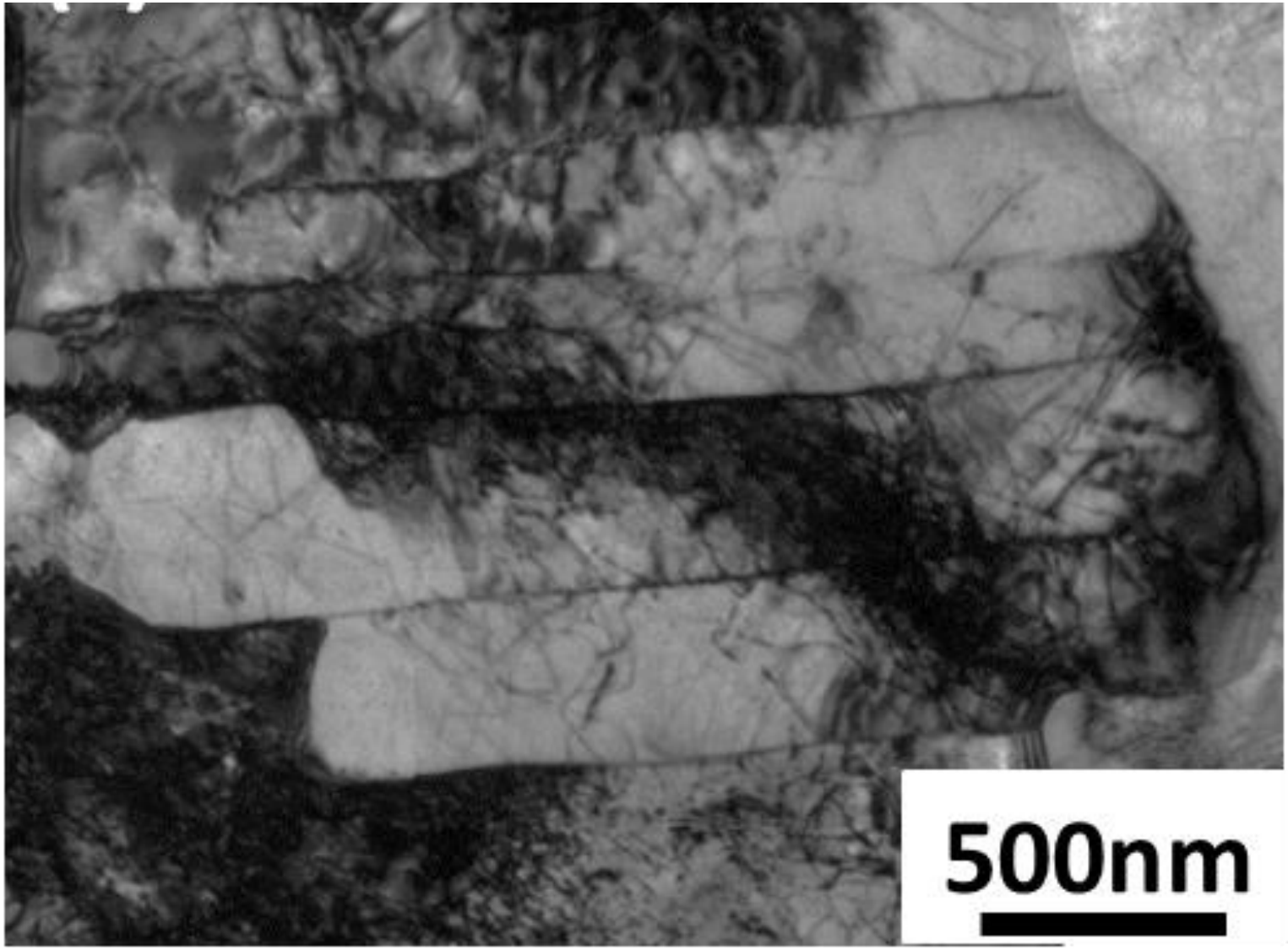
Advanced process for low-carbon bainitic steels

Optical microstructure of typical granular bainite



Question::
Can the nomenclature “granular bainite” signify the exact structure ?

