The Effect of Uranium on Iron and Steel*

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Synopsis

The effects of uranium addition up to 0.7 wt% on low and medium carbon steels and low alloy steels have been studied. In low carbon steels, uranium formed mainly intermetallic compound Fe_2U and it decomposed and dissolved in the austenite matrix at above 950°C , and precipitated at tempering temperature of about 500°C . Increasing carbon content in steel led to the formation of uranium carbide, and it was very stable and insoluble even in the austenite matrix at $1,200^\circ\text{C}$. Speaking of low alloy steels, high tension steel such as Si-Mn series was almost similar to ordinary carbon steel, but 0.5% Mo-B steel (low carbon bainitic steel) increased in hardness when quenched or normalized at high temperature, i.e., $1,150^\circ\text{C}$, and the level of secondary hardening rose in subsequent tempering. It showed that in case of double carbide with molybdenum, uranium was more soluble in the austenite matrix than that of UC. But in Cr-Ni-Cu steel, secondary hardening was very slight even when quenched at $1,250^\circ\text{C}$. The effect of uranium on scavenging of ingot had not been observed according to small ingots but slow cooling in a crucible caused the gravitational segregation of uranium compounds. Uranium did not affect the austenitic grain size and transformation points. Uranium had not the solubility in the ferrite and strain ageing characteristic had faded away. Corrosion resistance of steel was improved by the small addition of uranium.

I. Introduction

Uranium is being utilized as a nuclear fuel under the international regulations, (but its regulation has been released in 1958) and as a by-product of the enriched uranium manufacturing, the depleted uranium has been accumulating enormously in these several years. Since it is unfit for nuclear use, the utilization of it in the sphere apart from nuclear use has been considered especially for iron and steel, and a large number of studies have been made in the U.S. and Canada which are the principal producers of uranium. Especially in Canada, the government had intervened and wider studies had been made. From the results of this study, some interesting facts concerning the production of clean ingot, the improvement in corrosion resistance and creep resistance had been obtained.¹⁾

Here in Japan, in 1961, "The Special Committee for the Study of Uranium Steels" has been organized in the Japan Society for the Promotion of Science so that universities, laboratories and factories may share studies systematically from basic research to practical application. The authors are the chairman and a member of this committee, respectively, and are studying the basic effects of uranium as a scavenger and

alloying element on iron and steel.

In this paper, they reported on some laboratory tests concerning the influence of uranium addition up to 0.7 wt% on carbon steels and low alloy steels.

II. Preparation of Specimens

The steels selected in this study are low carbon steels of up to 0.25% C, medium carbon steels ranging from 0.3 to 0.4% C and low alloy high tension steel as Si-Mn, Mo-B and Cr-Ni-Cu steels, and uranium addition to each specimen is less than 0.7%. Production of specimens was conducted by a small vacuum arc melting furnace with the use of plain carbon steel, electrolytic iron and washed pig iron. Alloying elements except uranium were added in the form of pure metals and ferroalloys. At each melting, 0.04~0.1% of aluminium was added by means of final deoxidation, and uranium was added as a form of lump ferro-uranium (2~5 mm ϕ), the uranium content of which was 88%. The holding time after the addition of uranium to tilting was 30~100 seconds according to the amounts of addition. The weight of the ingot is about 3.5 kg in case of a single casting and 1.8 kg in the split casting. The number of specimens of this study is about 60 charges and the chemical compositions of typical specimens are shown in Table 1. The recovery of uranium in steel remarkably varied ranging from 20 to 88% with the mean value being 53%. Because uranium reacts with nonmetallic elements especially with oxygen, it is considered that the recovery scatters not only with the oxygen content but also by the reaction with the refractory material (MgO). It was shown that the recovery decreased noticeably when the time of addition to tilting became longer. Accordingly, it is considered that the reaction with refractory material and slag may have occurred; the melting crucible after being used indicated a high count of radioactivity.

