Effect of Alloying Elements on Machinability and Hot Workability of α-β Titanium Alloy Containing Fe and C

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Many studies have been conducted on titanium alloys to improve their machinability and hot workability. They are inferior in machinability and hot workability when compared with other structural materials, such as steel and aluminum alloys. The KS EL-F (Ti-4.5Al-4Cr-0.5Fe-0.15C) that has been developed has mechanical properties equivalent to those of Ti-6Al-4V at room temperature and has superior hot workability. It was found that increasing Fe and decreasing Cr concentration in the chemical composition of KS EL-F improves both machinability and hot workability. The modified alloys (Cr: 1 to 2.5%, Fe: 1.25 to 2%) were found to decrease tool tip wear by almost 30% and the hot deformation stress by about 10%. Furthermore, decreasing Cr suppressed aging embrittlement caused by the precipitation of $TiCr_2$.

Introduction

As typified by Ti-6Al-4V alloy, α-β type titanium alloys have excellent specific strength, heat resistance and corrosion resistance, and are often used for parts for aircrafts, automobiles and motorcycles[1). Titanium alloys are increasingly used for joint parts with carbon fiber reinforced plastic (CFRP), because they have a coefficient of thermal-expansion close to that of CFRP and do not cause electrolytic corrosion. This application is now commonly found; for example, it was used in the fuselage of the Boeing 787, which made its successful first flight in November, 2009. The demand for titanium alloys is envisaged to increase in the field of aviation[2)]. The mechanical properties of α-β type titanium alloys can be adjusted by various heat treatments; however, commonly-used Ti-6Al-4V alloy suffers from a high machining cost, in addition to its high material cost, due to its poor forgeability and machinability compared with other materials such as steel and aluminum alloys. This has led to the development and use of various other alloys. KS EL-F is one of such alloys and has a significantly improved hot workability[3)].

The KS EL-F alloy contains carbon, which decreases the alloy's deformation resistance at elevated temperatures, while maintaining its strength at room temperature. However, TiC may precipitate, depending on thermo-mechanical treatment, and the precipitates can increase tool wear[4)].

This paper summarizes the results of the study on the effect of alloying elements on the machinability of the KS EL-F alloy, as well as the results found for the hot workability and machinability of modified compositions. Also discussed is the aging embrittlement of the modified compositions, since the KS EL-F alloy is known to exhibit aging embrittlement[5)] and has limited applications where elevated temperatures are encountered.

1. Experimental procedure

1.1 Sample preparation

To experimentally select an alloy system, eight alloys as shown in **Table 1** were prepared; the KS EL-F alloy (Ti-4.5Al-4Cr-0.5Fe-0.15C, hereinafter referred to as "EL-F") being the reference composition; six alloys containing Fe Mo, V, Ni, Mn, and Co, these elements being substitutes for Cr; and one alloy containing Sn as a substitute for Al. The chemical compositions were designed such that the Mo equivalent falls in the range from 6.25% to 6.35% and Al equivalent in the range around 4.5%. Chromium was replaced to prevent the precipitation of TiC and to suppress the production of aging precipitates, $TiCr_2$. Aluminum was replaced because the substitution was expected to further decrease the deformation resistance at elevated temperatures. The tested materials were melted by vacuum arc melting to prepare button ingots of about $\phi 40\times 20$mm in size, and each button ingot was forged into a size of about $\phi 25\times 55$mm. In order to clarify in more detail the effect of alloying elements on machinability, it is preferable to have a beta-annealed microstructure that consists of many alpha laths in beta matrix. To

Table 1 Chemical compositions of samples for machinability (mass%)

No.	Al	Cr	Fe	C	Others	Mo equivalent	Al equivalent
EL-F	4.5	4	0.5	0.15	—	6.25	4.5
5%Mo	4.5	—	0.5	0.15	Mo:5.0	6.25	4.5
7.5%V	4.5	—	0.5	0.15	V:7.5	6.25	4.5
2Fe-1Cr	4.5	1	2	0.15	—	6.25	4.5
4%Ni	4.5	—	0.5	0.15	Ni:4.0	6.25	4.5
3%Mn	4.5	—	0.5	0.15	Mn:3.0	6.35	4.5
3%Co	4.5	—	0.5	0.15	Co:3.0	6.35	4.5
7.5Sn-2Al	2	4	0.5	0.15	Sn:7.5	6.25	4.5

achieve this, all the compositions were annealed at a temperature of 1,100℃, which is higher than the beta transus, held at the temperature for 2 hrs. and subsequently air-cooled.

