The magnetic-field-induced precipitation behaviors of alloy carbides

T.P. Hou, Y. Li and K.M. Wu

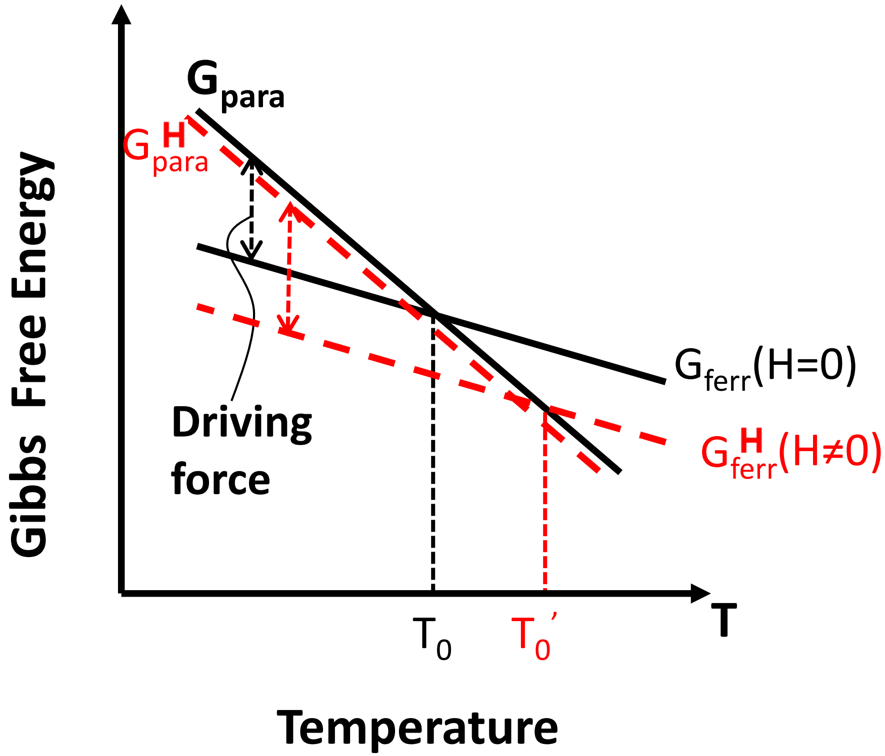
Wuhan University of Science and Technology

E-mail: wukaiming@wust.edu.cn

Acknowledgements

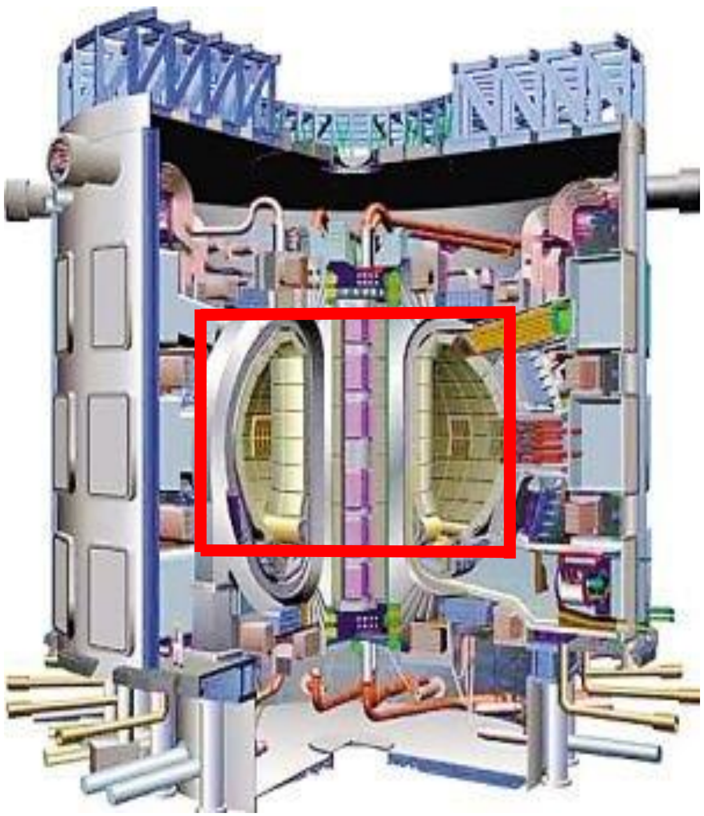
Professor M. Enomoto, Ibaraki University, Japan, for providing alloy specimens
State Ministry of Education (Grant No. NCET-05-0680)

Introduction



Influence of magnetic field on phase transformation

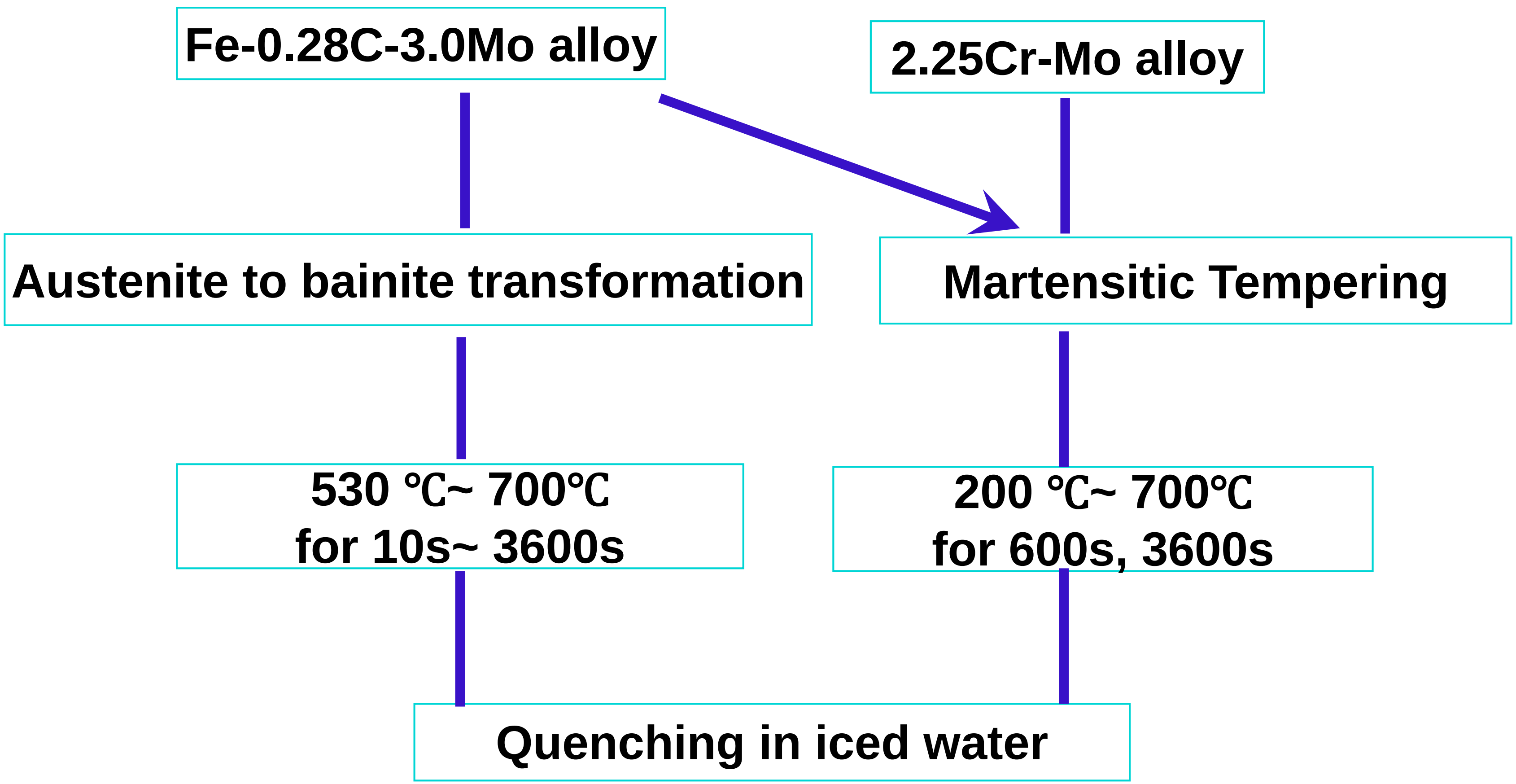
3-5 T, 400-550 ℃



Schematic diagram of the principle component in Tokamak in reduced activation steel