After grinding the skin, the ingot was hot forged at a temperature ranging from 900° to $1,100^\circ\text{C}$. By the addition of uranium over 0.5%, the forgeability was lowered and the ingot showed the high-temperature shortness. In the Fe-U system diagram, Fe_2U -Fe eutectic melts into liquid at $1,080^\circ\text{C}$, and from this point, it is considered that the high-temperature shortness is due to the small amounts of the liquid. Contractor¹⁾ and other investigators previously reported the high-temperature shortness of uranium-bearing steel, and

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this is seemed to be caused by the same reason. From this consideration the practical forging operation was done at the temperature below 1,080°C, and a sound forged bar which was comparable in forgeability with uranium-free steel could be obtained. It is desirable that the forging of uranium steel should be done at a lower temperature as possible. Thus the ingots were forged to 14 mmφ bars.

III. Experimental Results and Discussion

1. Effect on the Austenitic Grain Size

The austenitic grain size was measured for each specimen at 925°C using the carburizing method. The refining effect of uranium was very slight in comparison with those of other refining elements. The results of the grain growth measurement of 0.5% Mo-B steel showed that uranium could not prohibit its growth.

2. Effect on Scavenging of Ingot

The production of clean steel by using the phenomenon of gravitational segregation was reported in Canada.¹⁾ But the sedimentation and division of uranium compounds are not recognized in such laboratory-made small ingots. Nonmetallic inclusion counting has been carried out in the direction of forging and the results divided into silicates, sulphides, alumina and oxides. As shown in Fig. 1, no scavenging effect had been observed even with the addition of a large

amount of uranium. The silicates and sulphides which became the string type after forging decreased remarkably. From an increase in dot or lump type inclusions after etching for sulphide (boiled sodium picric acid), it is thought that the plasticity of uranium sulphide is very small. The alumina which became continuous as the dot particles increased slightly with addition of uranium. Spot type oxides inclusions were increased extremely by the increase of UO₂.

As mentioned above a small addition of uranium caused the morphological change of sulphide and in-

Fig. 1. Results of nonmetallic inclusion counting of forged bar

Table 1. Chemical composition of specimens (wt%)

	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	B	U*
Low carbon steel	0.05	0.12	0.30	—	—	—	—	—	—	—	nil
	0.06	0.11	0.30	—	—	—	—	—	—	—	0.10
	0.06	0.06	0.29	0.010	0.012	—	—	—	—	—	nil
	0.06	0.17	0.26	—	—	—	—	—	—	—	0.12
	0.06	0.18	0.34	—	—	—	—	—	—	—	0.23
Medium carbon steel	0.36	0.03	0.27	0.011	0.010	—	—	—	—	—	nil
	0.33	0.06	0.41	—	—	—	—	—	—	—	0.26
	0.38	0.08	0.50	—	—	—	—	—	—	—	0.47
Si-Mn steel	0.16	0.56	1.14	—	—	—	—	—	—	—	nil
	0.14	0.55	1.50	—	—	—	—	—	—	—	0.09
Mo-B steel	0.15	0.42	0.66	—	—	—	0.58	—	—	0.003	nil
	0.16	0.38	0.59	—	—	—	0.42	—	—	0.003	0.34
	0.17	0.38	0.59	—	—	—	0.29	—	—	0.005	0.49
	0.18	0.42	0.65	—	—	—	0.50	—	—	0.003	0.61
	0.14	0.50	0.53	—	—	—	0.50	—	—	0.003	nil
	0.11	0.41	0.38	—	—	—	0.64	—	—	0.003	0.38
	0.11	0.41	0.38	—	—	—	0.64	—	—	0.003	0.40
	0.14	0.50	0.53	—	—	—	0.50	—	—	0.003	0.26
U-B steel	0.12	0.40	0.55	—	—	—	—	—	—	0.003	0.48
Cr-Ni-Cu steel	0.24	0.50	1.68	—	—	1.09	—	0.43	0.68	—	nil
	0.23	0.31	1.81	—	—	1.02	—	0.52	0.65	—	0.12
	0.23	0.31	1.71	—	—	1.04	0.28	0.51	0.63	—	nil

* Total uranium.

crease of oxide, and clean ingots could not be obtained. This is due to the impossibility of gravitational segregation in small ingots and at rapid cooling, but it might occur in the slow cooling of molten steel in a melting crucible. An attempt in this problem was made in 4 kg melting. The chemical composition of the longitudinal section of this ingot is 0.19% C, 0.011% S, 0.009% P and 0.08% U. Longer pipes in which the slag was contained were formed at the center of ingot. Uranium content is 0.188% at the section of 15 mm from bottom of ingot, and above this section it is up to 0.05%. Sulphur printing of a longitudinal section had required a longer time than in the case of uranium free carbon steel and even after one hour the bottom section hardly reacted. Correlating with analytical results, it seemed the gravitational segregation of uranium compounds occurred at the bottom.

