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Warm Working of Metals and Alloys*

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The authors developed a warm working method of steels, i.e. the deformation in the blue brittleness temperature range.

Firstly the strengthening mechanism of warm working was made clear, that is, the increase of dislocation density due to the dislocations locked by carbon and nitrogen atoms. Moreover, the Bauschinger effect in this temperature range decreases due to the same mechanism.

Various deformation methods were newly investigated; twisting, straightening, surface rolling and pressing of joint holes for rails.

In warm twisting and straightening, high strength and relatively ductile materials were obtained, due to the decrease of Bauschinger effect and the increase of work hardening.

In warm surface rolling and pressing, high fatigue strength materials are obtained due to the increase of compressional residual stress and work hardening.

The authors applied the warm working to non-ferrous metals such as Al-alloys and Cu-alloys. Combining the deformation with precipitation hardening and low temperature annealing hardening, high electric conductivity, high strength and excellent machinability were obtained by warm working.

1. The purpose of warm working

In metallurgical engineering, the hot working is defined as the working in the temperature range of recrystallization, and the cold working is the working in the temperature range below the recrystallization temperature. Warm working which belongs to the cold working according to this definition, is not a working at room temperature, but a working in the temperature above room temperature.

Figure 1⁽¹⁾ shows the flow-stress temperature relation of mild steel at strain $\epsilon=0.15$. For each of two strain rates, there exists a flow stress peak, that is, 250°C and 400°C for $\dot{\epsilon}=10^{-3}\text{sec}^{-1}$ and $\dot{\epsilon}=1.2\text{sec}^{-1}$ respectively. The warm working is defined as a working in the temperature of this peak stress. The purpose of this process is to obtain high strength materials at some sacrifice of toughness. The increase of flow stress $\Delta\sigma_n$ in Fig. 1 corresponds to the strength increase due to warm working. For this mild steel, at 15% deformation, about 8 kg/mm², that is, 25% increase in strength, is attained by warm working.

The following are the characteristics of the flow

stress peak in steel.

(1) This peak shifts to higher temperature with the increase in strain rate⁽²⁾.

(2) This peak disappears in the absence of carbon and nitrogen⁽³⁾.

(3) The value of the peak stress is decreased by the addition of the carbide or nitride forming elements⁽⁴⁾.

(4) The value of the peak stress is larger for the steel containing a higher amount of carbon and also is influenced by the heat treatment⁽⁵⁾.

(5) In the tensile test in the temperature range around the peak stress there appears a serration in the flow stress strain curves⁽⁶⁾.

Fig. 1 Flow stress-temperature curves of 0.06% C steel

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At the strain rate higher than $\dot{\epsilon}=10^3 \text{ sec}^{-1}$, the temperature corresponding to the peak stress rises above 700°C , where recovery and recrystallization occur during deformation and cooling, and therefore the increase in strength is not expected.

At room temperature the strain rate of warm working is $\dot{\epsilon}=10^{-6} \text{ sec}^{-1}$ and the deformation process at such a slow strain rate does not exist in practice.

Therefore the reasonable temperature range of warm working is considered to be $150 \sim 500^\circ\text{C}$.

The existence of C and N is necessary for the increase in strength, but the minimum contents of C and N are as low as 10 ppm so far as may exist as solid solution, therefore warm working can be applied to cast iron, alloyed steels in addition to plain carbon steels⁽⁷⁾.

Not only the increase in the work hardening rate, but also the decrease in the Bauschinger effect is the superior characteristic of the warm working process⁽⁸⁾, and an application of this characteristic is the warm working straightening which is discussed in detail later.

Fig. 2 Mechanical properties of drawn wires (0.8% C patented steel wire)

2. Application to steel

2.1 Drawing⁽⁹⁾ (10)

Figure 2 shows the result on a patented 0.8% C steel. At the same amount of reduction, 0.2% yield stress of warm drawn steel is 30 kg/mm^2 higher than that of low temperature annealed steel after cold working. Elongation decreases a little. The number of twists and the number of repeated bending decrease for the same amount of reduction, but in the case of same 0.2% yield stress, these values are nearly the same. This means that the warm worked steel is not brittle in nature.

The effect of alloying elements, Cr and Ni, is also studied in the drawing process. Cr reduces the warm working effect slightly, but Ni shows little influence.