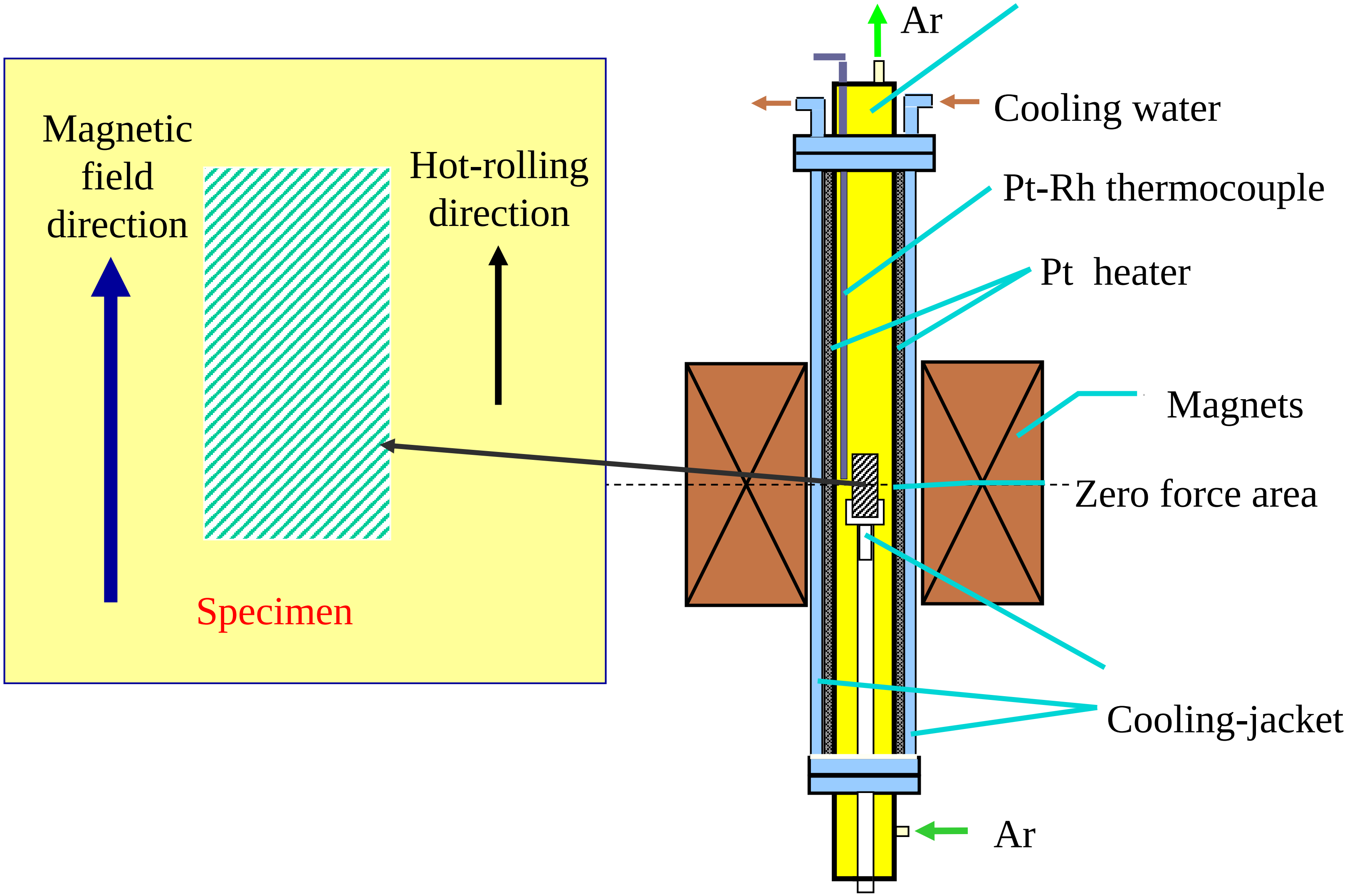
Nuclear fusion reactor Reece, R. J. 1988

Magnetic (12T) Heat Treatment of Alloys

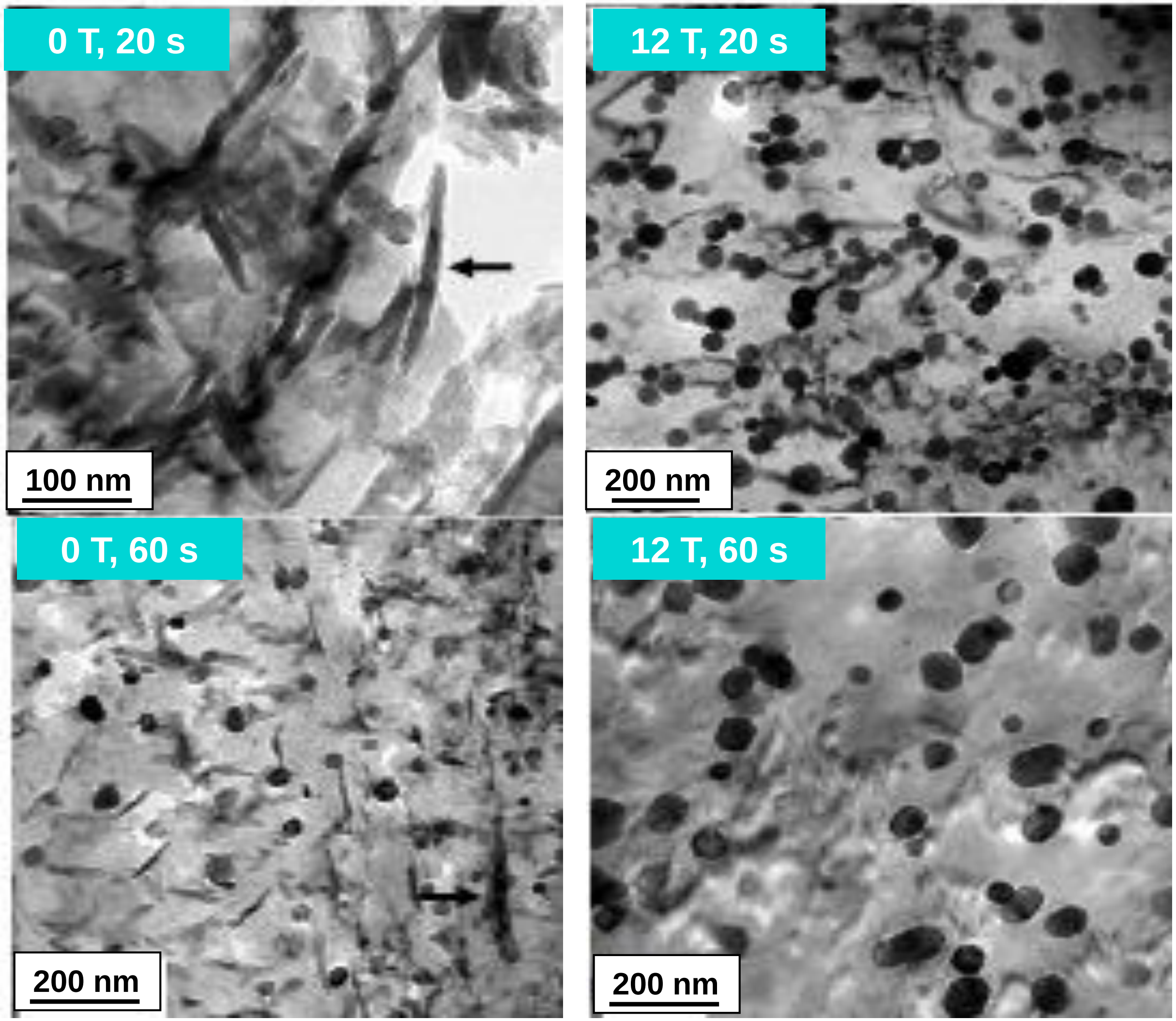


Two alloys, three heat treatments

Magnetic Heat Treatment Equipment



Steel Ⅰ: Fe-C-Mo, $\gamma \rightarrow \alpha$ at 530°C

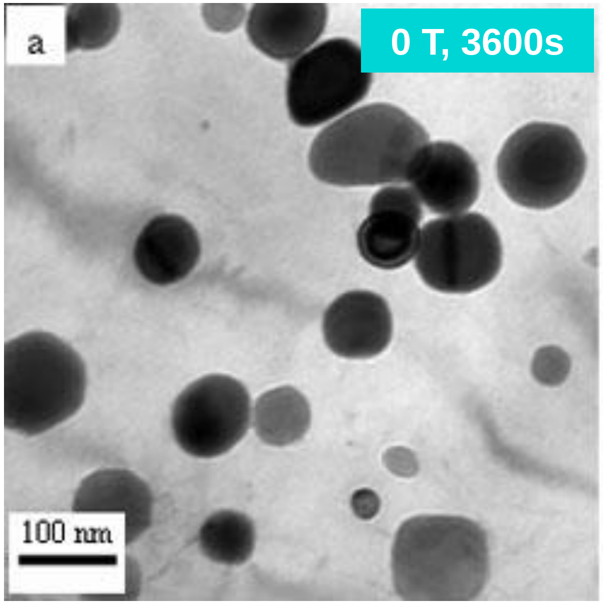


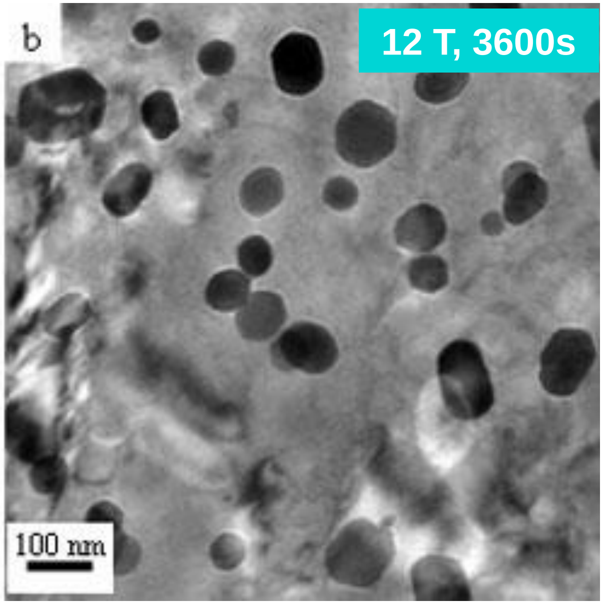
High magnetic field promotes the precipitation of M_6C