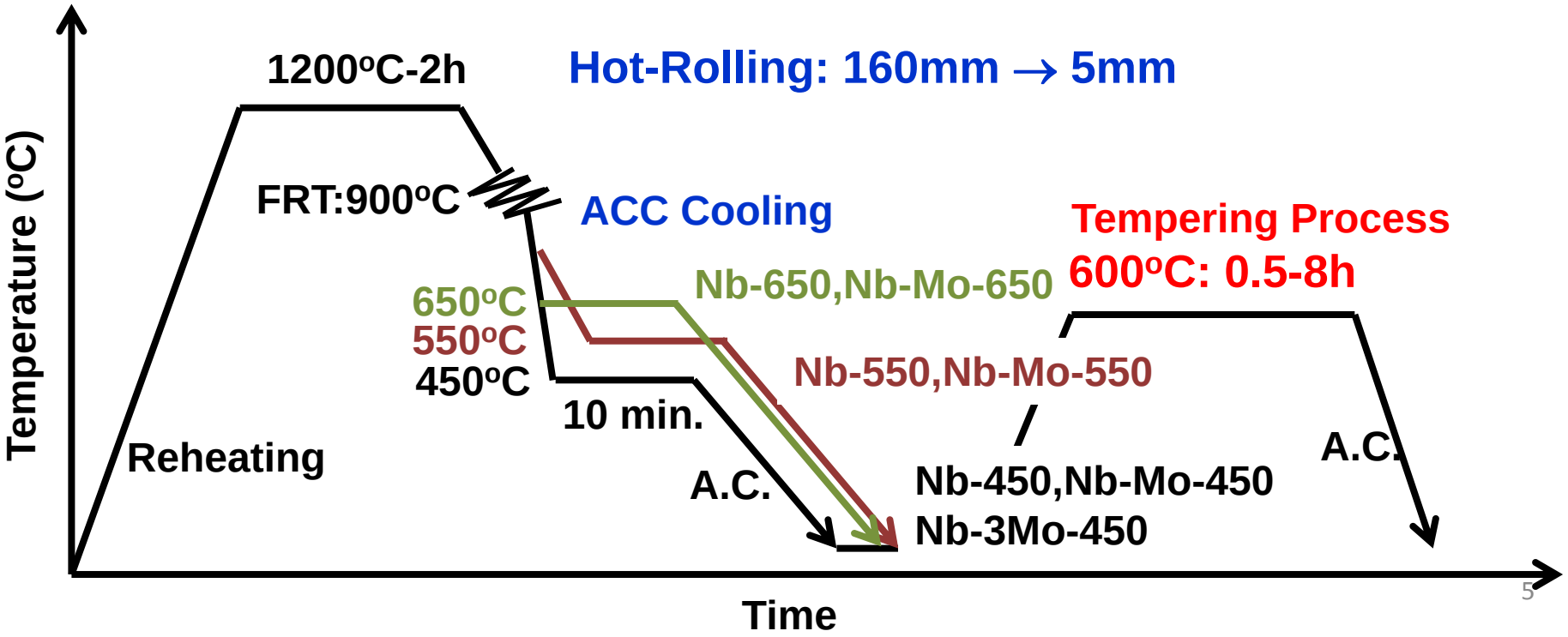
Typical TEM image of granular bainite



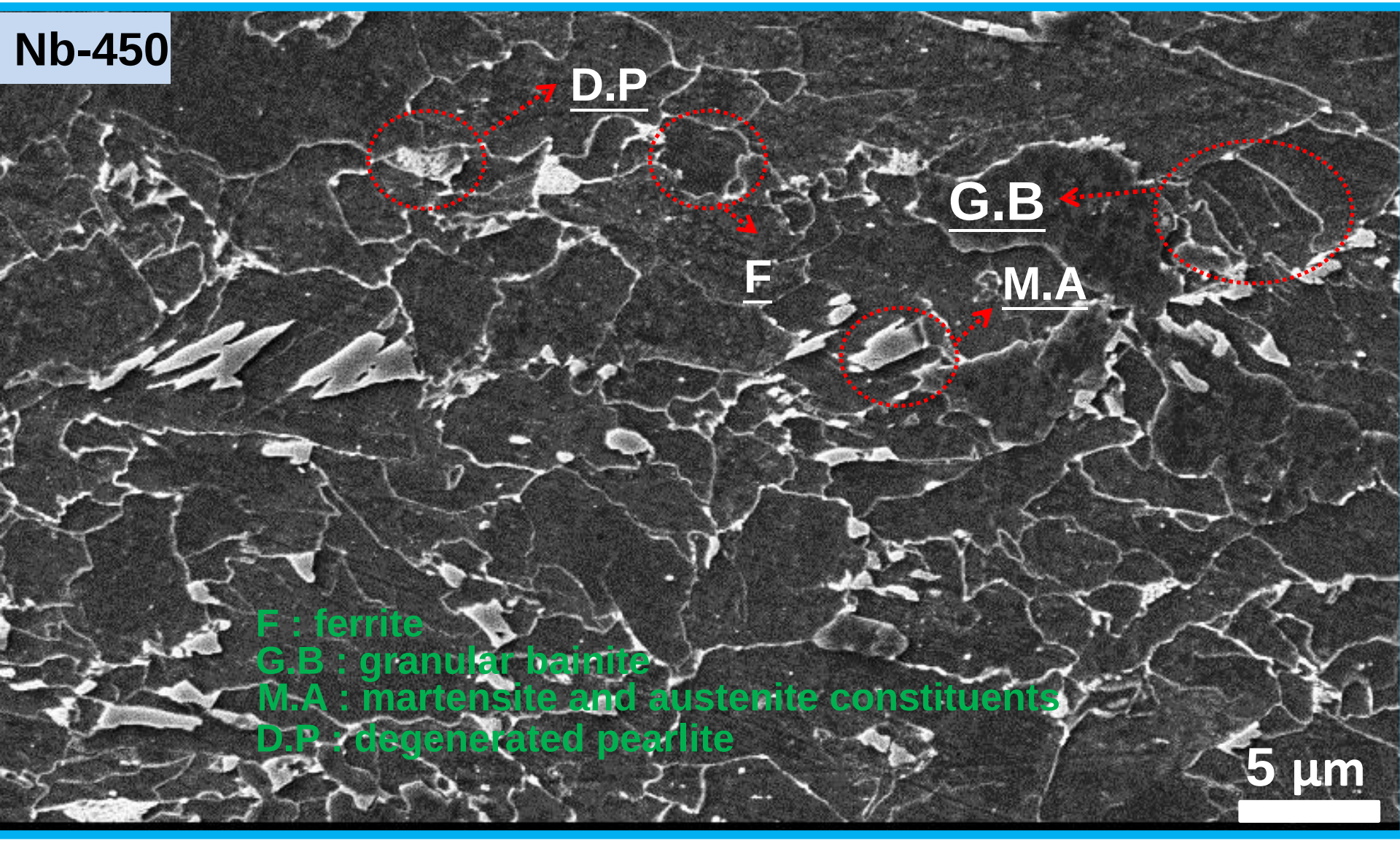
Experimental Procedure

Chemical compositions of hot-rolled strips, wt%

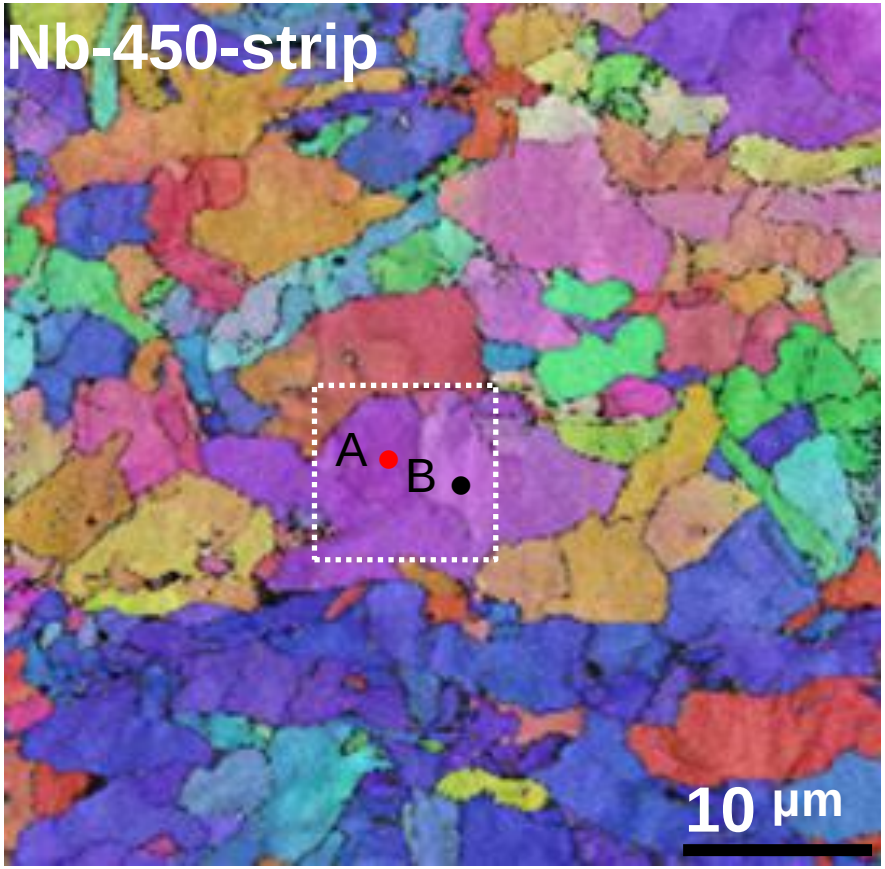
Strip No.	C	Si	Mn	N	Al	Cr	Ti	Nb	Mo
Nb	0.05	0.2	1.7	0.004	0.03	0.18	0.016	0.08	-
Nb-Mo	0.05	0.2	1.7	0.004	0.03	0.18	0.016	0.08	0.1
Nb-3Mo	0.05	0.2	1.7	0.004	0.03	0.18	0.016	0.08	0.3

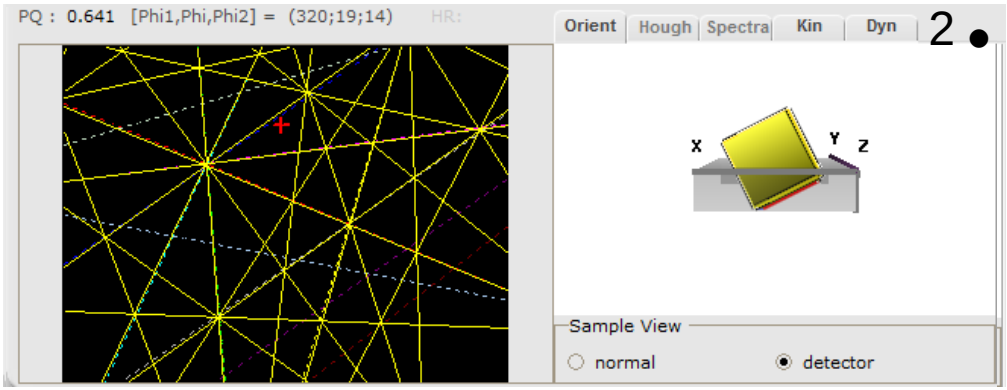


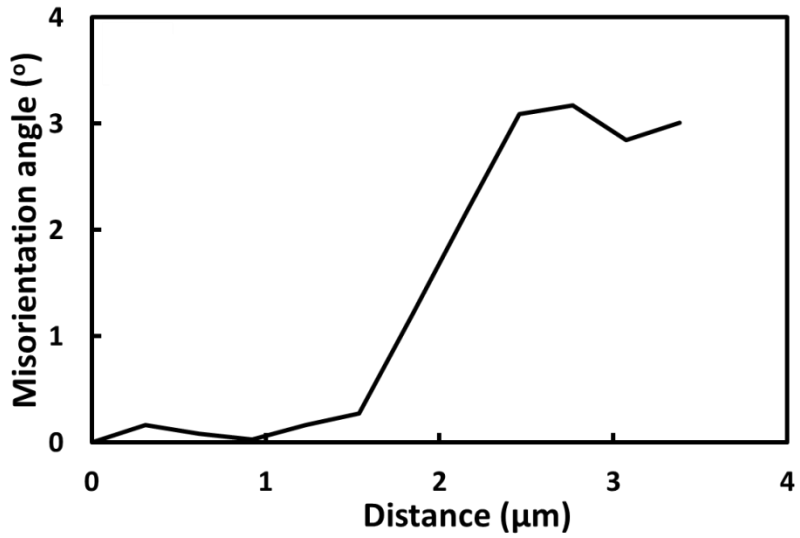
Vol.% 25 F; 63 G.B.; 9 M/A; 3 D.P.



Misorientation between sub-units in granular bainite







Sub-grain boundaries in granular bainite shows low angle boundaries in EBSD images.

Calculation for axis/angle pair

Euler angle for A :(324° 21° 12°)

A grain (AJS): $\begin{bmatrix} 0.905 & \overline{0.418} & 0.075 \\ 0.369 & 0.861 & 0.351 \\ \overline{0.211} & \overline{0.290} & 0.934 \end{bmatrix}$

Euler angle for B :(320° 19° 14°)

B grain (BJS): $\begin{bmatrix} 0.89 & \overline{0.448} & 0.079 \\ 0.404 & 0.858 & 0.316 \\ \overline{0.209} & \overline{0.249} & 0.946 \end{bmatrix}$

Rotation Matrix (AJB) = (AJS) $(BJS)^{-1}$:

$$\begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix} = \begin{bmatrix} 0.999 & 0.037 & 0.013 \\ \overline{0.037} & 0.999 & 0.035 \\ \overline{0.011} & \overline{0.035} & 0.999 \end{bmatrix}$$

$J_{11}+J_{22}+J_{33}=$
$1+2\cos\theta$
$u_1 = (J_{23}- J_{32})/2 \sin\theta$
$u_2 = (J_{31}- J_{13})/2 \sin\theta$
$u_2 = (J_{12}- J_{21})/2 \sin\theta$