Two compositions that were expected to be more excellent on the machinability (in **Table 2**) were then melted in a cold crucible induction melting (CCIM) furnace to prepare ingots of about $\phi 155 \times 165$mm in size. Each ingot was forged into a round bar with a diameter of $\phi 60$mm, and the bar was annealed at 800℃ for 1.5hrs. Each annealed bar was investigated for its hot-workability, machinability and aging behavior. The samples of Ti-6Al-4V and "EL-F" alloys, both used as reference materials, were prepared from commercially available round bars of $\phi 60$mm.

1.2 Evaluation method

The machinability of each composition was evaluated using an optical microscope to determine the flank wear width of the cutting edge of a tool-chip after cutting. The details of the cutting conditions are shown in each figure.

Microstructures were observed under an optical microscope on each sample, which was mirror polished and etched by an etchant (i.e., water : nitric acid : hydrofluoric acid= 80 : 15 : 1). Hardness was measured using a Vickers tester with a load of 10kg.

Hot workability was evaluated on specimens, as shown in **Fig. 1**, each having a dimension of $\phi 15 \times 22.5$mm with notches 0.3mm deep on both sides.

Table 2 Chemical composition of high Fe system test alloys

Alloy	Al	Cr	Fe	C
EL-F	4.5	4	0.5	0.15
F-1	4.5	2.5	1.25	0.15
F-2	4.5	1	2	0.15

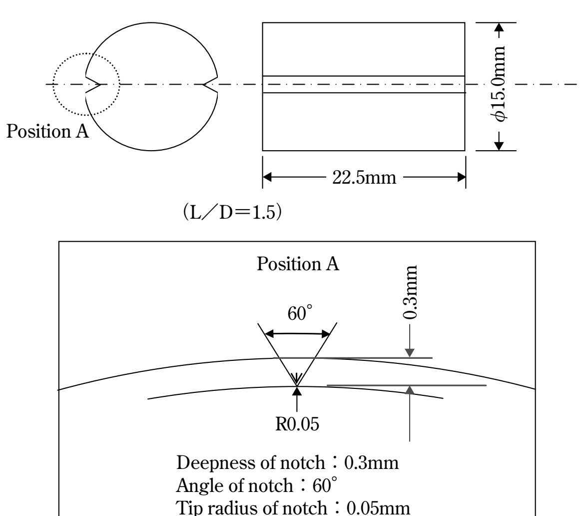

Fig. 1 Test specimen on limit of compressibility

The specimens were heated to 875℃ or 810℃ in an electrical furnace, held at their respective temperatures for 50min, and hot-pressed at 700℃ or 650℃, respectively, by a 1,600tonne press. The upper die was kept at a temperature ranging from 120 to 130℃ and the lower die at a temperature ranging from 150 to 170℃. The ends of each specimen were confined during the pressing. The strain rate was controlled to 1 to 2/s. The specimens were then investigated for the existence or non-existence of cracking at the bottom of the notches. A hot working simulator was used to evaluate deformation resistance on standard samples, each having a dimension of $\phi 8 \times 12$mm, at working temperatures in the range from 400 to 800℃. The crosshead speed of the tester was set to 15mm/s, and the maximum deformation stress was taken as the value for the deformation resistance.

To study aging behaviors, each annealed sample was reheated to a temperature ranging from 300 to 700℃, held at that temperature for 8hrs and subsequently air-cooled. Tensile tests were conducted to study the change in strength and ductility. The tensile tests, according to JIS Z2241, were conducted on test pieces, each having a parallel portion diameter of $\phi 6$mm and a gauge length of 30mm.

A database, Ti-DATA ver.2, was adapted for thermodynamic calculation software, Thermo-Calc ver.P, to determine the quasi-binary phase diagram and the solid solubility limit of carbon.