Since uranium emits α -, γ -ray at the newer period and its decay product emits β -ray, it is considered that the counting of radioactivity would reveal the uranium segregation. As the result of α -ray counting was very low, β -, γ -ray counting had been done using G-M counter. The results of counting from the area of 6×45 mm (prepared by Pb sheets) are shown in Fig. 2. It showed the high counting at the bottom and gradient decrease to the top of ingot and this indicated the gravitational segregation of uranium compounds. (The peak at 55~95 mm was obtained from slag occluded in a shrinkage pipe.)

transverse section revealed a dendritic pattern which showed the uranium distribution. Thus, the authors

Fig. 2. Results of β - and γ -ray counting by the Geiger-Müller counter on the transverse slit of longitudinal section showing the gravitational segregation of uranium and its decay products. Dotted line shows the influence of slag that has high uranium contents in the shrinkage.

An autoradiograph of the longitudinal and transverse sections at 5 and 25 mm from the bottom of the ingot showed a dim segregation of the uranium at below 15 mm as shown in Photo 1. The photo of the

recognized that slow cooling had caused the gravitational segregation of uranium even in a small ingot.

Uranium compounds formed in steel were reported as UN, US and UO_2 . Small amounts of melting have been carried out to detect the morphological feature of uranium bearing inclusions in steel. Namely, after melting mild steel of 100~150 g, uranium was added to the melt which had an excess of nitrogen, sulphur and oxygen, and as a result nonmetallic inclusions containing a considerable amount of uranium were obtained.

The figures of the inclusions obtained were all of fine cubic.

3. Effect on Transformation Point

In order to examine the transformation point of uranium steels (0.1% C steel and 0.3~0.4% C steel) thermal analysis has been carried out. A_3 point of steel indicated a tendency to rise and A_1 point rose slightly with the addition of uranium. But in the case of 0.3~0.4% C steel the effect of uranium was very small in comparison with low carbon steel. Contractor¹⁾ stated that the transformation point did not alter up to 0.3% of the uranium. It is thought that as the uranium decreased the carbon content of austenite, the transformation point should be moved to a lower carbon side of the diagram. However, in carbon steels the effect of uranium on the transformation point is complex because of the solubility rate of Fe_2U to austenite and the content of UC.

4. Effect on Microstructure

In low carbon steel, the apparent microstructural change affected by uranium addition can be seen in the formation of intermetallic compound, Fe_2U in accordance with Fe-U system diagram. This is when excessive uranium addition has been made after fixing carbon, nitrogen, sulphur and oxygen. Although Fe_2U forms eutectic with iron, with a small addition of uranium this could not be recognized in the microstructures. In Fe-C-U system diagram UC exists in wide range, but if the carbon content of steel increased, the uranium would form not only UC but a certain amount of Fe_2U . Photo 2(a) shows the as-normalized structure of steel containing 0.06% C and 0.23% U, and film-type precipitates would be considered probably as Fe_2U . The precipitates increased with the content of uranium.

The increase in the carbon content of steel caused a greater increase in the amount of UC. Photo 2(b) shows the as-normalized structure of steel containing 0.38% C and 0.47% U. Impurities of the grain boundary were scavenged with uranium, the figure of pearlite lost its uniformity, and at the same time the lump gray carbide, UC increased. This carbide precipitates at the prior austenite grain boundary and it was colored

black by Murakami's reagent (Photo 2 (c)). UC has no relation to pearlite and no reaction with it. Consequently in the as-normalized state from above $30^\circ \sim 50^\circ\text{C}$ of A_3 point, uranium forms mainly Fe_2U and a small amount of UC in low carbon steel and an increase in carbon content results in the increase in amounts of UC, which precipitates in film or massive type at prior austenite grain boundary.