The engineers in the Russale Company in U.S.A. have studied warm drawing of low alloyed steels. The company obtained a patent and is now making products which have the same strength as the tempered steel, higher fatigue strength and better machinability. Warm drawn wires of high carbon steel have remarkably high strength, but relatively poor twisting number. Recently, Kobe steel Company⁽¹¹⁾, by combining the warm drawing and the cold drawing, developed a new process which reduces the strength slightly, but raises the twisting number.

The warm working patented by the Russale Company is concerned with the drawing of steels process and rolling process which is accompanied with the reduction of the sectional area. However, the discussion of the strengthening mechanisms shows that the amount of the strength increase by warm working is decided by the combination of temperature and plastic deformation. Therefore, this process is also applicable to bending, repeated bending, torsion and straightening, which is not accompanied with the reduction of the sectional area in the working process.

2.2 Bending⁽¹²⁾

Research was carried out at Toyo steel Company on the warm bending of tinned steel sheets. Table 1 shows the result on 0.03% C rimmed steel sheets 0.23 mm thick which were bent by the roller in the

Table 1 The result of warm bending of 0.03% C rimmed steel

	Rock well hardness (30 t)	Tensile test			
		Tensile strength kg/mm^2	0.2% proof stress kg/mm^2	Elongation %	Yield elongation %
Bending at 300°C	62.2	40.7	40.1	25.0	7.5
Low temperature annealing (300°C)	53.3	36.2	33.5	39.0	10.7

680°C × 48 sec → 300°C → 5 sec keeping (low temp. annealing)
cooling → warm bending

Pb-Bi bath. In this process, the specimens were bent during cooling after annealed at 680°C. Low temperature annealing was performed by keeping the specimens at that temperature. The hardness of cold worked steel is nearly the same as that of low temperature annealed steel, so that a 20 % rise in both the hardness and yield stress was attained by warm bending. As the result of it, a high strength, short yield point elongation and ductile thin tinned sheet is obtained by the warm working process. As for the hardness distribution along the cross section, it increases from inside to the surface, so it is particularly useful for can making.

2.3 Repeated bending^{(1) (26)}

Setting 7 rollers and arranging distances between rollers suitably, repeated bending was done by drawing the wire through these rollers. The results on 4 mm square rods are shown in Table 2. For a 20 % increase in drawing stress, the increase in strength is about 40 %. We applied this method to working of sheet and Fig. 3 shows the result of straightening of the I-beams. This indicates that warm working is useful for straightening of die steel.

Table 2 Drawing stress of repeated bending through rollers and mechanical properties of drawing wire

	Drawing stress kg/mm ²	Yield stress kg/mm ²	Tensile strength kg/mm ²
Cold drawing			
Cold drawing+low temp. annealing	6.68	28.5	34.5
Warm drawing	8.32	41.0	52.0
Warm drawing			
Cold drawing	1.21	1.44	1.41

Fig. 3 Vickers hardness distribution of cross section of I-beam worked at 300°C (0.1% C-steel, I-beam)

2.4 Twisting^{(13) (26)}

As one of the working methods which is accompanied with no reduction of the sectional area, warm working was applied to twisting of the pipes and rods. Figure 4 (a) shows the result of application of twisting to the 0.1 % C steel rods. It shows that to obtain the same strength, the torsional deformation needed for warm working is less than a half of that by cold working. At the same level of strength, there was no difference of elongation and area reduction in tension test. It is worth noting that, as is shown in Fig. 4 (b), a warm-worked steel has

Fig. 4 Torsional characteristic of torsioned bar both at room temperature and at warm temperature (0.1% C steel)

higher yield stresses in backward than those of cold worked steel. That is, while the cold worked materials deform easily to the backward stress, the warm-twisted materials have higher resistance and less anisotropy of strength. They can be used as the twisted steel rods for concrete and torsion spring. For high carbon steels and also for pipes, the results of the same tendency have been obtained.

2.5 Straightening of pipes^{(14) (26)}

Figure 5 shows the results of the experiment carried out on an industrial scale in order to raise the strength of the lap-welded mild steel pipes. Before this, a preliminary experiment showed that the strength of the warm-straightened material increased by 20%. During the cooling process after lap welding of hoop at 1430°C, straightening at nearly 300°C was done varying the roll gap.