Axis Angle Pair

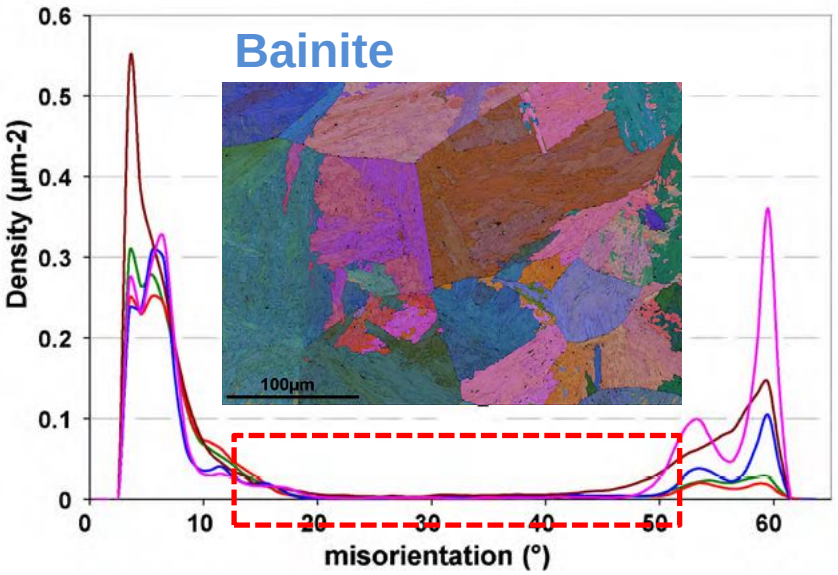
$(0.667\ \overline{0.231}\ 0.708)$

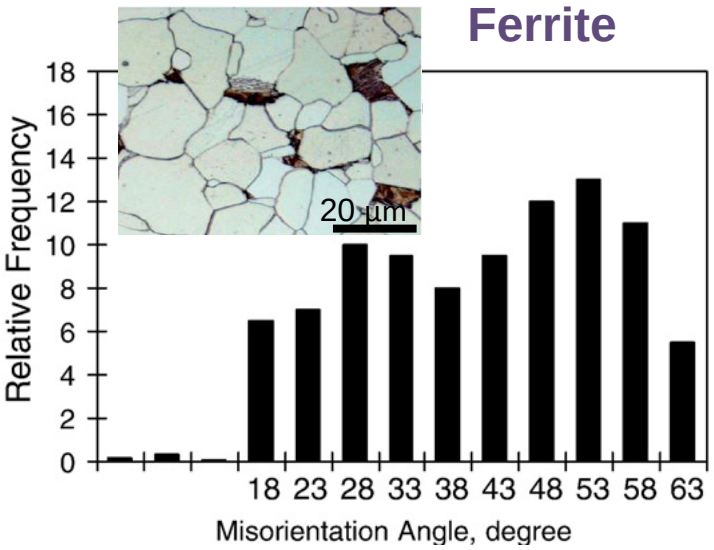
2.994^o

The minimum angle!

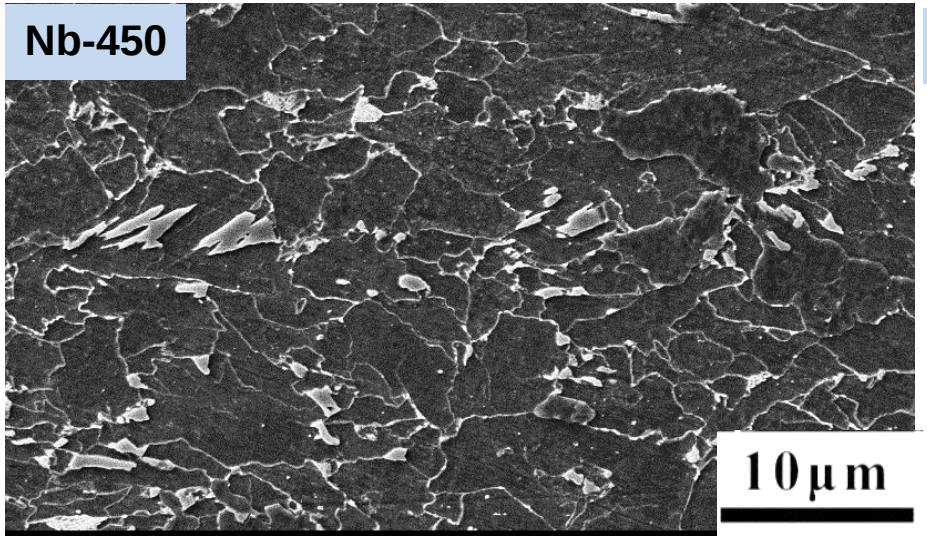
No.	Axis			Angle (°)
1	0.6671	-0.2312	0.7082	2.99
2	-0.5216	-0.5769	-0.6286	119.8
3	0.523	0.6296	0.5745	120.5
4	-0.0015	-0.7052	0.709	172.5
5	0.7379	-0.674	0.0354	176.4
6	-0.7395	-0.0301	0.6725	176.1
7	-0.9957	0.0021	-0.0926	89.9
8	-0.0406	0.9981	-0.0457	95.5
9	-0.674	-0.738	-0.0316	175.9
10	0.6305	-0.5238	-0.5728	120.2
11	0.5949	-0.5378	0.5974	114.1
12	-0.0474	0.0027	0.9989	174.8
13	0.9957	0.0921	0.0021	90.6
14	0.6724	0.0339	0.7394	176.6
15	0.0479	0.0427	-0.9979	95.3
16	-0.6277	0.5786	0.5209	120.1
17	-0.5955	-0.5929	0.5421	113.7
18	0.0453	-0.999	0.0027	174.6
19	0.0503	-0.9977	-0.0446	84.7
20	0.0654	-0.7075	-0.7037	179.8
21	-0.0468	0.0524	0.9975	85
22	0.5618	0.6095	-0.5594	126.3
23	-0.5573	0.5597	-0.6134	126
24	-0.9979	-0.0452	-0.0473	179.7