2. Experimental results and discussion

2.1 Effect of alloying elements on machinability

In general, tool wear increases with an increase in the hardness of the work material. All of the compositions shown in Table 1 have an almost identical Vickers hardness of 310 ± 10HV, hence the effect of hardness is regarded as negligible in this study. The microstructure of each composition exhibits a $\beta_{\text{-anneal}}$ structure, as shown in **Fig. 2**, with

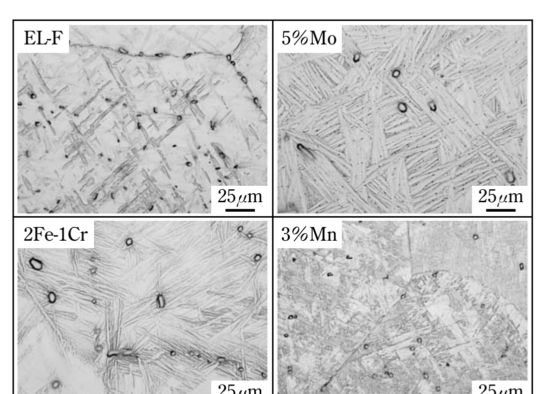

Fig. 2 Microstructure of representative samples

a small amount of TiC remaining.

Dry cutting was conducted with the cutting parameters as follows: cutting speed, 100m/min; feed rate, 0.1mm/rev; cutting depth, 0.5mm; and cutting distance, 50m. The flank wear widths after cutting are shown in **Fig. 3**. Compared with the tool wear by the EL-F reference composition, the materials designated as 5% Mo and 2Fe-1Cr show favorably small wear volumes. On the other hand, the materials designated as 7.5% V and 4% Ni show a tool wear volume almost the same as that of EL-F, and the ones designated as 3% Mn, 3 Co and 7.5Sn-2Al show wear volumes greater than that of the reference material.

As shown in Fig. 2, the 5% Mo and 2Fe-1Cr materials, each exhibiting a small wear volume, have alpha laths that are slightly larger. In general, larger strain concentration in a secondary shear zone facilitates the generation of cutting chips, improving machinability[6]. Because large alpha laths are considered to inhibit the strain concentration, the structure containing the phase was originally regarded to be unfavorable for machinability. Nevertheless, the structure exhibits a smaller tool wear volume, indicating that the substitution of Cr with Fe and/or Mo effectively reduces tool wear.

On the other hand, a large volume fraction of TiC precipitates increases tool wear, as shown in **Fig. 4**[4]; hence, it is preferable to make the solid solubility limit of carbon as large as possible when designing a composition. Using the thermodynamic calculation software, Thermo-Calc, the solid solubility limit of carbon near the beta transus was calculated for each composition of 5% Mo, 7.5% V, 1Cr-2Fe, 4% Ni and 7.5 Sn-2Al. The results are shown in **Table 3**. **Fig. 5** depicts a quasi-binary phase diagram in which the horizontal axis represents the carbon concentration of EL-F and 2Fe-1Cr materials. The addition of carbon should not noticeably deteriorate machinability as long as the carbon is added within the solid solubility limit shown in Table 3, because tool-wearing TiC precipitates near the beta-transus. Conversely, if the addition exceeds the solid solubility limit, the precipitation of TiC must be inhibited by adjusting the conditions of hot-working and/or annealing, including the annealing temperature and time. As shown in Table 3, the solid solubility limits of carbon for the 5% Mo material and for 2Fe-1Cr material are

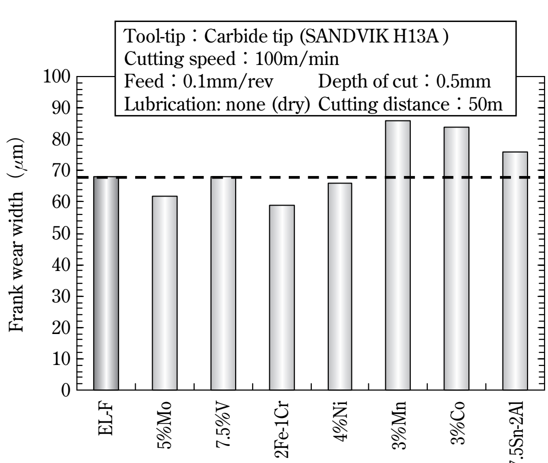

Fig. 3 Frank wear of test alloys for machinability

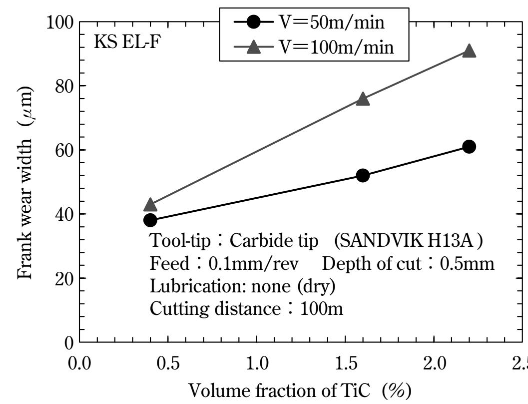

Fig. 4 Influence of TiC volume fraction on frank wear of cutting tool tip[4]