In alloy steels, microstructure of Si-Mn steel, for example, was almost similar to uranium-free carbon steel, but the single change is a slight coarsening of the ferrite grain size of uranium-bearing steel. In 0.5% Mo-B steel, the bainitic structure was not changed by the addition of uranium when normalized at above 30°C of A_3 point, but insoluble carbide remained at the prior austenite grain boundary. When it was normalized at a higher temperature, i.e. $1,150^\circ\text{C}$, the bainitic structure of the uranium-bearing steel became finer and the formation temperature of bainite was probably lowered (Photo 2(d)). In the case of a decrease in molybdenum content and increase in uranium content, fine bainite has been obtained in normalization at $1,150^\circ\text{C}$. But at an excess uranium, i.e. 0.61%, insoluble carbide was remained at the prior austenite grain boundary (Photo 2(e)). Instead of molybdenum,

when uranium was added only, U-B steel could not show the bainitic structure at normalizing from 920°C . But the increase in normalizing temperature caused the bainite-like fine structure in 0.48% uranium steel. Consequently in low carbon bainitic steel, the effect of uranium appeared when the normalizing temperature was high enough. This is caused by the solubility of uranium in the austenite matrix. The study of this point will be treated further in the next section.

In Cr-Ni-Cu steel, because of its small diameter and rapid cooling, the microstructure was almost martensitic. No change had been observed in martensite by the addition of uranium.

5. Solubility of Uranium to Austenite Matrix

As the atomic diameter of uranium is considerably larger than of iron, and from the viewpoint of the size-factor proposed by Hume-Rothery,³⁾ uranium belongs to the insoluble element in α -iron. In Fe-U system diagram there is no evidence in solubility of uranium to austenite, but it is believed that above 910°C there is a gradual increase in solubility. The dissolution of uranium in austenite in a practical heat treatment can only be possible when the compounds of uranium lose their stability and it is considered that Fe_2U ,

(a) Longitudinal section

(b) Transverse section
(25 mm from the bottom of ingot)

(b) Transverse section
(5 mm from the bottom of ingot)

Photo 1. Autoradiograph of the slowly cooled ingot in a melting furnace showing the gravitational segregation at the bottom of ingot.
(Exposure: 140 hr., $\times 1 \times 1/1$)

UC and double carbides may show different characteristics from each other. In order to study the solubility of uranium to austenite qualitatively, the heat treatment of steel in which uranium forms mainly Fe_2U , UC and double carbides has been carried out using low carbon steel, medium carbon steel and low alloy steel, respectively.

First, 0.06% C steel containing mainly Fe_2U was austenitized from 950° to $1,250^\circ\text{C}$ for 1.5~3.0 hours and then water quenched. Psuedo-martensitic structure could be obtained in the uranium-bearing steel as shown in Photo 3 and increased in hardness, but at below 950°C , this structure could not be obtained. Then, tempering characteristic curves had

- (a) 0.06% C, 0.23% U; grain boundary precipitates, Fe_2U ; etched by 2.5% nital. ($\times 600\times 1/1$)
- (b) 0.38% C, 0.47% U; gray uranium carbide, UC; etched by 2.5% nital. ($\times 280\times 1/1$)
- (c) 0.38% C, 0.47% U; uranium carbide at prior austenite grain boundary colored by Murakami's reagent. ($\times 400\times 1/1$)
- (d) 0.50% Mo, 0.6% U; lower bainitic structure; etched by 2.5% nital; normalized at $1,150^\circ\text{C}$ and tempered at 700°C . ($\times 400\times 1/1$)
- (e) Carbide distribution in bainitic structure and insoluble carbide at prior austenite grain boundary; colored by Murakami's reagent. ($\times 400\times 1/1$)
- (f) Precipitated carbide at boundary of ferrite leaves and insoluble carbide at prior austenite grain boundary. ($\times 3000\times 1/1$)

Photo 2. Microstructures of steels containing uranium

been obtained by the tempering of this specimen ranging from 350° to 600°C for one hour. For example, the result of austenitization at 1,050°C is shown in Fig. 3. It was observed that uranium caused the secondary hardening at 450°~550°C and this suggested that at higher temperature uranium had a solubility to austenite and precipitated as Fe_2U in subsequent tempering. Maximum hardness could be obtained at quenching from 1,050°C, and even in case of 1,100°, 1,150° and 1250°C there were slight increase in quenching hardness and in secondary hardening. It is thought that this resulted from the difference of liquid and solid uranium which was caused by the melting point of Fe_2U -Fe eutectic. Slow cooling such as oil quenching or furnace cooling did not show pseudo-martensitic structure and secondary hardening. The X-ray identification using $\text{FeK}\alpha$ line indicated that this structure was ferrite and showed that normal growth of ferrite was inhibited with dissolved uranium in austenite.