In the case of 5 mm roll reduction, the results of the flattening test and expand test are poor, but in the case of 3 mm, yield stress rises by 20% and other results are in the range of JIS. The result of the impact test done at the same time showed no brittleness under the roll reduction between 0~5 mm. When reheating the material which is already warm-worked, below the warm working temperature, no loss of warm working effect is observed.

Anyway, this process is useful for engineering industry, because straightening is done during cooling without considering about heating.

2.6 Fillet deformation of joint holes for rails⁽²⁶⁾

In rails, more than a half of their failure rises at the point near the joint holes. So we did⁽¹⁵⁾ pressing and fillet for this hole in the range of warm working temperature, expecting to raise the fatigue

Fig. 5 Mechanical properties of warm straightened pipe (0.1% C steel)

limit. The results are shown in Fig. 6. The fatigue limit rises by warm working from 24 kg/mm² to 30 kg/mm². Considering the strengthening mechanism given below, the warm working is effective not only for the annealed material but also for the hot rolled material and normalized material and heat treated material. Therefore, we can expect the increase in the fatigue limit by using warm pressing and fillet to the hole axis and hole plate.

2.7 Surface rolling⁽¹⁶⁾

The propeller shaft of the ship is generally susceptible of cracks. In order to increase the strength—specially fatigue strength, surface treatment is done such as carburizing, nitriding, surface quenching and shot peening. In addition to these methods, surface rolling is done recently as one of the useful surface treatments and the increase in the fatigue limit is obtained.

Surface rolling was carried out in the warm working temperature range, with the result given in Table 3 and Fig. 7 (a) (b). Setting 0.1% C steel rod to a lathe and revolving it, the rod is pressed by two rollers at both sides and the rollers are moved at a constant velocity, while it is heated by a burner. It is apparent from Table 3 that in the tensile test the yield stress of the warm worked material is 7~8 kg/mm² higher than that of the cold worked material and an increase in the tensile strength is 4 kg/mm². In the torsion test, the shear yield stress increases by 4 kg/mm². It is also apparent from Fig. 7 (a) that hardness becomes higher from the inside to the surface and the in-

Table 3 Mechanical properties of surface rolled 0.1% C-steel

	Tensile test			Torsion test
	0.2 % proof stress kg/mm²	Tensile strength kg/mm²	Elongation %	0.2 % Proof shear stress kg/mm²
Raw material	20.2	39.0	42	13.4
Cold working	29.0	41.2	38	15.2
Cold working+low temp. annealing	30.0	42.0	20	15.9
Warm working	37.6	46.1	21	19.2

Fig. 6 Fillet deformation of joint holes of sheet for rails

crease is notably large in case of warm worked material with about $H_V=40$. As is expected from these results, fatigue strength rises by 4~5kg/mm² or 25%, as shown in Fig. 7 (b).

2.8 Straightening of cold drawn steel wire

Figure 8 shows the result of straightening of 0.7~0.9% C steel wire using rotary bending straightener. Material is made of hot rolled and 60% cold drawn (AD). Among the low temperature annealing conditions (B), 370°C×1 hr is the industrial one and 300°C×5 min is the condition under which the highest strength can be attained.

The results are as follows.

1. After cold straightening the strength—specially 0.2% yield strength, decreases greatly but after warm straightening it rises greatly.
2. The strength of the low temperature annealed material is considerably smaller than that of the warm straightened material.
3. Elongation increases considerably by straightening and elongation of the warm-worked material is large enough.
4. As shown in Table 4, it is notable that relaxation value is especially excellent.

Fig. 7 Properties of surface rolled 0.1% C steel

In this way warm straightening is very useful for the PC steel wire. For the variation of the strength of the cold worked material due to straightening, both the increase of work hardening, $\Delta\sigma_u$ in Fig. 1, and the extent of softening by the Bauschinger effect in the case when the direction of stress is reversed during working have great influence. In case of warm working, the restraint of the softening due to the Bauschinger effect contributes mainly to the increase in strength by straightening.