The distribution of misorientation angle

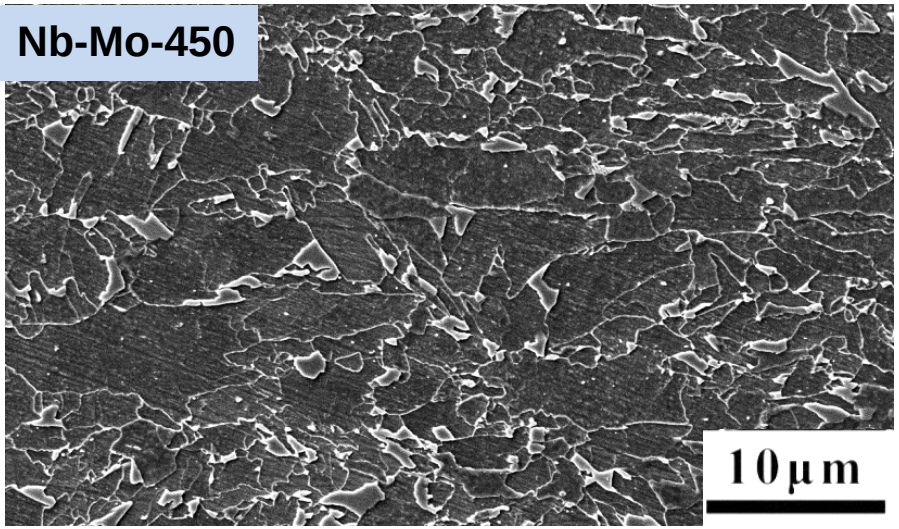


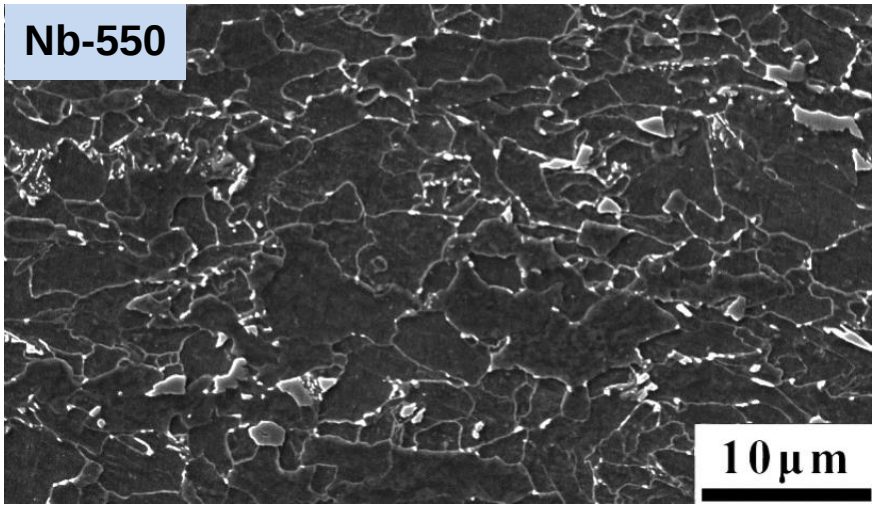


25 F, 63 G.B., 9 M/A, 3 D.P.

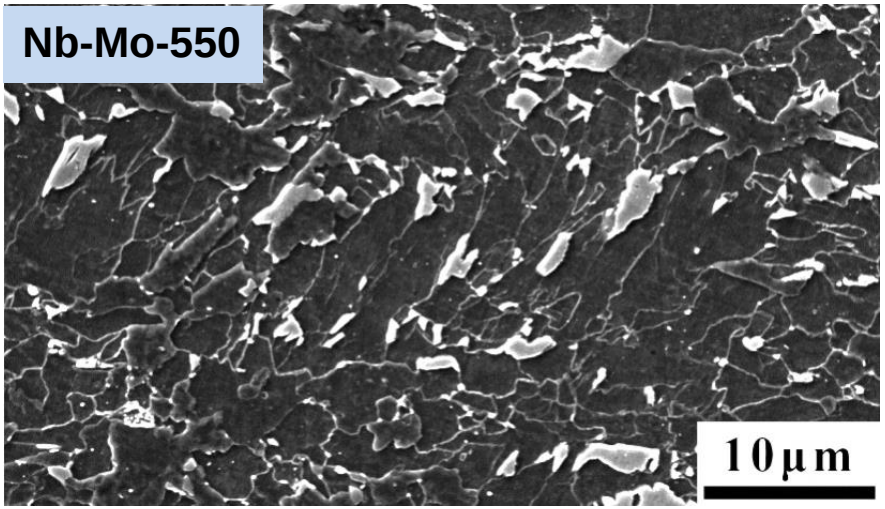


14 F, 66 G.B., 19 M/A, 1 D.P.





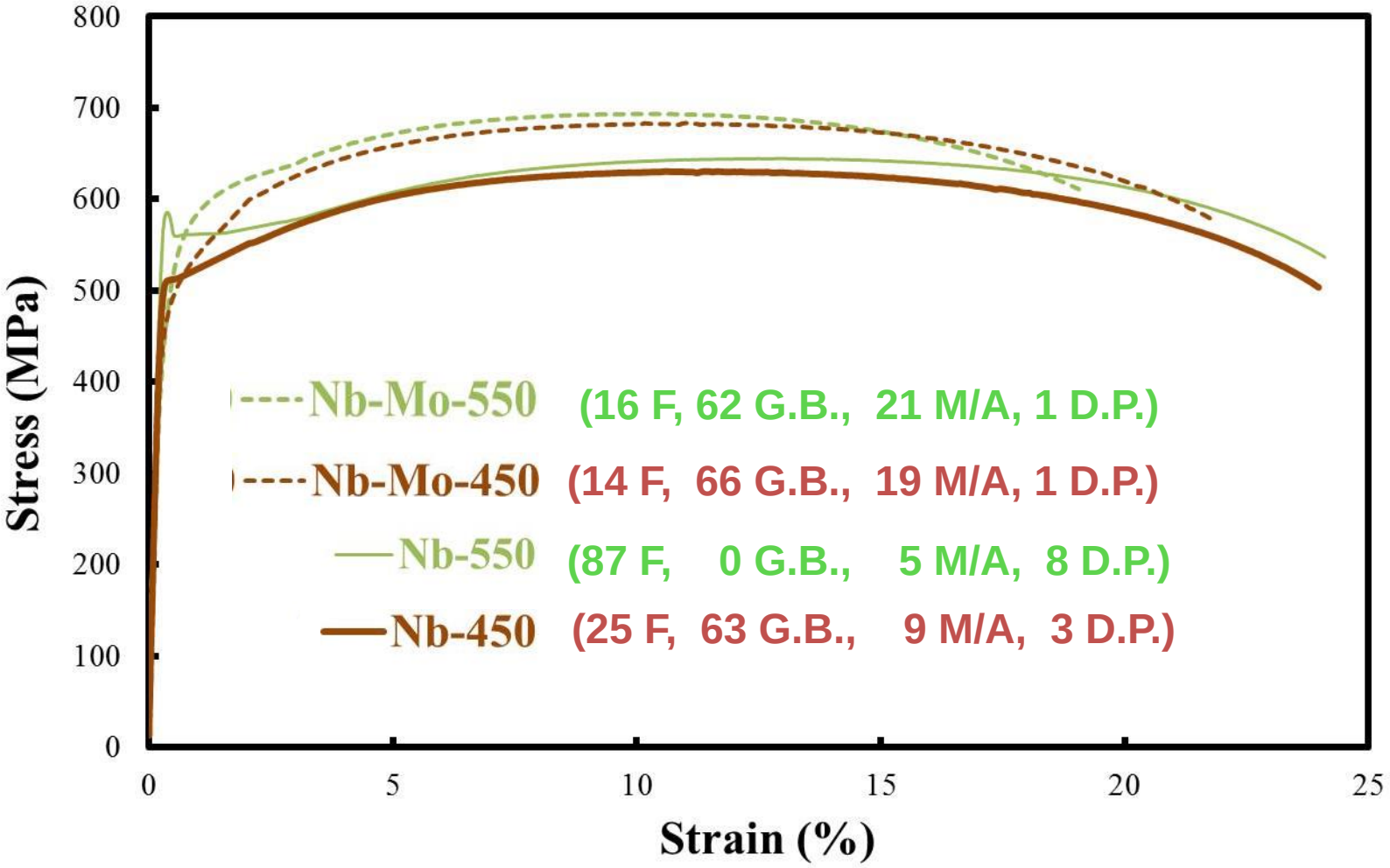
87 F, 0 G.B., 5 M/A, 8 D.P.



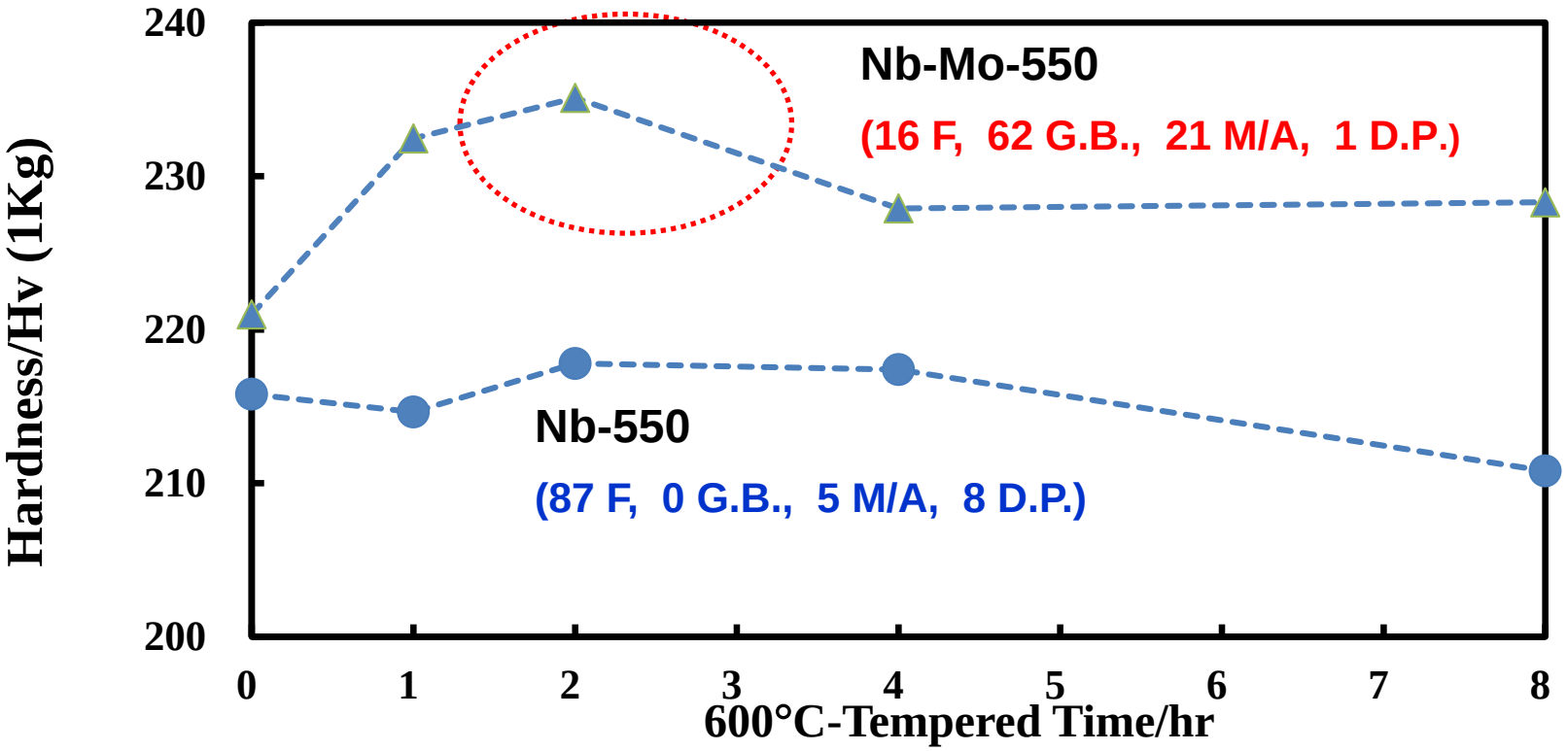
16 F, 62 G.B., 21 M/A, 1 D.P.

Adding 0.1wt% Mo can increase the hadenability of bainite.