Second, an increase in carbon content of steel brought an increase of UC and a decrease of Fe_2U . In 0.3~0.4% C steel, heat treatment similar to low carbon

U nil

0.10% U

Photo 3. Microstructures of steel containing 0.06% of carbon resulting from solution treatment at 1,050°C showed the pseudo-martensitic structure in uranium steel.

steel has been carried out. In these steels as-quenched structure was martensitic and the effect of uranium on microstructure could not be revealed. Austenitizing treatments were at 1,000°, 1,100° and 1,200°C for two hours respectively, then water quenched. By the subsequent tempering ranging 400°~600°C for one hour, the tempering characteristic curves were obtained. As shown in Fig. 4, in medium carbon steel

Fig. 3. Tempering characteristics of 0.06% C steel with and without uranium after solution treatment at 1,050°C

Fig. 4. Tempering characteristics of medium carbon steel after quenched from 1,200°C

the results are different from those of low carbon steel, and at 1,000° and 1,100°C steel containing 0.26% of uranium acted almost similar to uranium-free steel, i.e., no secondary hardening had occurred. When quenched from 1,200°C, 0.26% uranium steel showed some secondary hardening, but in case of 0.47% uranium steel only slight temper resistance which was different from secondary hardening in low carbon steel was seen. It is thought that UC is very stable even at 1,200°C and not soluble in the austenite matrix.

Third, in low alloy steel, Si-Mn steel was almost similar to medium carbon steel and even at 1,200°C no secondary hardening had occurred. In this steel uranium forms probably stable carbide.

Fig. 5. Tempering characteristics of Mo-B steel containing various contents of molybdenum and uranium after quenching from 1,100°C

On the contrary, in the case of Mo-B steel, in tempering curves at 1,100°C as shown in Fig. 5, the hardness level rose with increase in uranium content even in decrease in molybdenum, especially in the 0.5% Mo-0.61% U steel. In this steel slight secondary hardening had occurred. As shown in the figure, remarkable secondary hardening cannot be seen in martensitic structure of low carbon steel. But uranium forms double carbide with molybdenum, and reveals secondary hardening. It is suggested that double carbide would decompose and dissolve at a lower temperature than in the case of UC.

In Cr-Ni-Cu steel, as-quenched hardness of urani-

um bearing steel was the lowest at 1,050°C and no secondary hardening had not been observed, but slight secondary hardening had occurred by the quenching at 1,200°C, and it indicated that uranium formed double carbide also with chromium and dissolved into austenite to some extent, but for a small amount of uranium addition hardening effect was very slight.

Consequently, a number of studies concerning the heating response of uranium compounds in low and medium carbon steels, and low alloy steels revealed the solubility of uranium to austenite when uranium formed Fe_2U or double carbide with molybdenum. When uranium forms mainly simple uranium carbide, it is very stable and not soluble. Double carbide with chromium is soluble too, but less than molybdenum.

6. Effect on Ferrite

It is generally believed that uranium has not any solubility to ferrite. In order to establish this point briefly, a qualitative examination has been carried out. 0.06% C and 0.12% U steel compared with uranium-free steel was heated to 750° and 800°C which were below and above β - γ transformation point of uranium, 774°C, then water quenched, and aged for under twenty hours at room temperature and under fifteen hours at 150° and 300°C. The results showed no change in hardness in any case of ageing. Therefore, uranium has not the slightest solubility to ferrite and after all it exists as an inacted compound in ferrite range. As it is supposed, in this case, that the work hardening of steel would not be altered by the uranium addition, silicon-killed uranium steel was prepared for the study of strain ageing characteristics, and the examination of work hardening has been carried out. The chemical compositions of this steel are 0.13% C, 0.10% Si, 0.31% Mn and 0.42% U and those of compared plain carbon steel are 0.10% C, trace of Si, and 0.41% Mn. According to the experiment, as the work hardening characteristics of uranium steel had not changed in comparison with uranium-free steel, it is confirmed that uranium would not affect on the plasticity of ferrite. After ageing at room temperature and 150°C for 24 and 10 hours respectively, the strain ageing characteristics of cold rolled silicon-killed steel with and without uranium have been studied. The rates of cold reduction of specimens were 10, 30, 50, 70, and 90%. As uranium acted fixing interstitial atoms as nitrogen and carbon in steel, the strain ageing had fade away.

