—특별 강연—

Magnetic and Electrostatic Grain Refinements in Solids*

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1. INTRODUCTION

The heat treatment of materials has progressed from an art to a science in the last half century, and it is commonly thought that all possible factors of heat treatment that would influence the physical properties of materials have been explored. The effects of a magnetic field and an electrostatic field are the factors which have recieved very little attention up to this time.

R. Skorski's paper considers the possibility of the refinement of grains reulting from magnetic annealing.

For a long time it has been recognized that grain refinement depends on surface tension of the grains in the same sence as flow of liquid through a capillary tube depends on surface tension of the liquid. The lower the surface tension of the liquid is, the easier it flows through a capillary tube, because liquids with a lower surface tension can form droplets of a smaller diameter. Most important is the fact that surface tension of a liquid depends on its electrostatic state. This effect has been demonstrated in the experiments using water in a glass vessel.

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II. MAGNETIC GRAIN REFINEMENT

It is claimed that the refinement of grains of a material can influence the mechanical properties as shown in Tables 1 and 2. These claims have been recognized. A theoretical calculation based on classical and quantum mechanical considerations has already been stated to the effect that the annealing above and below the Curie point of steels causes a refinement of the grain size. Above the Curie point this effect is the result of short range ferromagnetism. There has been experimental work conducted to test the validity

Table 1.

The mechanical properties of Armco Iron heat treated at 800°C for 15 minutes and furnace cooled

Yield strength (psi)	Ultimate strength (psi)	%Elongation
Magnetic field 3500(oe)		
40, 000	47, 000	44
40, 000	49, 000	44
38. 000	47, 000	42
39, 000	48, 000	43
37, 000	47, 800	43
No field		
29, 000	47, 000	39
35, 400	47, 200	40
37, 400	46, 200	38
36, 000	48. 000	33
36, 000	47, 400	39

Table 2.

The mechanical properties of 1040 steel heat treated at 800°C for 15 minutes and furnace cooled

Yield strength (psi)	Ultimate Strength (psi)	%Elongation
Magnetic field 3500 (oe)		
70,000	105,000	24
73,000	97,000	25
71,000	105,000	26
70,000	96,000	23
70,000	96,000	25
No field		
64,000	97,000	23
70,500	103,000	25
66,000	98,000	23
67.000	98,000	22
68,000	98,000	23

of the theory.

The difference in grain size of the Armco Iron annealed in a constant magnetic field as compared to that treated normally is very evident as shown in Figure 1. The same result is observed in the 1018 steel as shown in Fig. 2. In the higher carbon 1040 steel, a much smaller difference is detected for the fifteen minute annealing time.

The reason for the refinement can be considered to be an increase in surface tension induced by the magnetic field. Surface tension can be defined as, considering a sphere,

$$P=\sigma/r_0$$

where σ=surface energy

r_0=radius of the sphere

Consider the attraction force between opposite poles of a magnetic dipole of length, L, and with magnetic charges, P

Magnetic moment, M, of the dipole is:

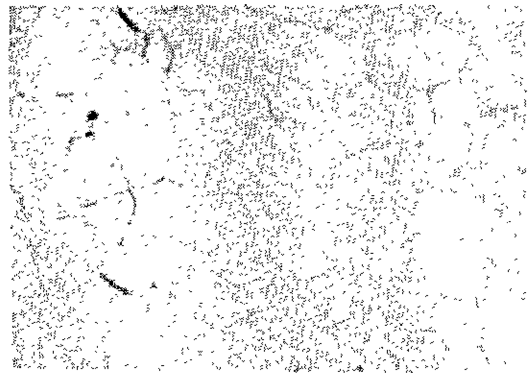
$$M=PL \qquad (1)$$

mechanical moment of the dipole is:

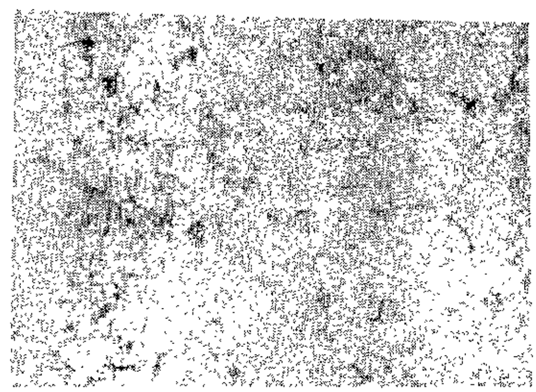
$$N=MH \qquad (2)$$

Hence, the force, F, of the moment, N, is:

$$F=\frac{N}{L}=\frac{PLH}{L}=PH \qquad (3)$$



Temp. 800°C   Time 15min.   Field none   Magn. 250X   Etchant 2% Nital



Temp. 800°C   Time 15min.   Field 700(oe)   Magn. 250X   Etchant 2% Nital

Figure 1. Photomicrograph of Armco Iron annealed at 800°C. and furnace cooled. Lower specimen was treated in a 700(oe) field. Note the difference in grain size.

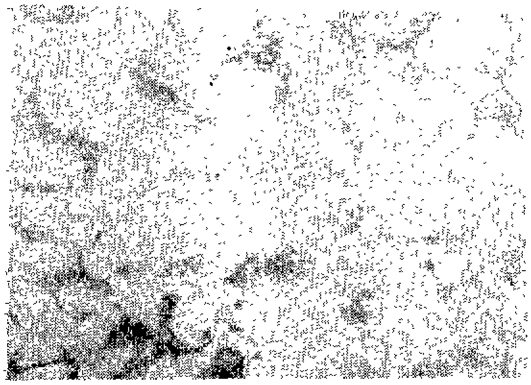
The induction of the pole with charge, P, at distance, r, from its center is:

$$B=\frac{P}{4\pi r^2} \qquad (4)$$

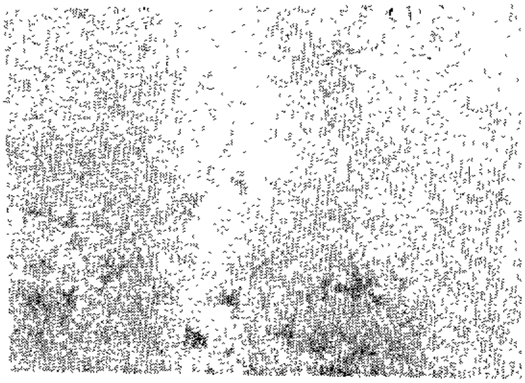
On the other hand, the induction $B=\mu H$ where μ is the magnetic permeability, a magnetic field Hp induced by a magnetic pole with the charge P is:

$$Hp=\frac{P}{4\pi r^2\mu} \qquad (5)$$

Hence, the force of attraction between two poles of opposite signs as it is in a ferromagnetic bar is:



Temp.	Time	Field	Magn.	Etchant
800°C	15min.	none	250X	2% Nital



Temp.	Time	Field	Magn.	Etchant
800°C	15min	700(oe)	250X	2% Nital

Figure 2. Photomicrograph of 1018 steel annealed for 15 minutes at 800°C. The small grain size is seen in the specimen in a magnetic field of 700(oe).

$$F=\frac{P_1P_2}{4\pi r^2\mu} \tag{6}$$

This corresponds to the Coulomb law. When the two magnetic poles approach so that their centers coincide, the work done is: PHL. Hence, the energy, W, in the magnetic bar is:

$$W=BHSL \tag{7}$$

where, S is the surface of the magnetic poles. Since, SL is the volume of the ferromagnetic bar therefore, the magnetic energy density, E, in the bar is:

$$E=BH \tag{8}$$

Hence, the force

$$F=PH=BHS=\mu H^2S \tag{9}$$

From this, one finds the tension caused by the magnetic field on the surface of the magnetic poles of the magnetic bar is:

$$Pm=\frac{\mu H^2S}{S}=\mu H^2 \tag{10}$$

Since the intensity of the magnetic field is a square term, the direction of the field is of no consequence. Therefore, the effect of the magnetic field on ferromagnetic grain is the apparent increase of its surface tension by the component μH^2, and the total surface tension is:

$$Pt=\frac{\sigma}{r_0}+\mu H^2 \tag{11}$$

Hence, the annealing of ferromagnetic grain in a magnetic field allows the formation of a new grain size with a diameter r_1 smaller than the diameter r_0 (corresponding to the absence of a field).