Steel Ⅰ: Fe-C-Mo, $\gamma \rightarrow \alpha$ at 530°C

	0 T		12 T	
Time	1000 s	3600 s	600 s	3600 s
Type	M_2C, M_3C	M_6C	M_6C	M_6C

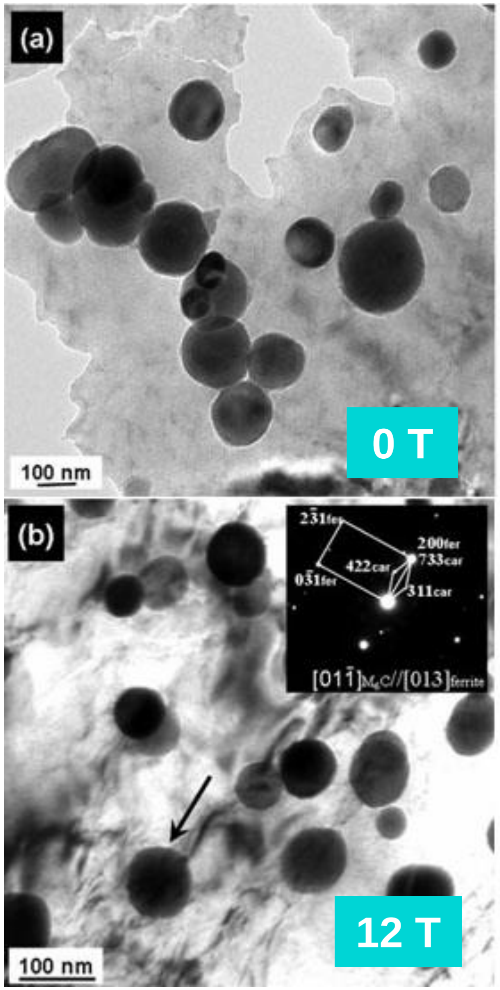
Magnetic field promotes the M_6C precipitation

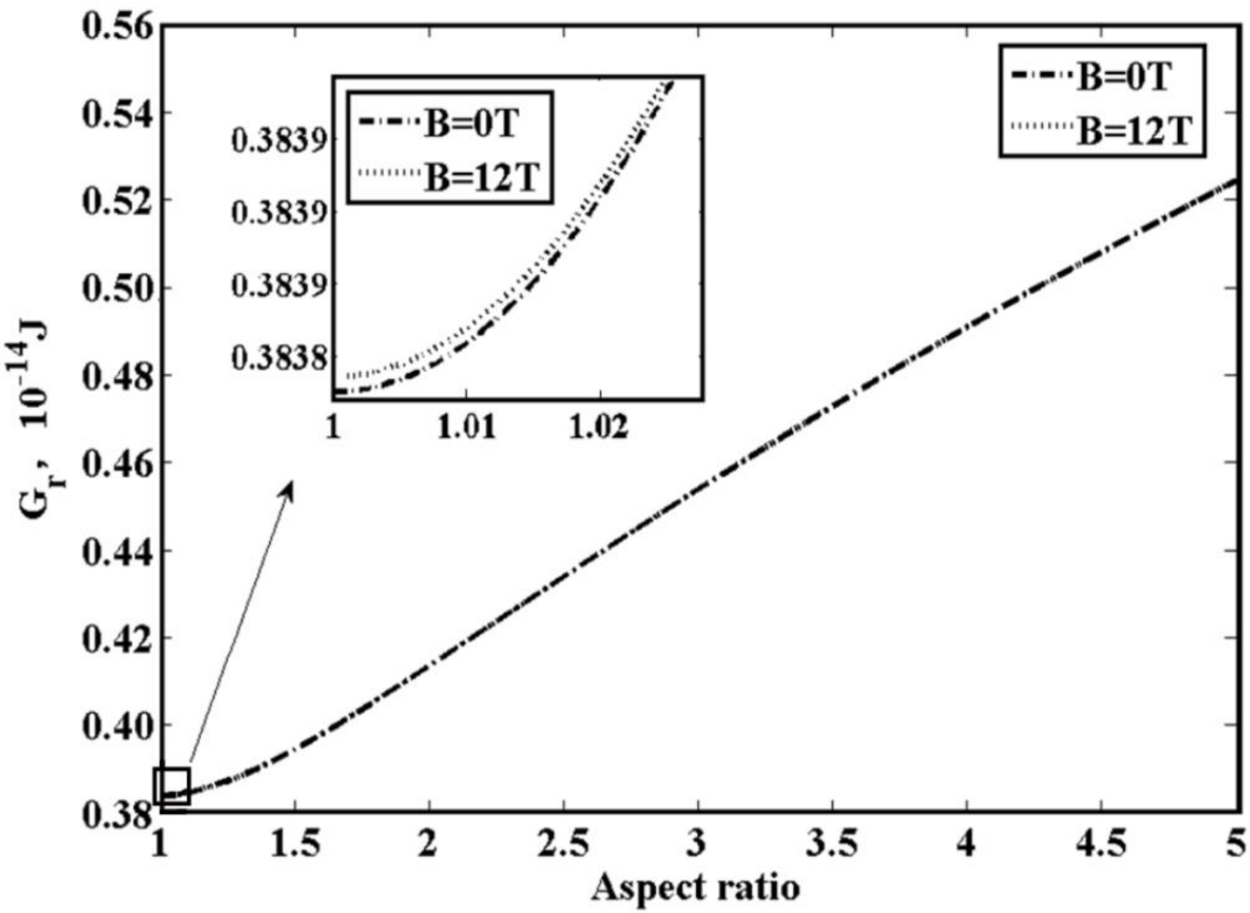




Magnetic field has no influence on the morphology of M_6C

Steel Ⅰ: Fe-C-Mo, γ → α transformation

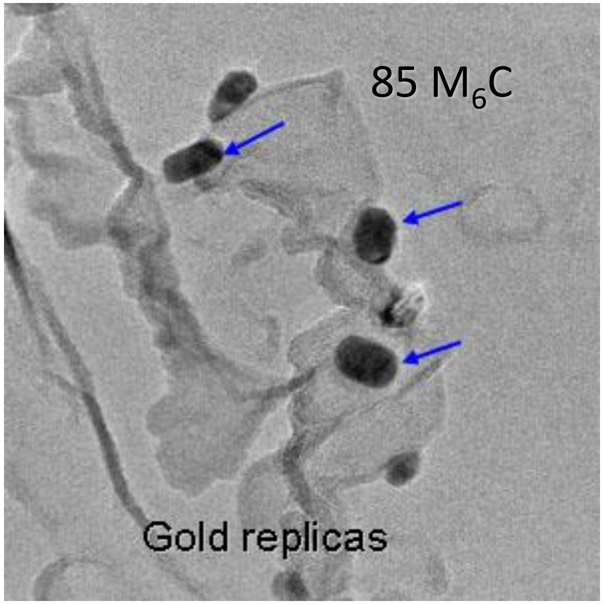




No visible influence on alloy carbide morphology

Steel Ⅰ: Fe-C-Mo, $\gamma \rightarrow \alpha$ transformation

Temp.	0 T				12 T			
	Fe (wt.%)		Mo (wt.%)		Fe (wt.%)		Mo (wt.%)	
	Average	σ	Average	σ	Average	σ	Average	σ
530°C	38.69	0.98	61.30	0.98	67.16	4.48	32.78	4.48