3. Strengthening mechanism

Figure 1 shows that flow stress increases with a decreasing temperature below the temperature of the minimum flow stress. Flow stress of metals and

Table 4 Relaxation value after 10 hr

	Cold straightening %	Cold straightening + low temp. annealing %	Warm straightening %
A ₁	3.41	0.6	0.7
A ₂	2.81	0.7	0.8
A ₃	3.30	0.5	0.4

A₁: 0.7% C-steel (60% cold drawing)

A₂: 0.8% C-steel (60% cold drawing)

A₃: 0.9% C-steel (60% cold drawing)

AD: as-drawn wire

CS: cold straightening of as-drawn wire

B: blueing in lead bath

WS: warm straightening of as-drawn wire

[Time (min) indicates the keeping time in lead bath for blueing and the pre-keeping time before working for warm straightening]

Fig. 8 Mechanical properties of straightened high carbon steel wires

alloys is generally divided into two components⁽¹⁷⁾; the athermal component σ_p due to the internal structure, mainly dislocation density, and the thermal components σ_t dependent upon both temperature and strain rate, below the temperature range of recovery and recrystallization. In body centered cubic metals and alloys, the mechanical equation of state is valid⁽¹⁸⁾, even if temperature and strain rate are changed below the temperature of the minimum flow stress.

The value of σ_p , that is, internal structure does not change at a given strain, whereas the value of σ_t only changes. (This is verified by the experimental results showing no change in hardness of mild steel at the same strain⁽¹⁾.)

It is reported that the increase of flow stress in warm working temperature range corresponds to the increase of work hardening, in re-compression at room temperature after compression at warm working temperature⁽¹⁾. Warm working has been known to be effective to various steels, for example, low carbon steels, medium carbon steels, high carbon steels and low alloyed steels⁽¹⁰⁾. Therefore it seems quite reasonable to consider that the increase in strength is due to the strengthening of ferrite, mainly due to increase in dislocation density in ferrite.

Figure 9⁽²⁰⁾ shows electron micrographs of 0.02 % C steel. The annealed specimen hardly contains any dislocations (a). Though the specimen 4 % rolled at room temperature shows some increase in dislocation density (b), the increase in dislocation density of the 4 % rolled specimen at 300°C is most remarkable.

From the facts that the optimum warm working temperature increases as the strain rate increases, and that the effect of warm working disappears in absence of carbon and nitrogen atoms, the increase in mean dislocation velocity corresponds to the increase in diffusivity of carbon and nitrogen. Nowadays, the most commonly used explanation for this phenomenon is the dynamic strain aging related to the formation of the Cottrell atmosphere^{(3) (19)}.

It was found that the repetition of cold working and blueing several times raised the strength nearly to that of the warm worked material⁽¹⁹⁾, and that the activation energy of the elementary process of plastic deformation was about 20 kcal/mol, proving that the rate determining process was the diffusion of carbon and nitrogen in ferrite^{(2) (20)}.

It is, therefore, concluded that the strengthening in warm working is due to the rapid rate of increase of dislocation density caused by the decrease in the mean free path of dislocations "locked" by carbon and nitrogen atoms.

The Bauschinger effect⁽⁸⁾, mentioned previously to express the straightening process of drawn wires, is discussed below.

Figure 10⁽⁸⁾ shows the change in the Vickers hardness with compressive strain in the compression test after 2 % and 6 % tension both at room temperature and at warm working temperature.

The hardness reduction in cold compression after cold tension at 6 % is $\Delta H_v^2 = 25$, on the other hand that after warm working (tension) is $\Delta H_v' = 10$, and no hardness reduction in warm compression was

Fig. 10 Hardness variation with compressional strain after pre-tensile strain

(a) Annealing (900°C × 1 hr)
(b) 4 % rolling at room temperature
(c) 300°C × 5 min annealing after 4 % rolling at room temperature
(d) 4 % rolling at 300°C

Fig. 9 Photo of electron microscopy. ($\times 12\,000 \times \frac{3}{7}$), 0.02 % C- α iron

found. Therefore though the softening in cold compression due to the Bauschinger effect is large, it can be reduced significantly in warm compression⁽⁸⁾.

It can be considered that the Bauschinger effect in general accompanies the reduction of hardness due to the annihilation of the dislocations which contribute to plastic strain in reverse direction in the early stage, on the assumption that dislocation morphology introduced by plastic deformation should have directionality⁽²¹⁾. Presence of grain boundaries, precipitates and substructure enlarge this effect because of piling up of dislocations at those barriers. And this effect decreases with decreasing mobility of dislocations.