Mechanical Property

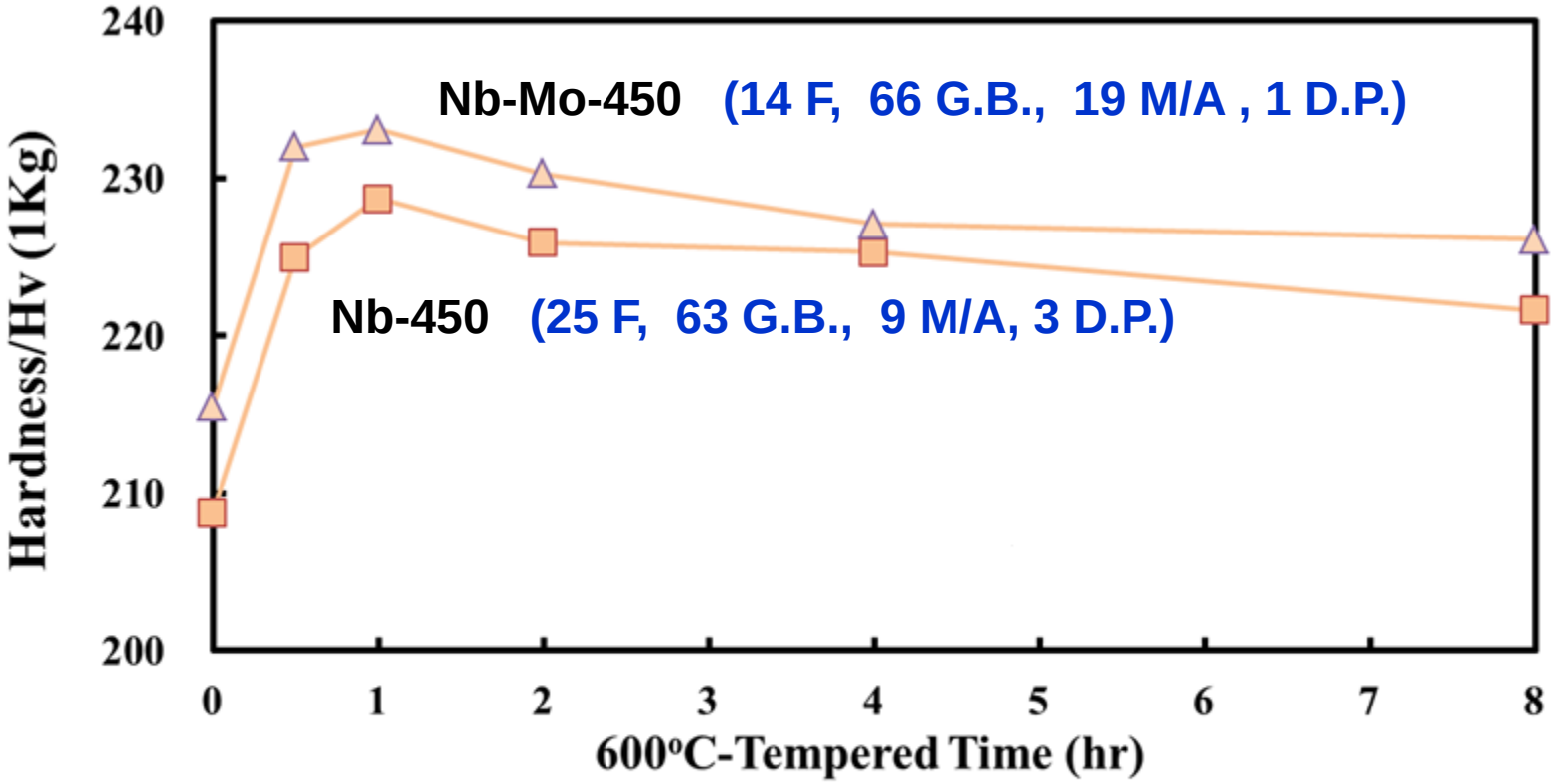


Hardness variations of Nb-550 and Nb-Mo-550 samples after tempering at 600°C for different intervals.



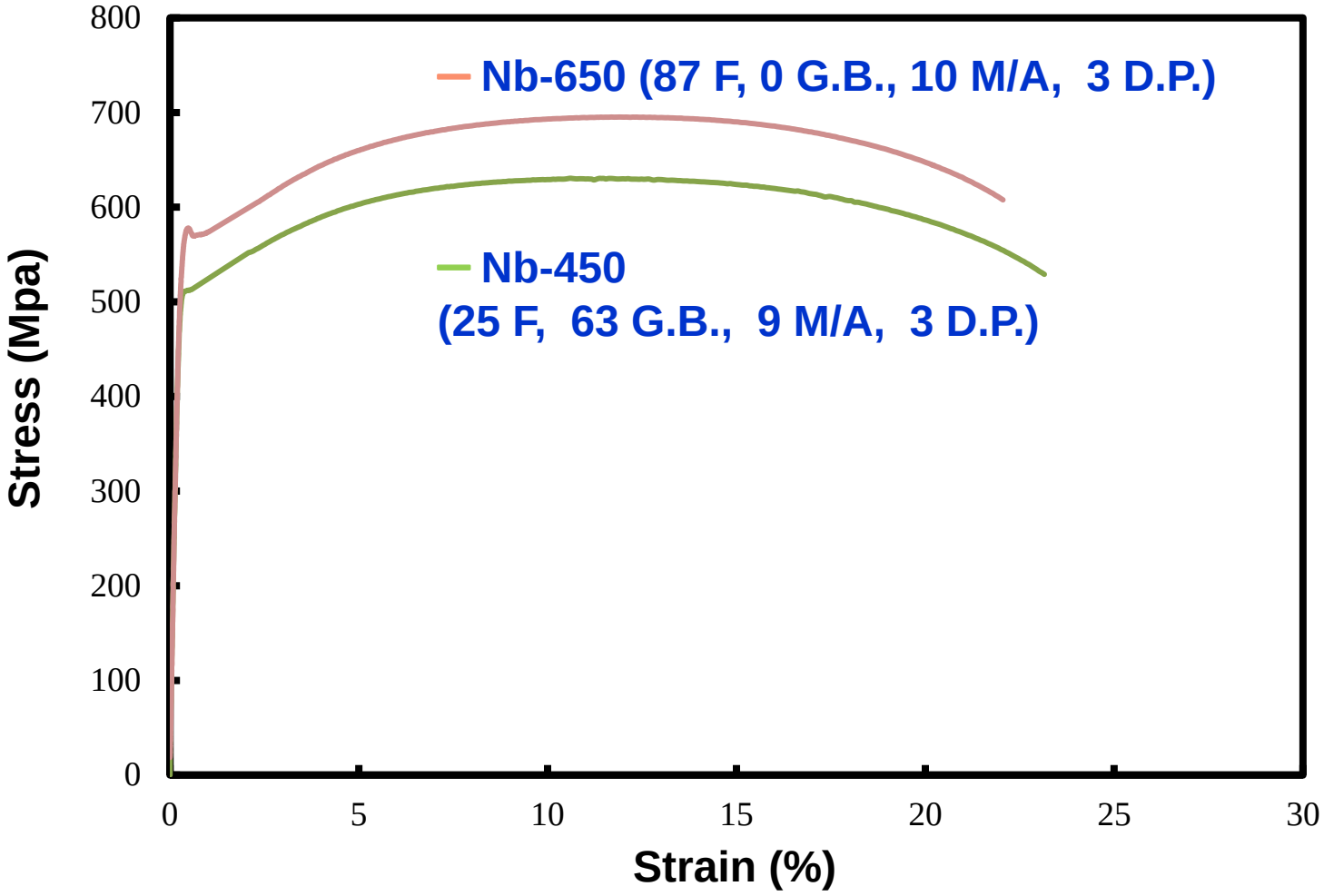
The Nb-550 strip with ferrite structure has no secondary hardening effect during tempering at 600°C!

Hardness variations of Nb-450 and Nb-Mo-450 samples during tempering at 600°C.