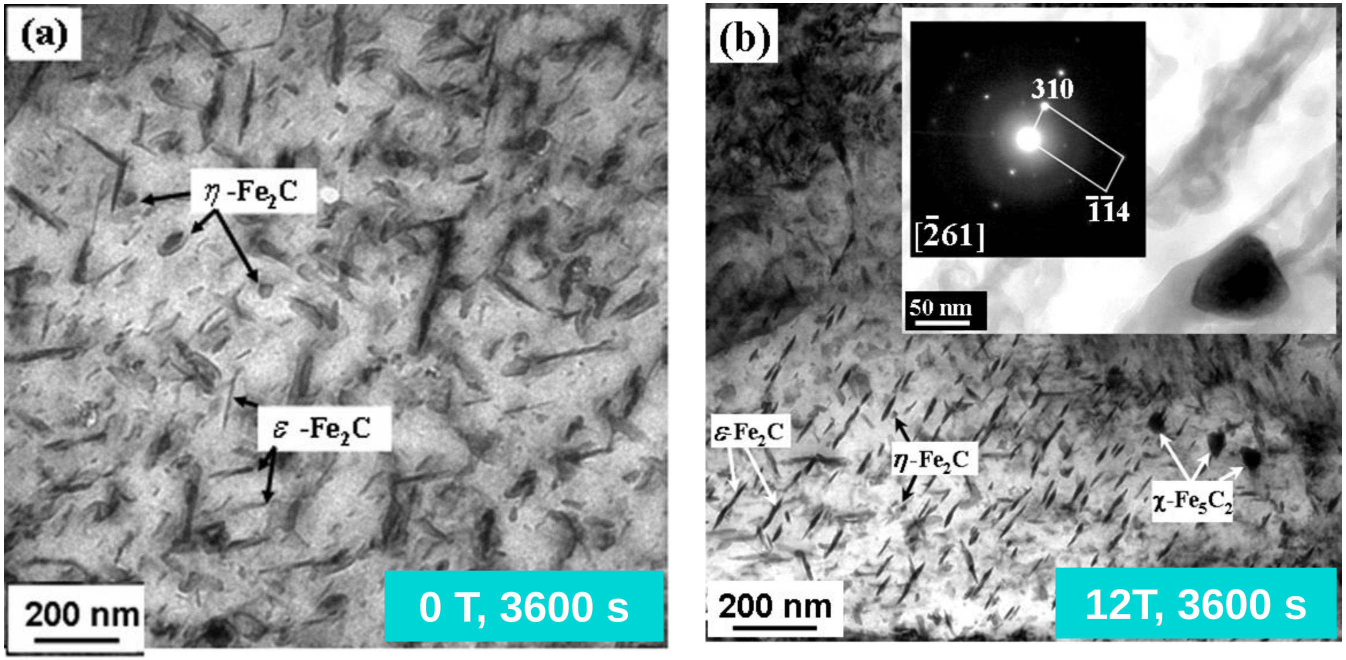
EDS analysis

Higher than the content without the magnetic field

0 T, Fe (wt.%)	
38-45 (700℃~900℃)	Ref. [Sato T, 1962]
36.4-38.6 (727℃）	Ref.[Uhrenius B,1975]
58.15 (874℃）	Ref. [Woodyatt LR,1979]

Magnetic field increases the Fe concentration in M_6C

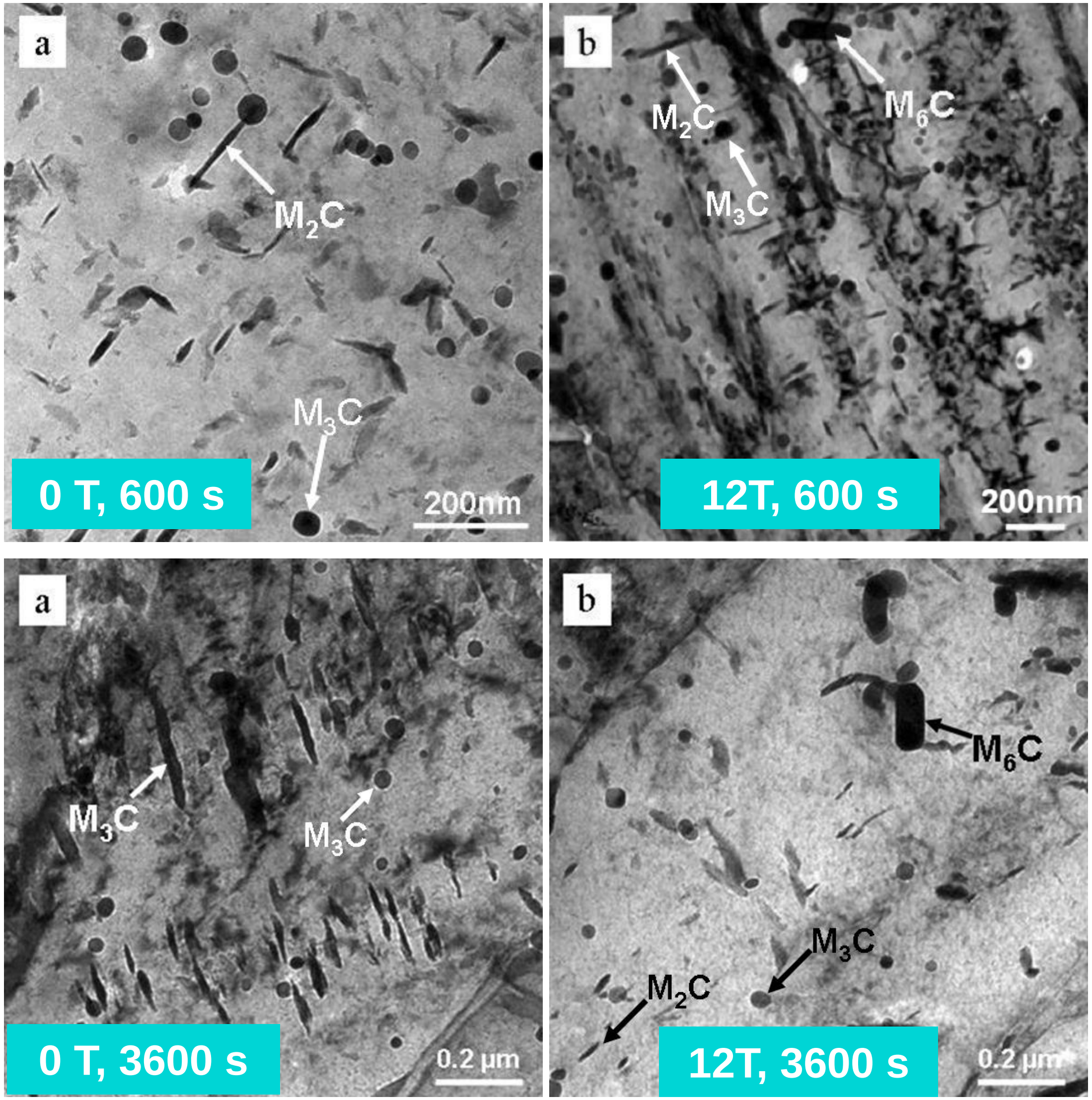
Steel Ⅰ: Fe-C-Mo, Tempered at 200 ℃



	0 T		12 T	
Time	600 s	3600 s	600 s	3600 s
Carbide types	ε-Fe_2C η-Fe_2C	ε-Fe_2C η-Fe_2C	ε-Fe_2C η-Fe_2C	ε-Fe_2C η-Fe_2C χ-Fe_5C_2

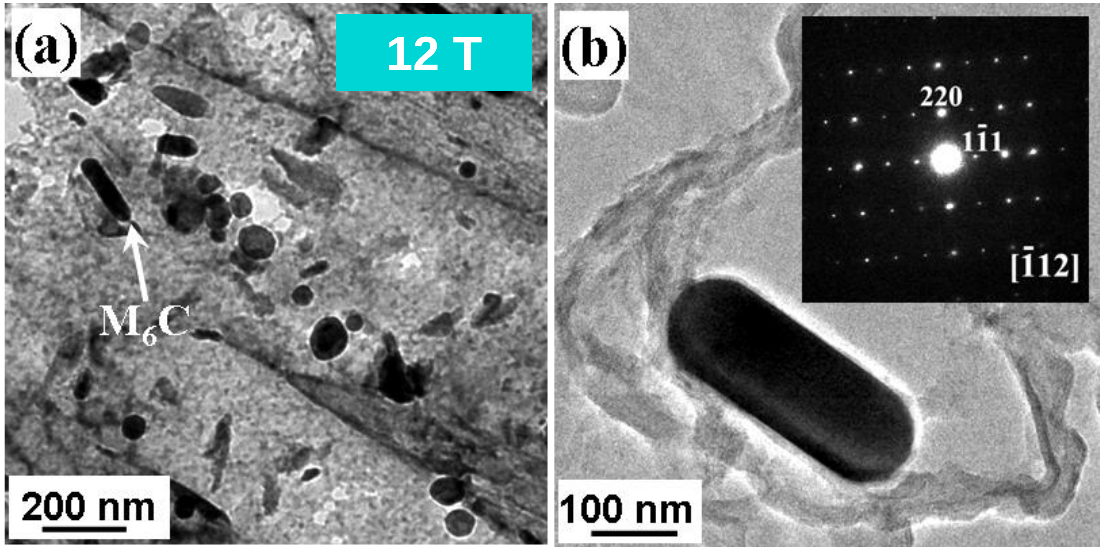
High magnetic field promotes the precipitation of χ-Fe_5C_2