As mentioned above, dislocations are locked firmly in the warm worked material, so that dislocations themselves are difficult to move and annihilate each other, therefore it can be interpreted that strain aging reduces the Bauschinger effect⁽²¹⁾.

It is evident that the strength of steel after straightening process whose mechanism is due to stress direction change with high frequency, largely depends on the Bauschinger effect, especially when using the cold worked materials which contain many dislocations.

The internal structural change due to the Bauschinger effect influences elongation and reduction of area, in connection with the residual stress distribution.

Anyway, because of less softening accompanied with the Bauschinger effect, warm working process will become a center of industrial attention.

4. The application to non-ferrous metals and alloys

The warm working of non-ferrous metals and alloys is characterized by utilizing the precipitation hardening or low temperature anneal hardening of alloys, while in steels the phenomenon similar to static strain aging has been utilized.

4.1 Al-alloys⁽²²⁾

The results of Al-Mg (0.4 %)-Si (0.6 %) alloy, ... electrical conductive material with high strength and excellent corrosion-resistance ..., are shown in Fig. 11.

In general, for this alloy, precipitation hardening during tempering after heavy drawing at room temperature after quenching, has been utilized. On the contrary, warm working is to carry out working and aging simultaneously, by raising the working temperature up to the temper aging temperature. As shown in Fig. 11, the strength of the warm worked material at high reduction is higher than that of the temper-aged material at the optimum temperature after cold working.

Furthermore, specific resistivity of the former

is lower by about 7 % than that of the latter, therefore, it is possible to obtain a material which has higher strength and electrical conductivity than by the conventional processes.

The phenomenon during warm drawing is principally the combination of imperfect aging and working. Then, it is considered in a sense that higher strength is due to aging promoted by working.

However, it appears that the mechanism of this increase in electrical conductivity is not clear yet and this kind of study may help the future development of electrical conductive materials.

4.2 Copper alloys

(a) Cu-Cd (1.4 %)⁽²³⁾

The results of the application of warm working process to the Cu-Cd alloy which exhibits enormous hardening in low temperature annealing are shown in Fig. 12.

Low temperature anneal hardening is the phenomenon of hardening due to annealing of the cold worked materials at the temperature below the recrystallization temperature.

For this alloy, the Vickers hardness increases by about twenty through tempering at the temperature between 200°C and 300°C for a given time after working.

Though, according to the solubility curve, its precipitation hardening due to aging can be expected, practically little hardening occurs through tempering after quenching.

From the figure, warm-worked material is seen to have higher strength and electrical conductivity.

Especially, unlike the warm working of the precipitation hardening materials such as the Al-Mg-

Fig. 11 Mechanical properties and specific resistivity of Al-Mg-Si alloy

Si and Cu-Cr alloys, this alloy is characterized by the higher strength and electrical conductivity over the whole range of reduction, when warm worked.

This can be satisfactorily explained by assuming that the hardening of Cu-Cd alloy is due to strain aging corresponding to the increase in dislocation density, and not due to precipitation hardening. Therefore the hardening mechanism appears to be the same as that of warm worked steel.

(b) Cu-Zn (60/40 Brass)⁽²⁴⁾

Figure 13 shows the results of machinability of 60/40 Brass produced by warm drawing.

Similar to Cu-Cd, a little higher proof-stress and hardness are obtained by warm working, moreover machinability is improved.

It is considered that the machinability is improved by fine dispersion of lead particles, since its warm working temperature is near the melting temperature of lead.

As shown from a few examples of non-ferrous

alloys, the applicability of warm working process will be expanded considering the improvement of not only the strength but the electrical conductivity and the machinability.

5. Conclusions

It has been shown that the warm working to be carried out at the temperature range, which has been considered to be the taboo for mechanical engineers, improves mechanical and electrical properties and saves materials.

The author wishes to have useful discussions made particularly by mechanical engineers. The warm working of steels and age-hardening non-ferrous alloys, except warm drawing of steels, is a new attempt, which is a kind of thermo-mechanical working.

Compared with the conventional process, the warm working process costs less.

The author believes the future development of this process

Fig. 12 Mechanical properties and specific resistivity of Cu-Cd alloy

Fig. 13 Machinability of drawn wires of 60/40 brass

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