7. Effect on Hardness and Mechanical Properties at Room Temperature

The results of hardness tested on all specimens in the normalized condition showed a gradual increase in the content of uranium. This is due to the formation of Fe_2U and UC. For example the hardness of medi-

um carbon steel increased from H_{RB} 89 to 94 with the addition of 0.29% of uranium. Hardness of low carbon bainitic steel had not been increased with the addition of uranium at normalizing from 920°C but at 1,150°C uranium-free steel decreased hardness for the growth of austenite grain, on the contrary the hardness of uranium steel containing 0.40% of uranium increased from H_{RC} 12.5 to 16.0.

For the determination of mechanical properties at room temperature, tensile tests have been made with the specimens of 10 mm ϕ and 35 mm at parallel length. The results of medium carbon steel as normalized from 900°C are shown in Fig. 6. Tensile strength and the yield point somewhat increased similarly to the increase in hardness, and no decrease in elongation and reduction of area was observed. It is concluded that these results are based on the scavenging effect of uranium and the formation of uranium carbide.

Fig. 6. Mechanical properties at room temperature of the steels normalized at below 900°C

Decreased impact strength at room temperature is shown in the same figure. In low carbon steel the decreasing could be recognized at 0.07% of uranium and at 0.20% an almost completely brittle fracture appeared. The impact strength at sub-zero temperature was very low and the transition temperature of Si-Mn steel containing 0.09% of uranium was -20°C

in comparison with -40°C of uranium-free steel. The harmful effect of uranium on impact value appeared in all specimens. Contractor¹⁾ reported the decrease in impact strength and the reason was due to an abnormal structure containing uranium oxide and oxisulphide, but the authors could not detect the abnormal structure.

8. Behavior in End-Quench Hardenability

The effect of uranium on the end-quench hardenability of steel has a close connection with the solubility of uranium in austenite.

In low carbon steel with and without uranium containing up to 0.20% of carbon, the structure of quenched-end was ferrite and pearlite at quenching from below 950°C, but above this temperature uranium-bearing steel increased their hardenability enormously. For example, the quenched-end of low carbon steel containing 0.18% of carbon showed hardness of Hv 200, but uranium steel containing 0.21% showed more than Hv 500. And in the case of 0.20~0.25% C steel, quenched-end hardness of uranium-free steel was nearly Hv 500 at quenching of 950° and 1,075°C, and uranium steel containing 0.51% of uranium showed a deeper hardenability.

On the contrary in 0.3~0.4% carbon steel, because of the stability of uranium carbide, the increase in hardenability was very little at quenching from 1,000°, 1,100° and 1,200°C. In Mo-B steel, the hardenability bands of steel containing 0.58% Mo, and 0.42% Mo-0.34% U were almost similar at 1,000°C quenching and the effect of uranium was negligible. At 1,200°C quenching the hardness of the martensite region was almost the same, but in the bainite region the hardenability of uranium steel was remarkably high. The amount of hardness increases in the bainite region was Hv 50~80 with 0.34~0.61% of uranium. With these increases in hardenability it is thought that the double carbide of molybdenum and uranium has a high solubility to austenite and that the formation temperature of bainite has been lowered.

In Cr-Ni-Cu steel, the structures of the specimens were almost all martensite across their whole length at the quenching temperature of 1,000 and 1,200°C and the hardness was the same in any position, but the hardness of uranium steel was the lowest. This explains that differently from the double carbide with molybdenum, double carbide with chromium or UC has no solubility in austenite.