Steel Ⅰ: **Fe-C-Mo, Tempered at 530 ℃**



High magnetic field promotes the precipitation of M_6C

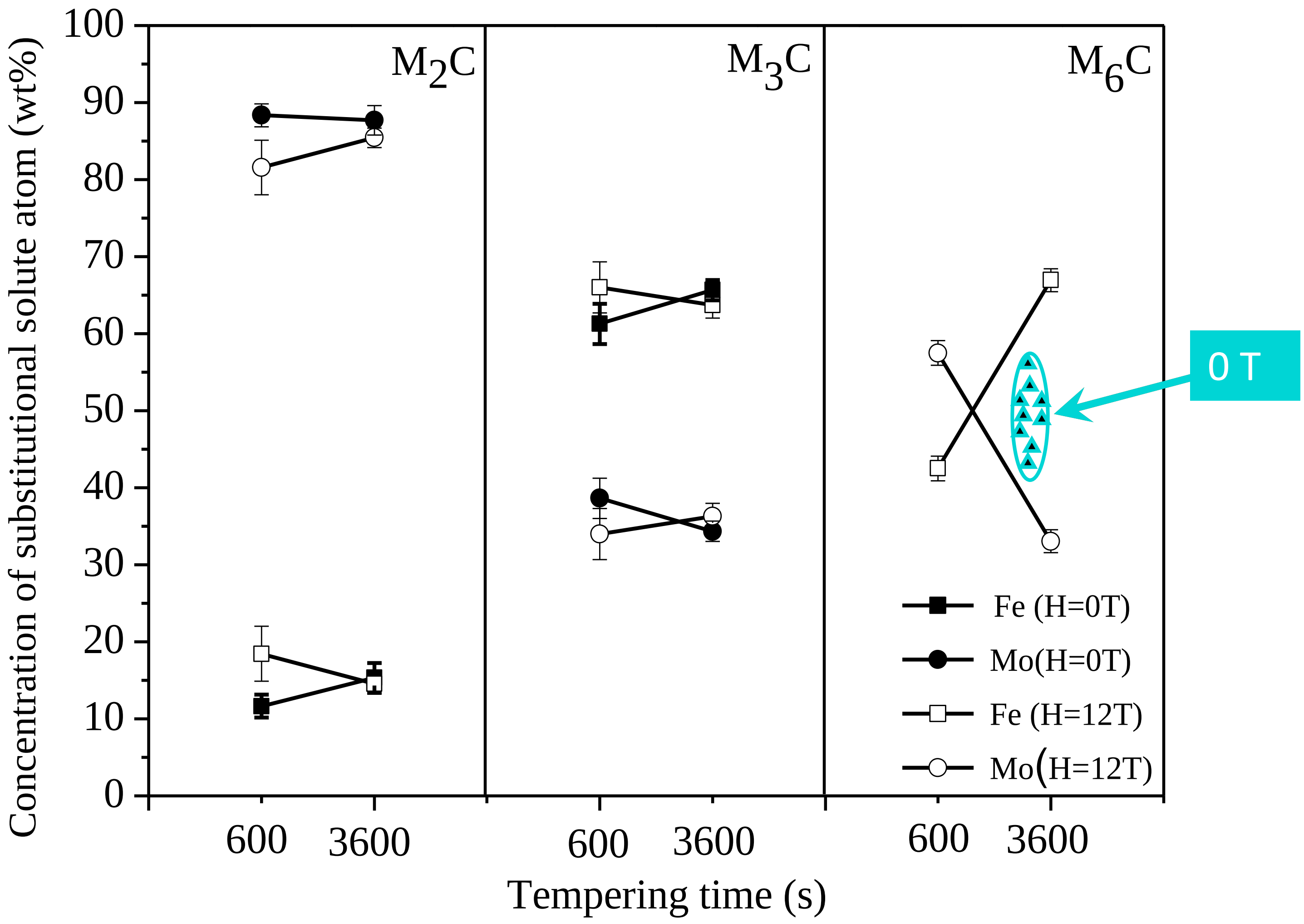
Steel Ⅰ: Fe-C-Mo, Tempered at 530 ℃



	0 T		12 T	
Time	600 s	3600 s	600 s	3600 s
Type	M_2C, M_3C	M_2C, M_3C	M_2C, M_3C, **M_6C**	M_2C, M_3C, **M_6C**

High magnetic field promotes the precipitation of M_6C

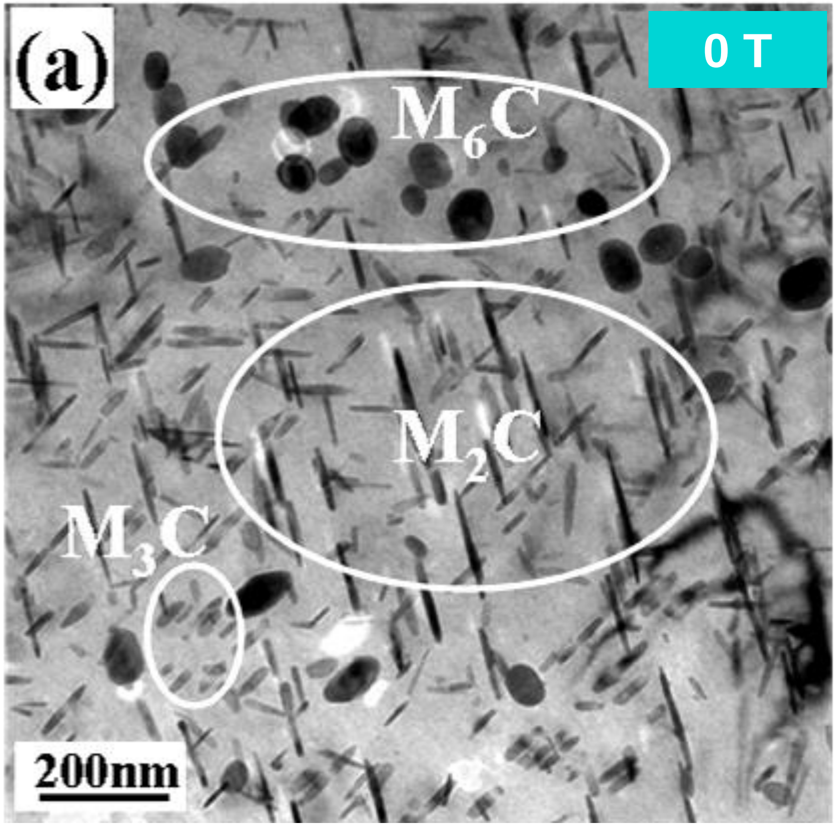
Steel Ⅰ: Fe-C-Mo, Tempered at 530 ℃



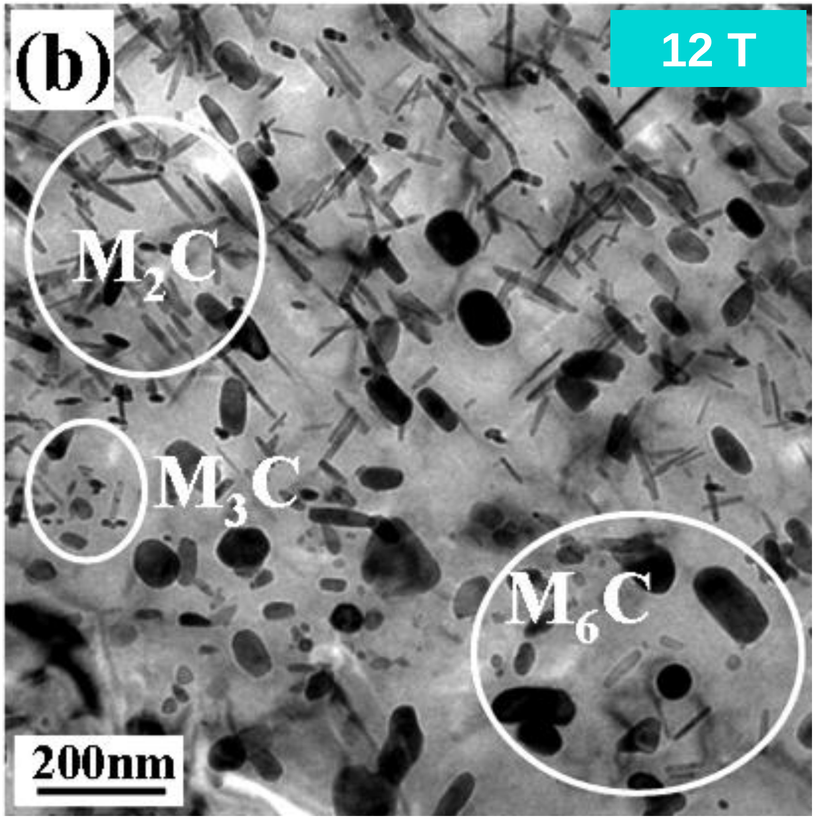
For M_2C and M_3C, no obvious change in concentration

For M_6C, the Fe atom concentration increases

Steel Ⅰ: Fe-C-Mo, Tempered at 700 ℃



700℃, 3600 s



700℃, 3600 s

High magnetic field has no visible influence on alloy carbide precipitation during high temperature tempering