Concisely:

$$Pt=\frac{\sigma}{r_1}=\frac{\sigma}{r_0}+\mu H^2 \tag{12}$$

which shows that $r_1<r_0$ (13)

The fact that grain refinement is observed above the Curie point as well as below can be interpreted in terms of short-range magnetism and is, therefore, consistent with theory. The noticeable lack of difference in grain size of the 1040 steel is probably due to the increased carbon content which slows the reaction time. Longer annealing times would produce the same difference as observed in other materials.

III. ELECTROSTATIC GRAIN REFINEMENT

A. Pressure on the Surface of a Liquid Sphere

It will be demonstrated that if the liquid surface is curved the pressure under such a surface is different from that which is above the surface. This is true because there is an additional pressure depending on the shape of the surface which could be negative or possitive depending on the curvature.

In order to calculate this additional pressure, take a film spread on a cylinder A B of the r radius as shown in Figures 3 and 4. Tension of the film is designated by σ; length of the cylinder and of the spread film over it perpendicular to the face of the drawing is l. The force acting on the boundaries of the film is marked by CD:

$$F=\sigma l \tag{14}$$

These forces are tangential to the film and to the cylinder. Let's extend the direction of the action of these forces until they close at point M and designate their resultant force F_0.

Assume that arch CD is small and draw radius OC and OD. The triangle ANM is similar to the triagle OCD. Then,

$$\frac{MN}{AM}=\frac{CD}{OC}=\frac{F_0}{F} \tag{15}$$

Hence, from the formula (14) $F=\sigma l$

$$F=\frac{\sigma l\ CD}{R} \tag{16}$$

But CD is equal to the projection of the film on the plane CD and for the small value of CD, this projection differs very little from the surface of the film. The F_0 which is perpendicular to the surface corresponds with the uniform pressure

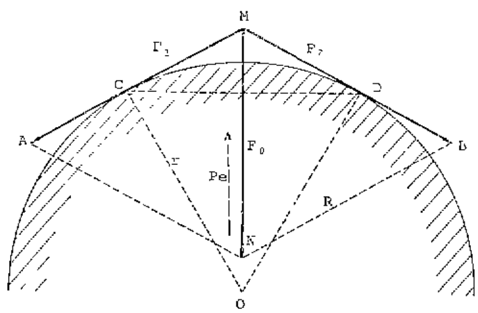


Figure 3. Distribution of pressure on a convex surface of liquid.

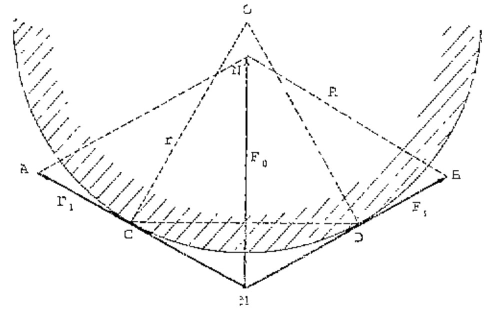


Figure 4. Distribution of pressure on a concave surface of liquid.

P acting over the whole film. Therefore,

$$P=\frac{F_0}{lCD} \tag{17}$$

Finally,

$$P=\frac{\sigma}{R} \tag{18}$$

B. Electrostatic Pressure

Take electric charge Q in a dielectric constant ε_r and surround it by a sphere of radius r, then pass the flux vector D through the surface of the sphere. According to Gauss law and because of symmetry:

$$Q=4\pi r^2 D \tag{19}$$

Hence,

$$D=\frac{Q}{4\pi r^2} \tag{20}$$

because in a dielectric

$$D=\varepsilon_r\varepsilon_0 E \tag{21}$$

where ε_0 is the dielectric constant in a vacuum and E is the electric field (intensity of the electric field). Therefore, the force with which charge Q acts on another charge Q′ located at r distance from the Q is:

$$F=\frac{QQ'}{4\pi\varepsilon_r\varepsilon_0 r} \tag{22}$$

This force is ε_r times smaller than the force acting between the same charges but in vacuum. It should be noted that this force has the newton unit.