Consequently, as shown in **III-5**, the hardenability of uranium steel would rise when uranium goes into austenite; but when uranium exists in the form of UC, a decrease of hardenability appears. Therefore, to make uranium steel increase in hardenability, uranium should be dissolved in austenite, heated more than

950°C at least.

9. Effect on Tempering Characteristics of As-Normalized Low Carbon Bainitic Steel

0.5% Mo-B steel is often used at 300°~500°C, and the improvement of mechanical properties in these temperatures is performed by the addition of vanadium or titanium, which raises the level of secondary hardening. Irvine et al.²⁾ reported the tempering characteristics of low carbon bainitic steel in detail. As the authors have found the increase in the hardness of uranium steel when normalized from high temperature, an examination of the tempering characteristics of bainitic steel containing uranium has been carried out. Naturally, there was no increase in hardness and secondary hardening by air cooling from 920°C. But as normalized at 1,150°C, for instance, and tempered, the relation between hardness and tempering parameter, i.e. $T(20+\log t)$ where T is the absolute temperature of tempering and t is the tempering time in hours, is shown in Fig. 7. The level of secondary hardening shifted with the addition of 0.26% of uranium, but in 0.40% of uranium tempering parameter removed to low temperature and short time side.

Fig. 7. Tempering characteristics of low carbon bainitic structure with and without uranium after normalized at 1,150°C

When other alloying elements such as vanadium, titanium, niobium and tungsten were compared with uranium, the effects of vanadium and titanium were most remarkable, and the effect of 0.40% of uranium was equivalent to that of 0.2% of niobium and 1.0% of tungsten. Increase in the level of secondary hardening should be up-held as well for a longer time. There was no decrease in hardness even after heating for 1,000 hours at 500°C.

After all, uranium in low carbon bainitic steel promises the useful effect only when it lowers the formation temperature of bainite according to the decomposition

of double carbide and the solubility in austenite. The carbide reaction during tempering has resulted from the precipitation of double carbide (Photo 2(f)).

10. Creep Strength of Uranium-Bearing Steel

It has already been pointed out through research conducted in Canada¹⁾ and U.K.⁴⁾ that the addition of small amount of uranium improved the creep strength of steel. The authors tried testing the influence of uranium addition to some low alloy steel upon their creep strain, and also recognized the beneficial effect of uranium. The example of results is illustrated in Fig. 8. It will be true that these effects of uranium simply added upon creep resistance are the same as in other carbide-forming elements.

Fig. 8. Results of creep tests of low alloy steel with and without uranium

11. Effect on Corrosion Resistance

Gertsman, Contractor and Biefer¹⁾ reported the improvement of corrosion resistance of carbon steel and low alloy steel containing small amounts of uranium with lack of microsegregation of uranium. For the purpose of estimating this problem in a small ingot, corrosion tests in 3~5% hydrochloric acid, sulphuric acid and nitric acid have been carried out at 50°C. Specimens of this test were 6φ×13 mm in size, as normalized at below 950°C and polished with #500 emery paper. The results of the test are shown in Fig. 9 about medium carbon steel for example.

Corrosion resistance against 5% hydrochloric acid was improved remarkably and the weight loss of specimens decreased. Even in small uranium addition to Si-Mn high tension steel, the weight loss was one-tenth after nine hours with addition of 0.09% of uranium. Surface condition of tested specimens was very smooth and it showed that corrosion had carried uniformly.

The results of the testing of 5% sulphuric acid were different from the results which had been reported by

Fig. 9. Results of corrosion tests against various dilute acid at 50°C

Gertsman et al. The weight loss increased with the addition of uranium and severe pitting occurred. This result was similar in all steels, so it was thought that so far as the small ingot was concerned, the reason was the short of scavenging effect of uranium.

Against 3% nitric acid, no beneficial effect of uranium was observed in all tests, and it was as nearly same as the result by Bieffer which had been worse than the authors' result.

The corrosion resistance of medium carbon steel to 3% sodium chloride at room temperature had not been improved by the uranium addition after 22-day testing.

Consequently, uranium steel has good resistance to dilute hydrochloric acid, but when diluting sulphuric and nitric acid, no useful effect was observed or it became even weaker. This may be caused by the lack of scavenging effect in uranium and containing a lot of inclusions because of a small ingot.