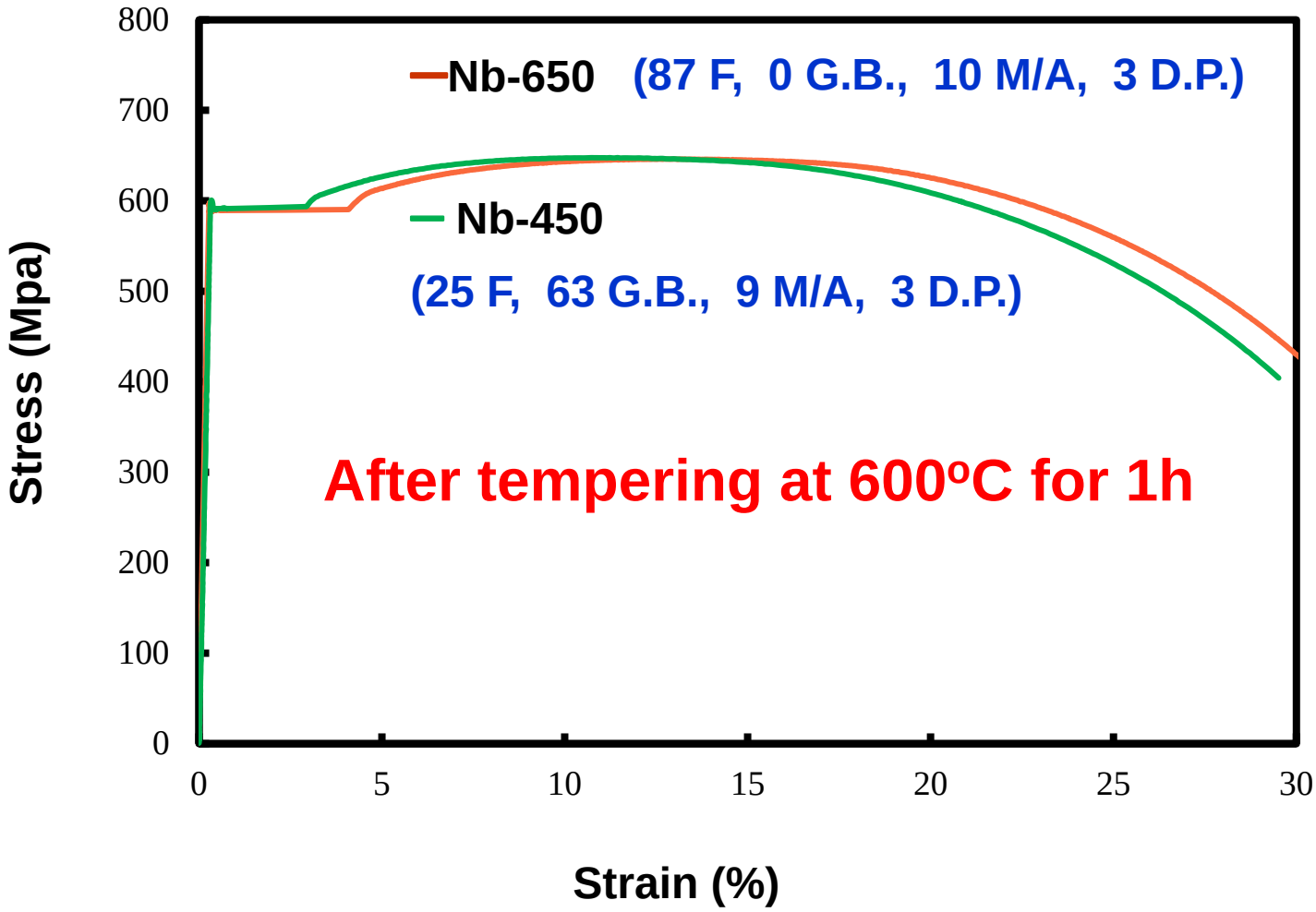


Nb-450 and Nb-Mo-450 samples are involved with the secondary hardening effect during tempering.

The comparison of mechanical properties between Nb-450 and Nb-650 samples

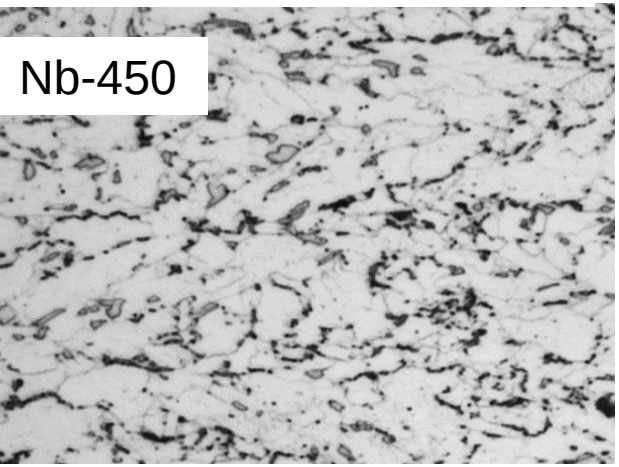


The comparison of mechanical properties between Nb-450 and Nb-650 samples after tempering at 600°C for 1h

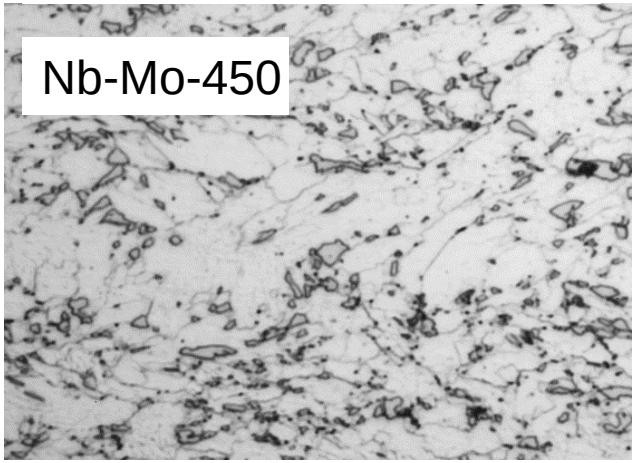


Microstructural Evolution

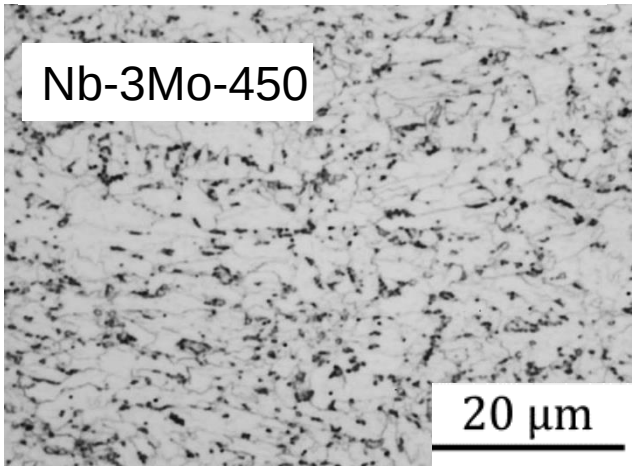
25 F, 63 G.B., 9 M/A, 3 D.P.



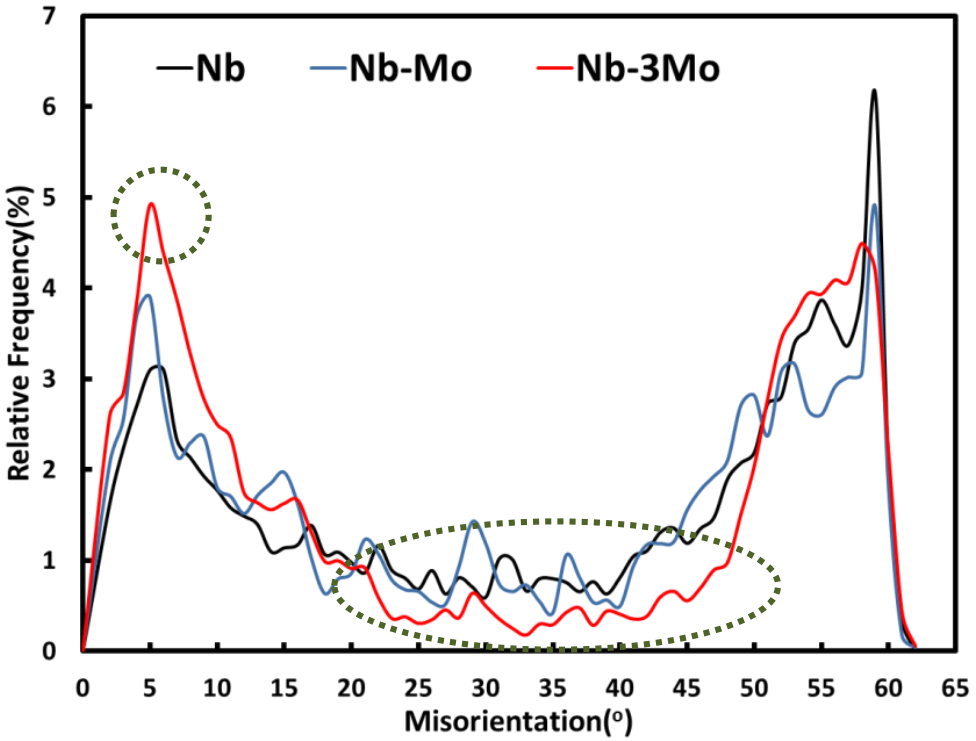
14 F, 66 G.B., 19 M/A, 1 D.P.



8 F, 79 G.B., 2 M/A. 11 D.P.



With increasing Mo, more granular bainite forms.