Take now a flat capacitor filled with a dielectric. The capacitor has charges $+Q$ and $-Q$ on opposite surfaces. The electric field inside the dielectric is E and the distance between the plates is d. It can be found that the force acting on the plate charge with Q is:

$$F=\frac{QE}{2} \tag{23}$$

From here it can be found that the work value when two plates approach together is equal to

$$\frac{QE}{2}d=\frac{QU}{2} \tag{24}$$

where U is a potential. On the other hand,

$$Q=DS \tag{25}$$

where S is surface area. Energy W contained in the capacitor field is equal to the work which one can get when the two plates approach together:

$$W=\frac{DESd}{2}=\frac{DEV}{2} \tag{26}$$

where V is the volume of the capacitor. Hence, electrical energy density in the dielectric is equal to

$$\frac{DE}{2} \tag{27}$$

which is the same as in the vacuum. The force acting on the plate of the capacitor can be expressed as

$$F=\frac{QE}{2} \tag{28}$$

and,

$$Q=DS \tag{29}$$

So.

$$F=\frac{DES}{2} \tag{30}$$

It can be seen that the capacitor plate is under the stress expressed by formula

$$W=\frac{DE}{2} \tag{31}$$

Tension is the ratio of force/surface. Such tension, P can be expressed:

$$P=\frac{\varepsilon_r\varepsilon_0 E}{2} \tag{32}$$

in vacuum,

$$P=\frac{\varepsilon_0 E^2}{2} \tag{33}$$

Such P acts contrary to the force F_0 in Figure 3 or outward from a body being electrically charged; it decreases surface tension of the body.

This effect can be demonstrated by the experiments shown schematically in Figure 5. The glass vessel in Figure 5 was filled with water up the top, then the water was allowed to flow under its own hydrostatic pressure through the capillary outlet. After a fall of the water level, its continuous flow became arrested and it could only drip through the capillary outlet because of the water surface tension. However, upon contacting the water with an electrically charged wire as shown in Figure 5, further flow of water through the capillary outlet was enhanced. This effect relies on the decrease of surface tension of the liquid droplets when

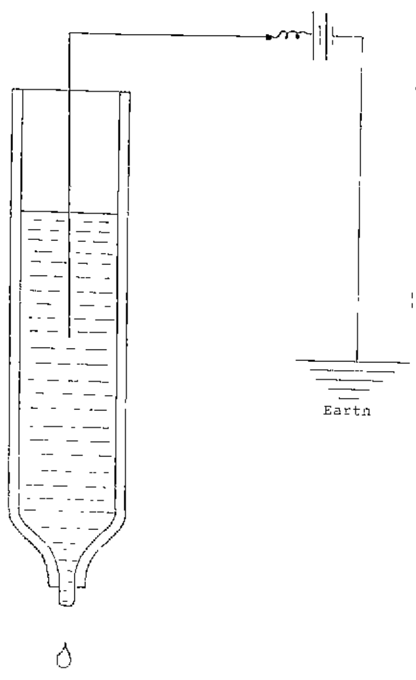


Figure 5. Influence of an electrostatic field on surface tension of water.

electrically charged.

Let's consider the drop of liquid at the capillary outlet which was formed when hydrostatic pressure became too low to promote further flow of the liquid through the capillary orifice in Figure 5. On the surface of such a sphere an inward pressure Pn is being exerted:

$$Pn=\frac{2T}{r} \qquad (34)$$

where r is the radius of the droplet.

When the sphere has an electric charge of the potential U relative to the earth, the capacity of the sphere is $4\pi\varepsilon_0 r$ (when the sphere is in the air $\varepsilon=1$). Then the charge is:

$$Q=4\pi\varepsilon_0 rU \qquad (35)$$

Hence, the intensity of the electric field on the surface of the sphere is:

$$E=\frac{Q}{4\pi\varepsilon_0 r^2}=\frac{U}{r} \qquad (36)$$

Therefore, there is a mechanical pressure Pe on the surface of the sphere. This pressure is directed upwards and is equal to:

$$Pe=\frac{\varepsilon_0 U^2}{2r^2} \qquad (37)$$

Then the resultant pressure P acting on the surface of the sphere is:

$$Pn-Pe=P=\frac{2T}{r}-\frac{\varepsilon_0 U^2}{2r} \qquad (38)$$

Notice that U is a square term, hence its sign is of no consequence.

It is clear that an application of an electrostatic potential (relative to the earth) to a solidifying dielectric will result in the refinement of grains.

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