Steel Ⅱ: 2.25Cr-Mo, Tempered at 550 ℃

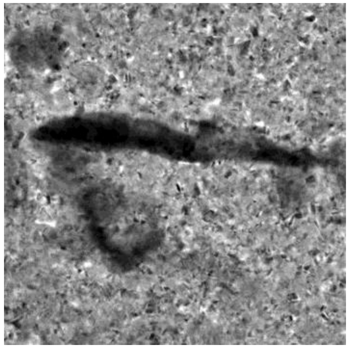
Tempered at 550°C for 600 and 3600 s

	Without a magnetic field		With a 12-T magnetic field	
Time	600 s	3600 s	600 s	3600 s
Type	M_2C, M_3C	M_2C, M_3C	M_2C, M_3C M_7C_3, $M_{23}C_6$	M_2C, M_3C M_7C_3, $M_{23}C_6$
Carbides	$(Fe, Cr, Mo)_2C$ $(Fe, Cr, Mo)_3C$	$(Fe, Cr, Mo)_2C$ $(Fe, Cr, Mo)_3C$	$(Fe, Cr, Mo)_2C$ $(Fe, Cr, Mo)_3C$ $(Fe, Cr, Mo)_7C_3$ $(Fe, Cr, Mo)_{23}C_6$	$(Fe, Cr, Mo)_2C$ $(Fe, Cr, Mo)_3C$ $(Fe, Cr, Mo)_7C_3$ $(Fe, Cr, Mo)_{23}C_6$

High magnetic field promotes the precipitation of $M_{23}C_6$ and M_7C_3 carbides

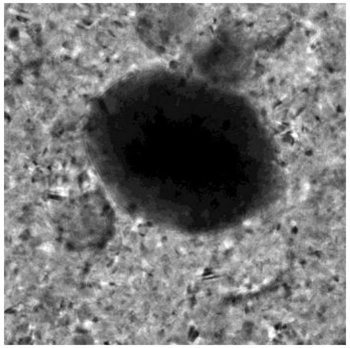
Steel Ⅱ: 2.25Cr-Mo, Tempered at 550 ℃

Gold replicas



M_7C_3 6:1

$(Cr_{2.24}Fe_{4.76})C_3$



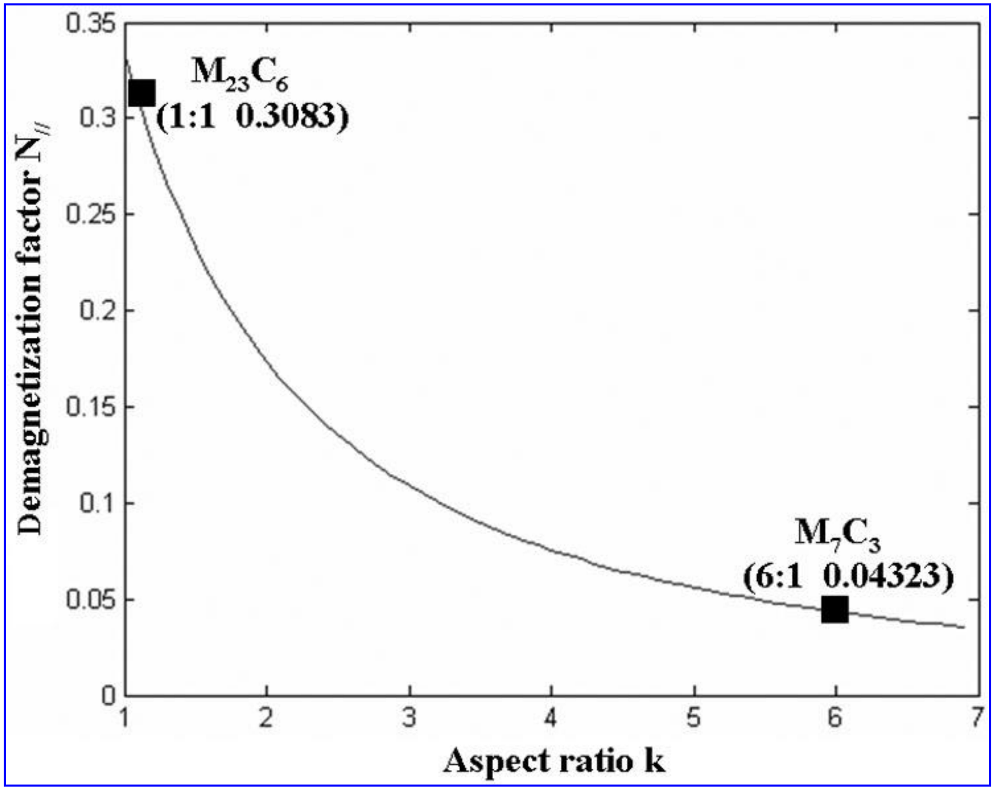
$M_{23}C_6$ 1:1

$(Cr_{4.02}Fe_{18.98})C_6$

$M_{23}C_6$	Fe	Cr	Mo	Mn
Thermo-Cal	25.2	49.8	19.5	0.03
J-MatPro	25.1	48.3	19.4	0.25
Experimental	70.35	14.16	9.30	6.19

The increased Fe content in the $M_{23}C_6$ and M_7C_3 carbide

$$N_{//}=\frac{4\pi}{k^2-1}\left[\frac{k}{\sqrt{k^2-1}}\ln\left(k+\sqrt{k^2-1}\right)-1\right]$$



No visible influence on alloy carbide morphology

Steel Ⅱ: 2.25Cr-Mo, Tempered at 200, 700 ℃

	0 T		12 T	
Time	600 s	3600 s	600 s	3600 s
Type	M_2C, M_3C, M_7C_3	M_2C, M_3C, M_7C_3	$M_{23}C_6$	$M_{23}C_6$

200℃: The magnetic field promotes the precipitation of $M_{23}C_6$

	0 T, 12 T
Time	600 s, 3600 s
Type	M_2C, M_3C, M_7C_3, $M_{23}C_6$

700℃: Alloy carbides are changed into paramagnetic state. High magnetic field has no visible influence on alloy carbide precipitation.

Discussion: Gibbs free energy

$$G^*(T,H) = G^*(T,0) - \int_0^M B \cdot dM$$

Chemical Gibbs free energy dependent on temperature

Magnetic Gibbs free energy mainly dependent on magnetic field strength and magnetization

Discussion: Weiss molecular field theory

$$B = B_0 + \lambda M$$

$$\boxed{M = NmB_j(\alpha(T))}$$

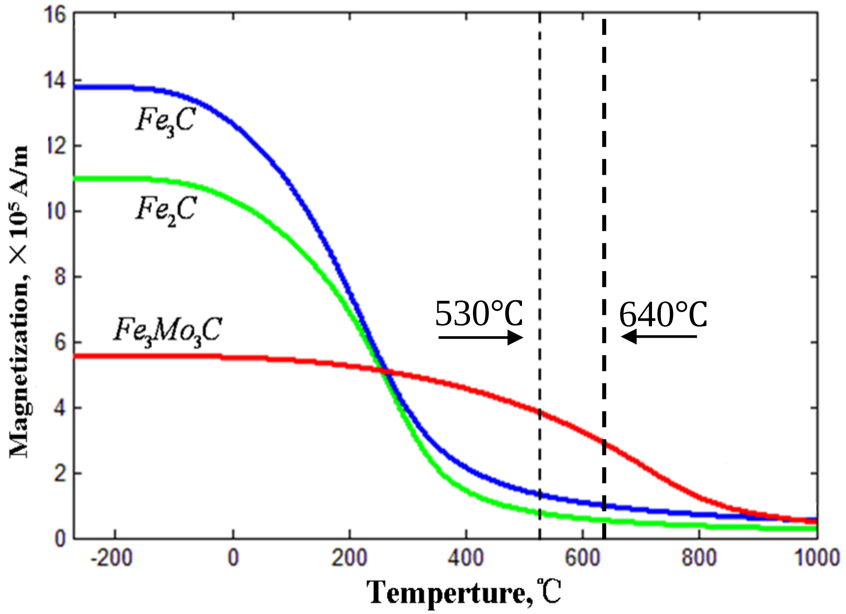
$$B_j(\alpha) = \left\{ \frac{2j+1}{2j} cth \frac{(2j+1)a_j}{2j} - \frac{1}{2j} cth(\frac{a_j}{2j}) \right\}$$