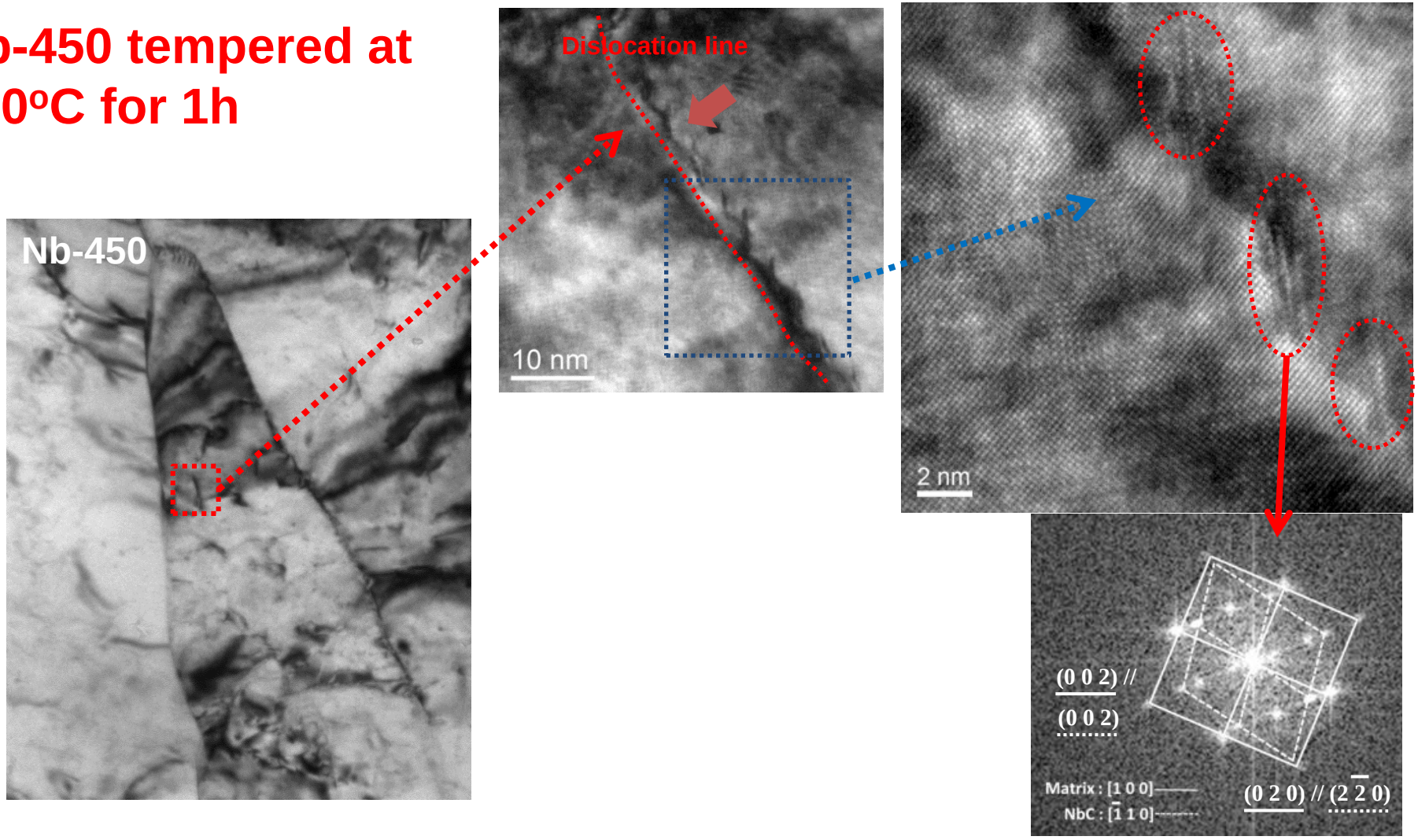


The dislocation density of granular bainite after tempering at 600°C for different intervals

Time/hr	Nb-450	Nb-Mo-450	Nb-3Mo-450
0 h	$(5.3\pm1.2)X10^{14}/m^2$	$(5.4\pm0.9)X10^{14}/m^2$	$(5.3\pm0.9)\ X10^{14}/m^2$
1 h	$(4.6\pm0.8)\ X10^{14}/m^2$	$(4.8\pm1.2)X10^{14}/m^2$	$(5.1\pm0.8)\ X10^{14}/m^2$
8 h	$(3.9\pm1.3)\ X10^{14}/m^2$	$(3.8\pm1.3)X10^{14}/m^2$	$(4.2\pm1.1)\ X10^{14}/m^2$

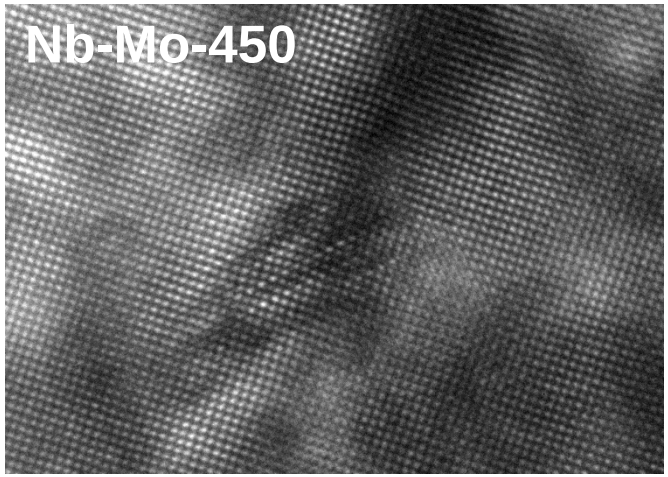
HR -TEM obsevation for Nb carbides in tempered granular bainite

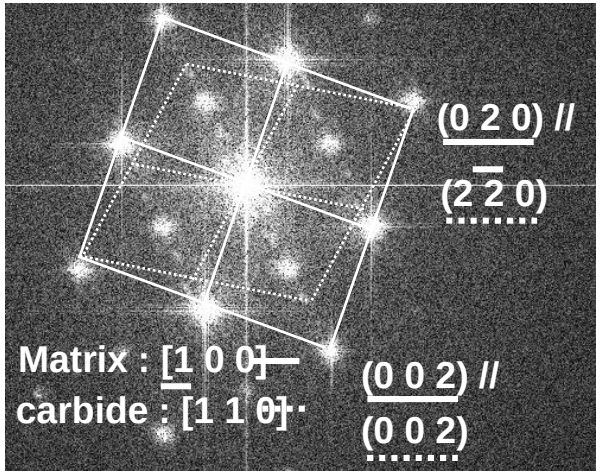
Nb-450 tempered at 600°C for 1h

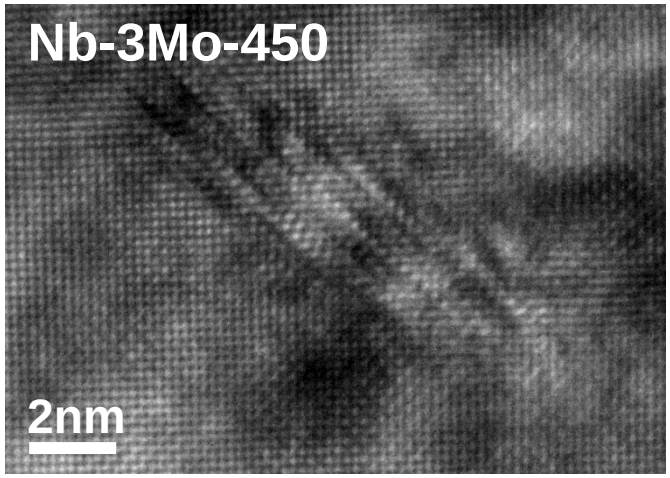


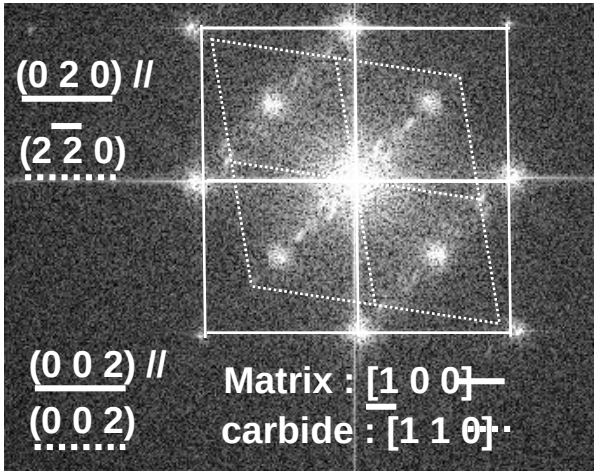
HR -TEM obsevation for (Nb,Mo) carbides in tempered granular bainite

Tempering at 600°C for 1h





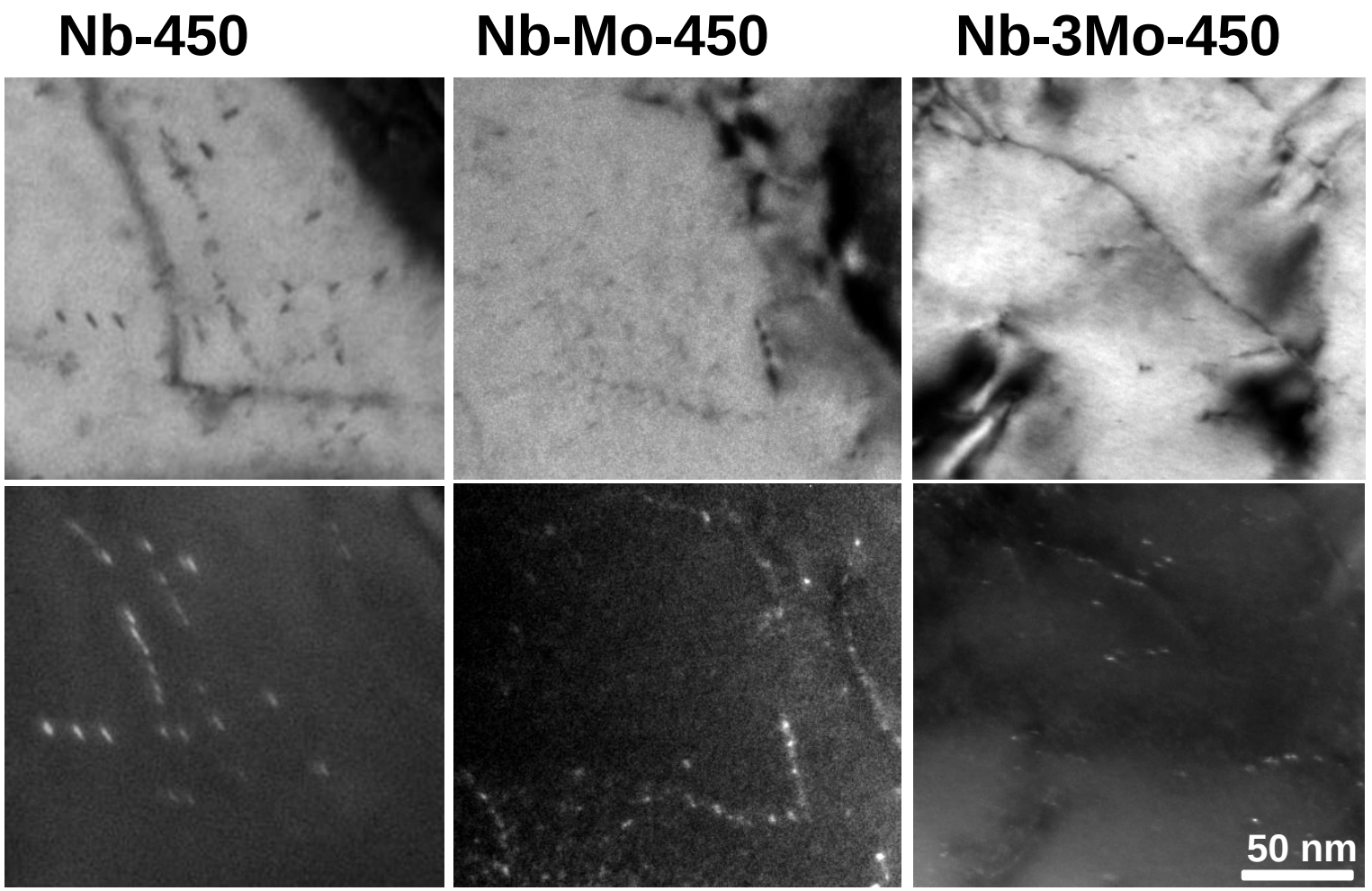




NaCl-type crystal

(Nb,Mo) carbides keep MC-type structure.