IV. Conclusions

The engineering effects of uranium up to 0.7% on low and medium carbon steels, and low alloy steels are

concluded as follows :

(1) The recovery of uranium in laboratory steel is varied ranging 20~88%, mean recovery being 53%. The decrease of recovery occurs with the increase in the holding time of uranium added molten steel in the melting furnace. So it can be expected that from this reason a great deal of uranium recovery is obtained with the holding time as short as possible after the complete dissolution and distribution of uranium into steel.

(2) Steel containing over 0.5% of uranium shows high temperature shortness and during forging sometimes severe cracking appears. It is considered that if forging can be done at lower temperature below 1,080°C, there is a certain increase of uranium content that promises sound forgings. High temperature shortness of uranium steel is due to Fe₂U-Fe eutectic at the austenite grain boundary which has relatively low melting point.

(3) The effect of uranium on the refinement of the austenitic grain size is very slight and it can not inhibit the growth of grain. This result is almost similar to that reported from Canada.

(4) As far as the small ingot is concerned, uranium has not the scavenging effect of steel, but slow cooling in a crucible causes gravitational segregation, and the heavy compounds of uranium sediment to the bottom of the ingot and clean steel as indicated in large scale melting practice. The small specimen which was made from tilting has a lack of cleanliness because the rapid cooling can't cause gravitational segregation. Uranium fixes sulphur in steel and its sulphide has not plasticity. Also oxide considered UO₂ increases with the addition of uranium and morphologically dot or lump type inclusions may increase. In an as-cast condition artificially made UN, US and UO₂ in steel are revealed as cubic type.

(5) The effect of uranium on the transformation point is very complicated, and clear results can not be obtained. But as the uranium decreases the carbon content of austenite, A₃ point will be raised to the lower carbon side of the equilibrium diagram.

(6) In as-normalized microstructure, uranium forms Fe₂U, UC and U(C, N) in the low carbon range and the amount of UC increases with increase in carbon content and it precipitates at the prior austenite grain boundary. In low carbon bainitic steel, no change has occurred by uranium when normalized at 920°C, but at 1,150°C, uranium lowers the formation temperature of bainite and makes it finer. No effect is observed in martensite structure.

(7) Secondary hardening occurs in low carbon steel in which uranium forms mainly Fe₂U at above 950°C, especially at 1,050°C. It shows that uranium has a solubility in the austenite matrix to some extent.

But the increase in the carbon content of steel results in the formation of UC and it is stable even at 1,200°C. In case of double carbide with molybdenum, it is more soluble than UC, and secondary hardening appears. The level of secondary hardening increases especially in bainitic structure. In case of double carbide with chromium, it is much less soluble than with molybdenum. End-quench hardenability increases when uranium goes into the austenite matrix.

(8) For uranium has not any solubility to ferrite, work hardening is not altered by the uranium addition but as a result of the stabilizing effect of uranium with nitrogen and carbon, strain ageing is diminished.

(9) Hardness, tensile strength and yield point increase slightly with the addition of uranium, but improvements in mechanical properties at room temperature have nothing to do with uranium addition under ordinary conditions.

(10) Corrosion resistance against hydrochloric acid has been improved remarkably, but against sulphuric

acid and nitric acid no beneficial effect is observed.

Postscript

For several years a lot of studies have been made by the members of "The Special Committee for the Study of Uranium Steel". These reports are now in preparation for publishing as a separate volume.

REFERENCES

- 1) Edited by R. F. Knight & D. K. Faurschou: "The Influence of Uranium Additions to Ferrous Alloys", Dept. of Mines and Technical Surveys—Ottawa, Mines Research Rep. R-95 (Apr. 1962) p. 320.
- 2) K. J. Irvine & F. B. Pickering: *J. Iron & Steel Inst.* (U.K.), **194** (1960), 2, 137–154.
- 3) W. Hume-Rothery & G. V. Raynor: "The Structure of Metals and Alloys", The Institute of Metals, London. (1956) P. 62, pp. 216–227.
- 4) G. T. Harris & H. C. Child: *J. Iron & Steel Inst.* (U.K.), **189** (1955), 4, 347–349.