$$\alpha_j = \frac{n_B \mu_B B}{kT}$$

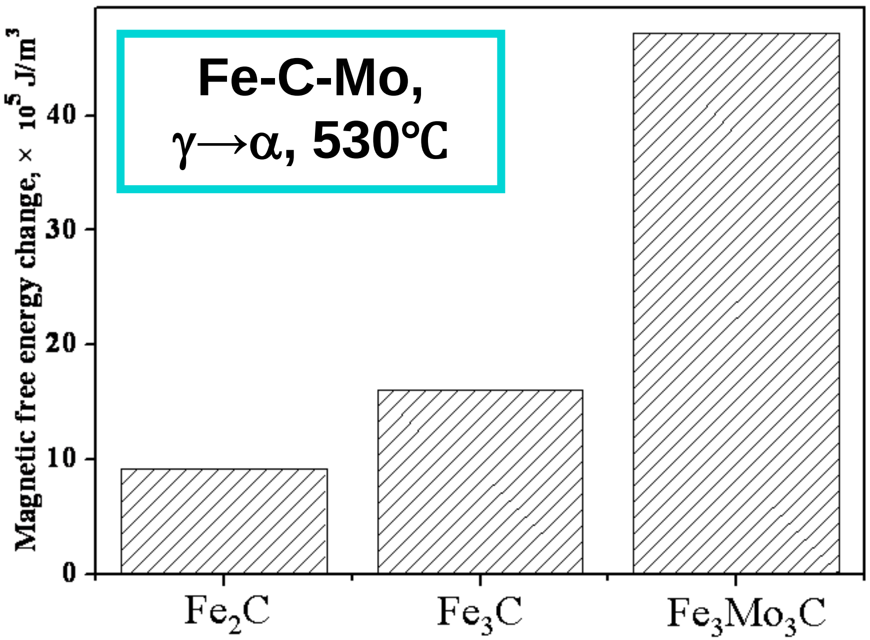
$$T_c = \frac{(j+1)Nn_B^2 \mu_B^2 \lambda}{3jk}$$

The theoretical calculation of the magnetization (M) with temperature (T)