TEM obsevation for the granular bainite tempered at 600°C for 8 h.



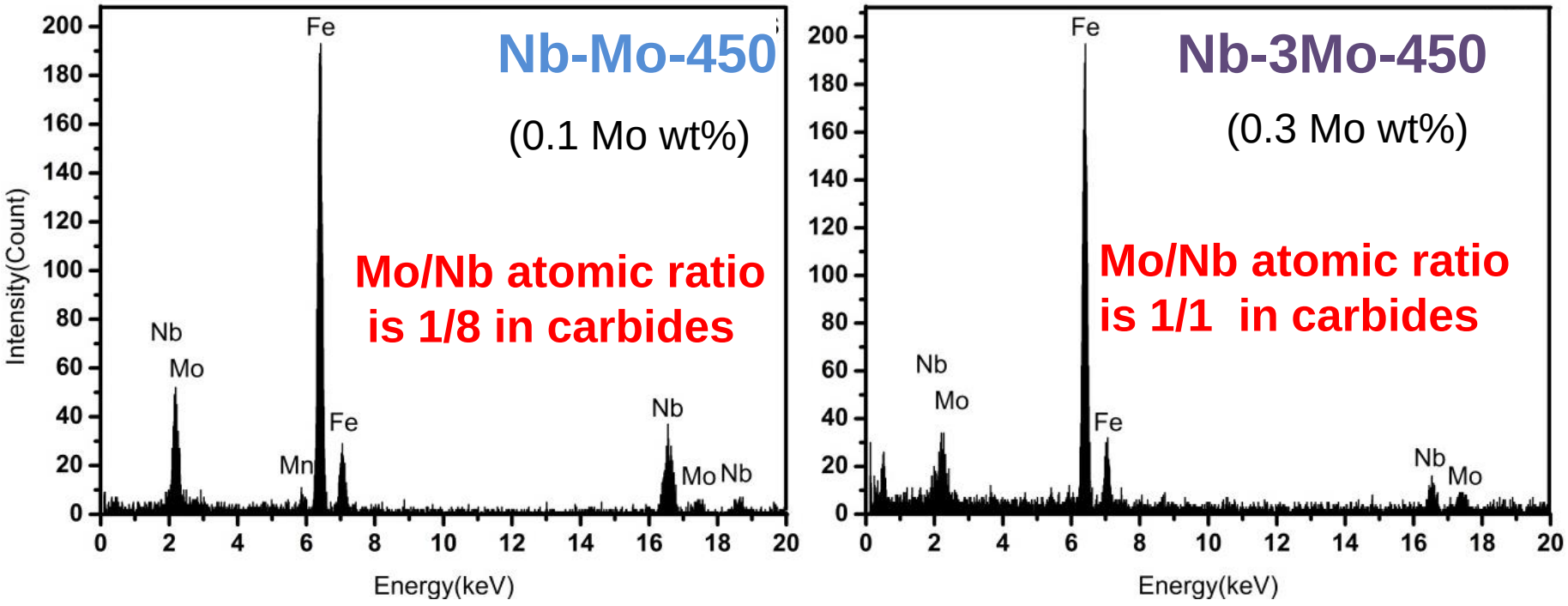
The size of Nb carbides and (Nb,Mo) carbides in granular bainite after tempering at 600°C for 1 and 8 h.

The Size of carbides (nm)

Tempering	Nb-450	Nb-Mo-450	Nb-3Mo-450
1h	3.7±1.1	3.8 ±0.6	4.4 ±1.6
8h	4.3±0.8	4.3 ±1.3	5.5 ±2.1

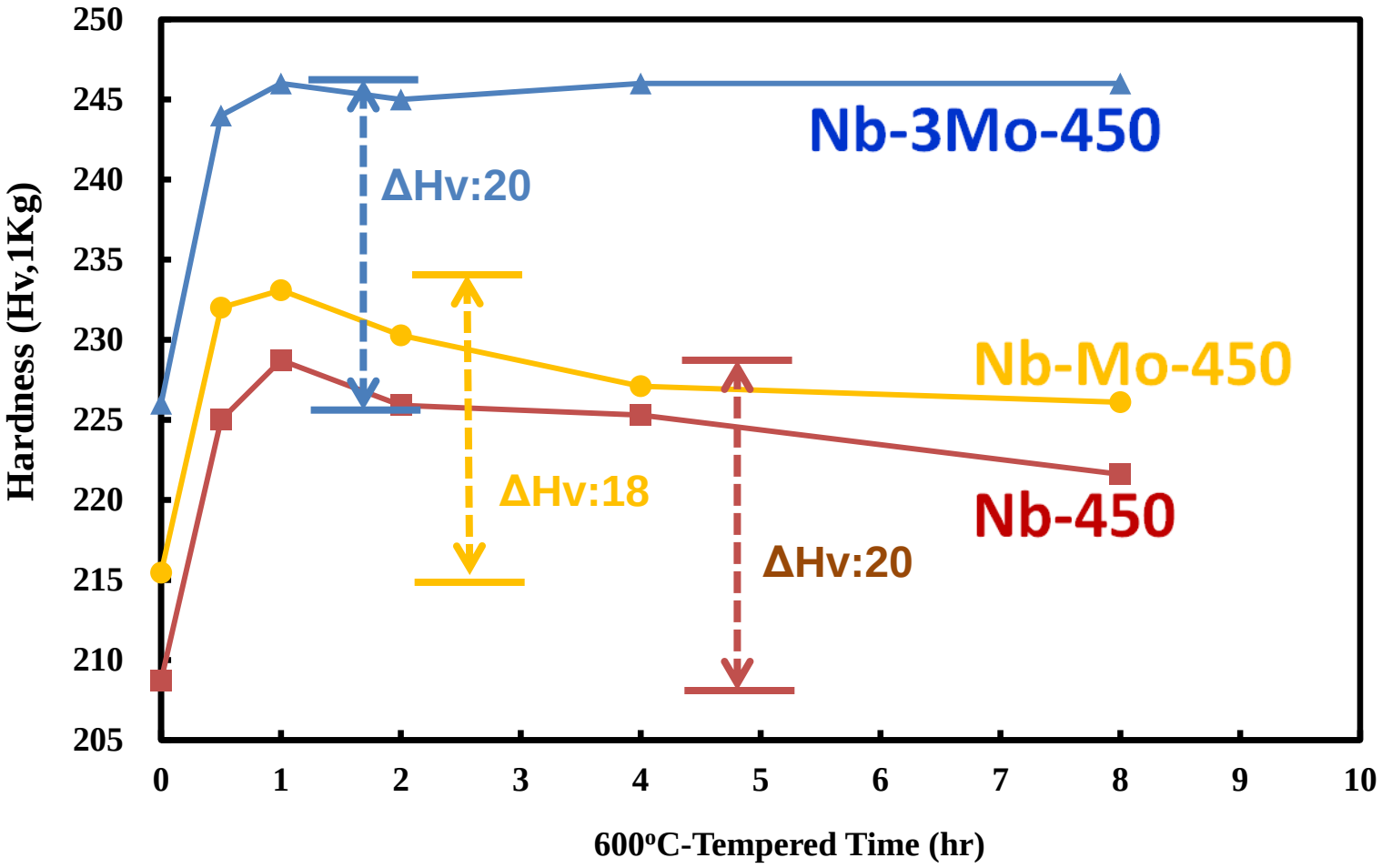
No significant coarsening phenomenaon occurs with adding Mo.

The atomic ratio of Mo/Nb in carbides of tempered granular bainite



After tempering at 600°C for 8 hours

Hardness variations of granular bainite after tempering at 600°C for different intervals.



Mechanical Properties of Nb-450, Nb-Mo-450 and Nb-3Mo-450 Strips

Yield/Tensile Strength (Mpa)

Tempered Time/hr	Nb-450	Nb-Mo-450	Nb-3Mo-450
0 h	512/630	479/683	575/679
1 h	594/652	619/678	672/718
8 h	586/638	605/655	651/702

Elongation (%)

Tempered Time/hr	Nb-450	Nb-Mo-450	Nb-3Mo-450
0 h	22	21	19
1 h	29	27	27
8 h	30	27	27

Conclusions

For the experimental low-carbon Nb-containing steel strips investigated, the results indicate that the Mo addition has the advantage of producing a high volume fraction of granular bainite, which can provide a significant secondary hardening during tempering.