Magnetic field promotes the M_6C precipitation

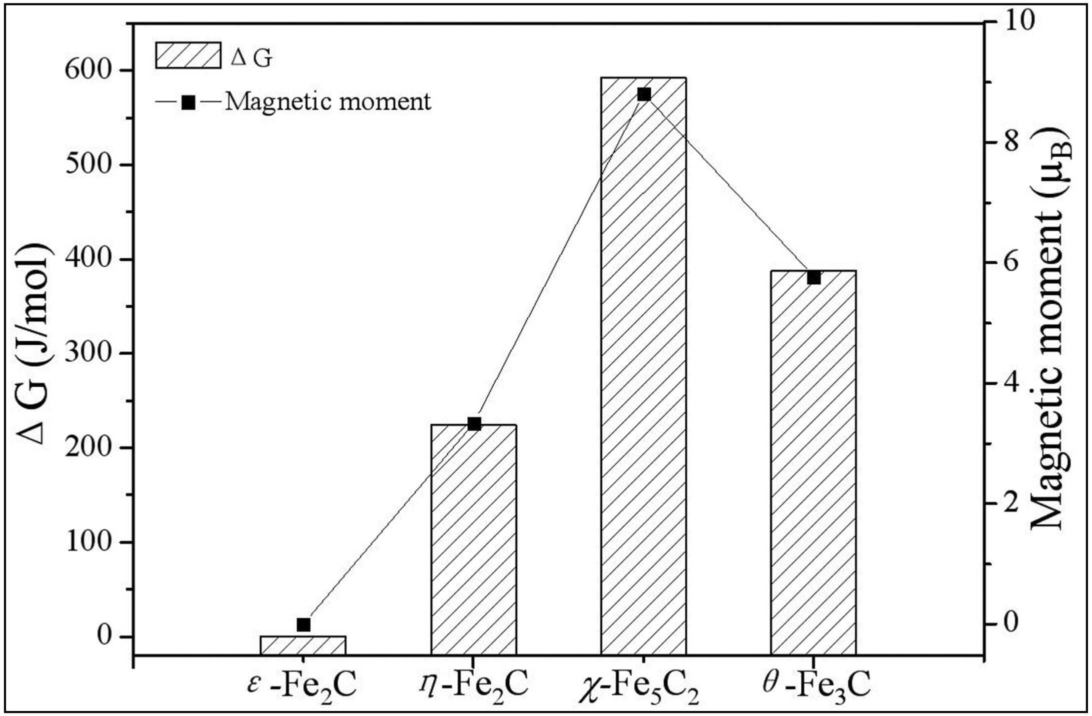


M-T curves



$$\Delta G^M = -\int_0^M \overrightarrow{B} \cdot d\overrightarrow{M}$$

Magnetic field promotes the Fe_5C_2 Precipitation

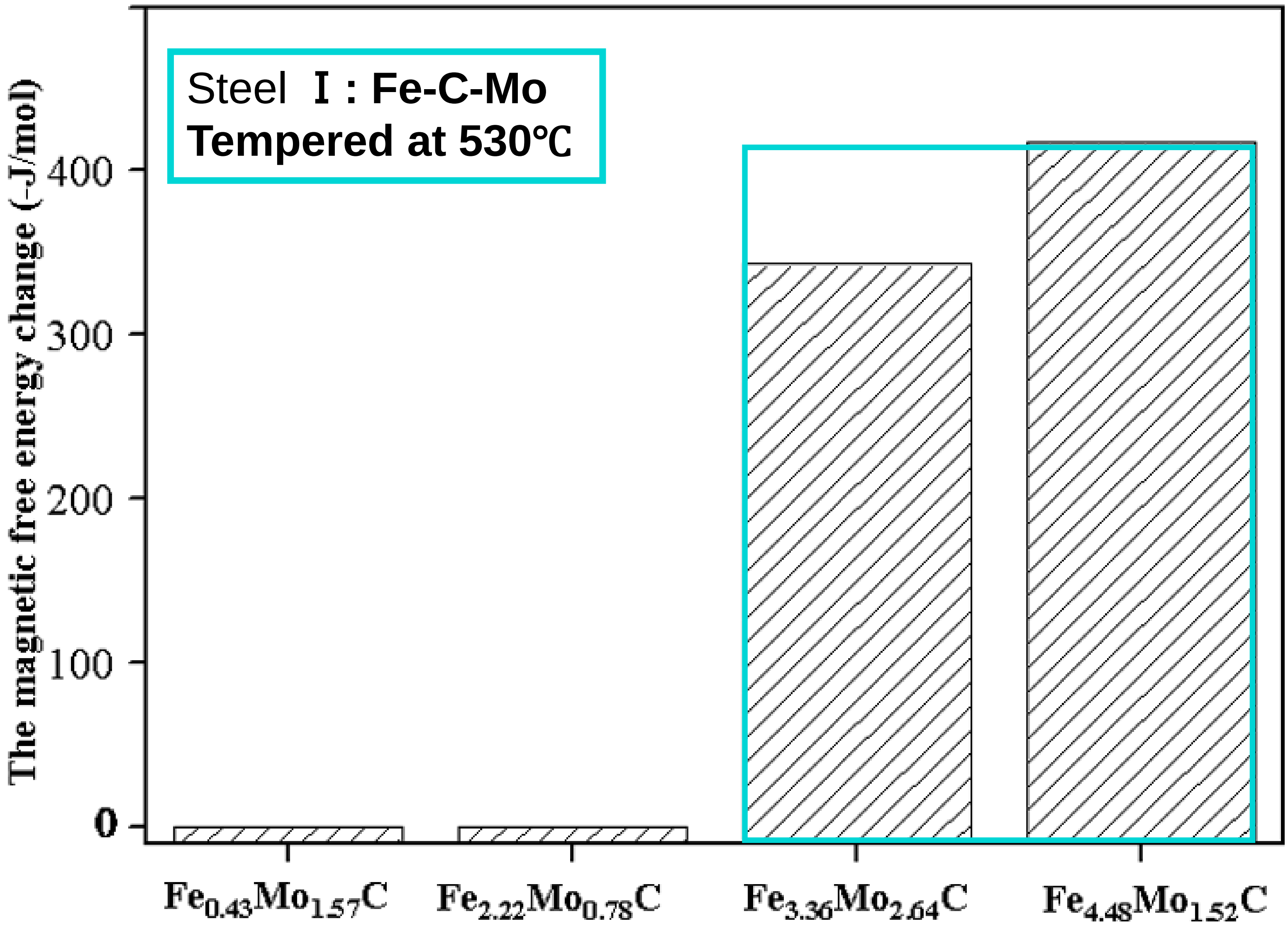


The magnetic free energy change and the magnetic moments

The magnetic free energy change of χ-Fe_5C_2 is the most remarkable

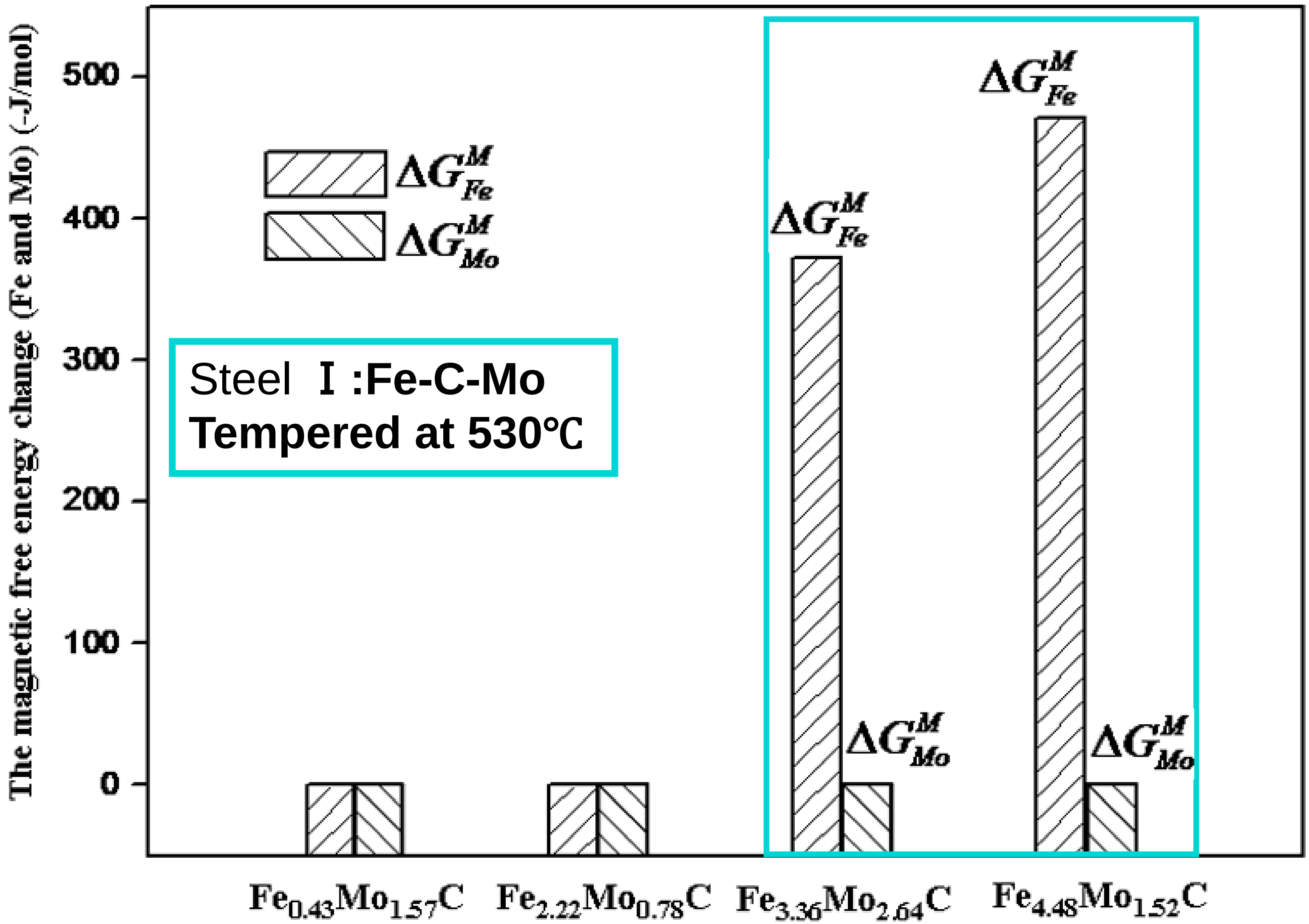
Steel Ⅰ: **Fe-C-Mo, Tempered at 200℃**

Magnetic field promotes the M_6C precipitation



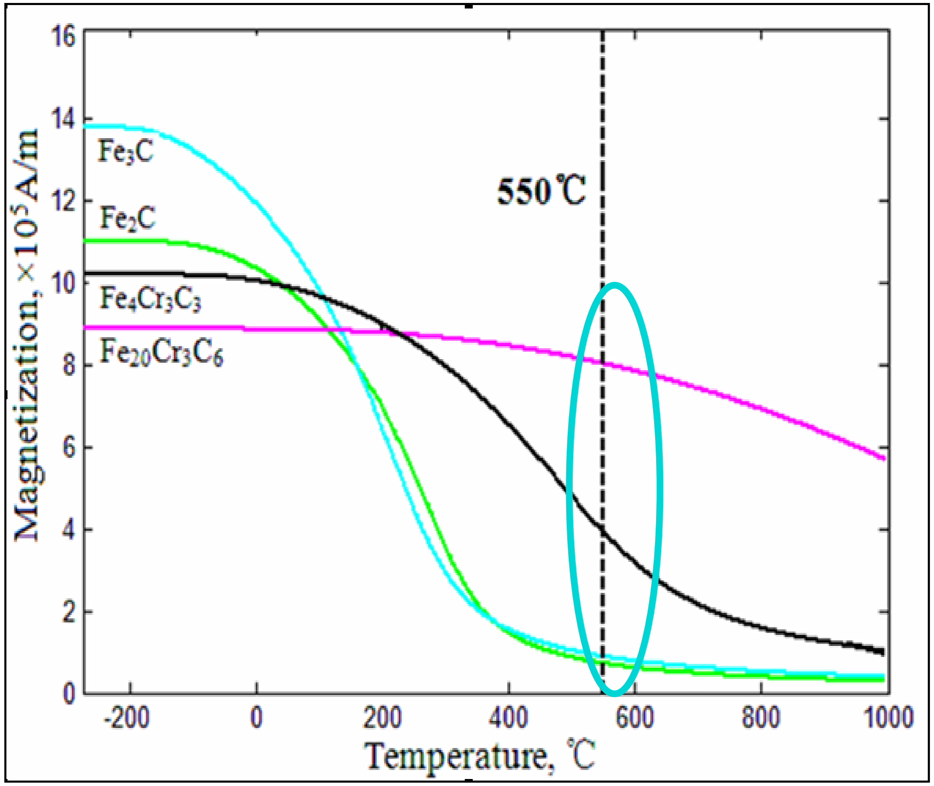
The magnetic free energy change of $(Fe,Mo)_6C$ is the most remarkable

Magnetic field increases the Fe concentration

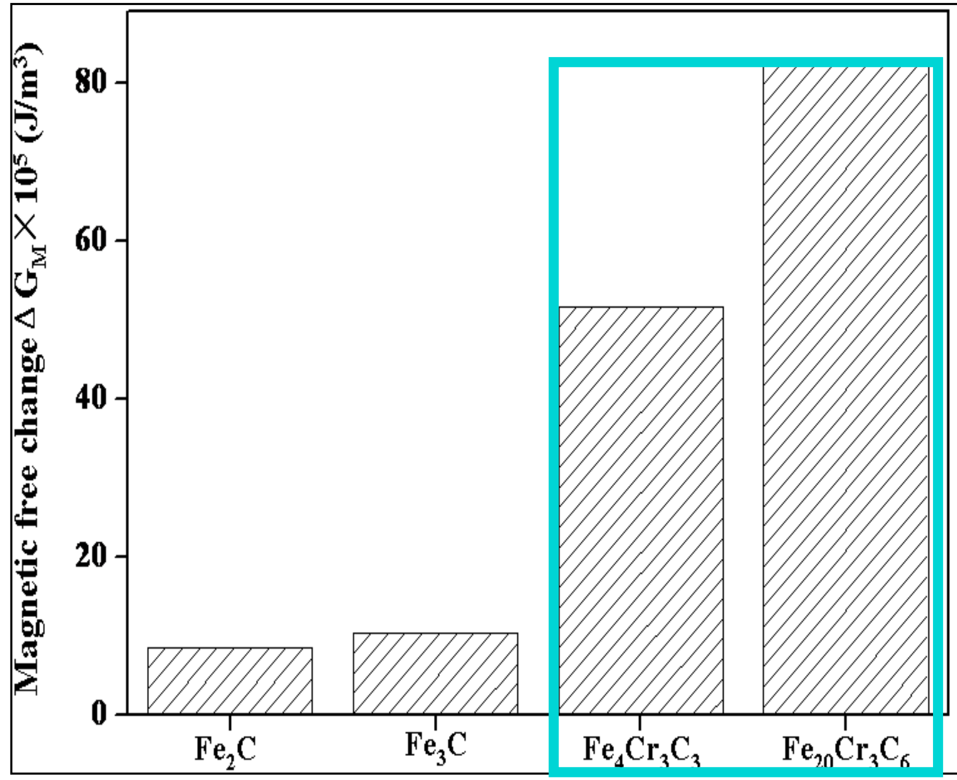


The magnetic free energy change of Fe is increased remarkably

M-T curves of $M_{23}C_6$ and M_7C_3, and their magnetic Gibbs free energy



The magnetization curve with the temperature



The magnetic free energy change

High magnetic field promotes the precipitation of $M_{23}C_6$ and M_7C_3

Steel Ⅱ: **2.25Cr-Mo, Tempered at 550℃**

Conclusions

The effect of high magnetic field on alloy carbide precipitation behaviors:

- The precipitation sequence of specific alloy carbide is changed
- The content of substitutional solute atom of Fe is increased
- No visible influence on alloy carbide morphology

The above three aspects are attributed to the magnetic free energy change with the presence of high magnetic field.