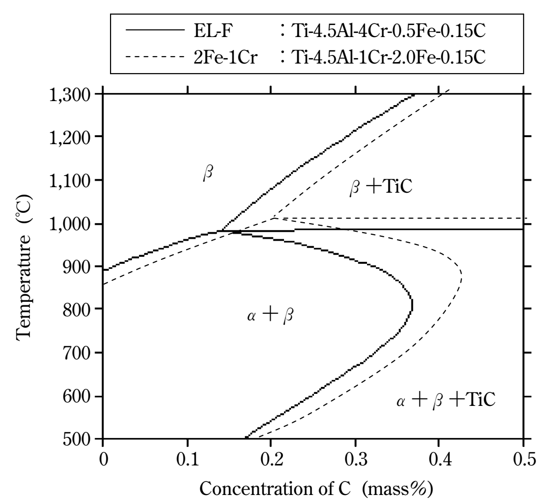

Fig. 5 Calculated phase diagram of Ti-Al-Cr-Fe-C system

Table 3 Solubility limit of C on beta transformed temperature in test alloys

No.	Solubility limit of C (mass%)
EL-F	0.140
5%Mo	0.182
7.5%V	0.133
2Fe-1Cr	0.198
4%Ni	0.118
3%Mn	no data
3%Co	no data
7.5Sn-2Al	0.259

greater than for the base material, EL-F. The greater solubility limit is preferable for inhibiting the precipitation of TiC, eliminating the need for specifically adjusting the conditions for forging, or for annealing.

As described above, it has been found that substituting Cr with Mo, or with Fe, effectively improves the machinability of EL-F. The substitution with Fe is preferable because the element is more widely found and less costly [7]. The following focuses on the compositions in which Cr is substituted with Fe.

2.2 Hot workability and machinability of α-β type titanium alloys containing high amount of Fe

Among alloying elements, Fe segregates significantly during actual production involving melting and casting. Taking this into consideration, the compositions shown in Table 2 were prepared for the evaluation of hot workability. **Fig. 6** shows the microstructures of the samples of these alloys. The samples have almost the same Vickers hardness of 340 ± 10HV.

Compression tests were conducted with the ends of each specimen confined to see if cracking occurred in the samples. **Fig. 7** shows the results of the evaluation. Compared with the conventional α-β type titanium alloy, Ti-6Al-4V (hereinafter referred to as "Ti-64"), the EL-F and the compositions with high content of iron, i.e., F-1 and F-2, have very high crack limits. In particular, the high-Fe compositions have crack limits even higher than that of EL-F. Also studied was the deformation resistance of each alloy. As shown in **Fig. 8**, the deformation resistance of Ti-64 depends less on temperature, while both EL-F and the high iron compositions (F-1, F-2) have deformation resistance that decreases significantly at elevated temperatures. At 600℃, F-1 and F-2 have a deformation resistance almost 10% smaller than that of EL-F. At 600℃, Fe, in α phase, has a diffusion coefficient approximately two orders of magnitude higher than that of Cr and, in β phase, three to four orders of magnitude higher than the same. Hence it is presumed that the decreased Cr and increased Fe content promote diffusion, further decreasing deformation resistance.

Fig. 9 compares tool wear, wherein each sample was cut at various cutting speeds ranging from 10 to 100m/min for a distance of 100m. Compared either with Ti-64, or with EL-F alloy, the alloys with higher Fe content wear the tools much less and exhibit the most favorable machinability. Comparing them with the results shown in Fig. 4, they exhibit smaller tool wear, despite the same cutting conditions and the doubled cutting distance. The decreased wear can be attributed to the microstructure, shown in Fig. 6, in which coarse TiC precipitates do not exist, and equiaxial α structure has been formed to be different from α lath structure shown in Fig. 2. In general, the equiaxial α structure has a fracture toughness lower than that of the alpha lath [8], which is considered to facilitate the generation of cutting chips and to decrease tool wear.

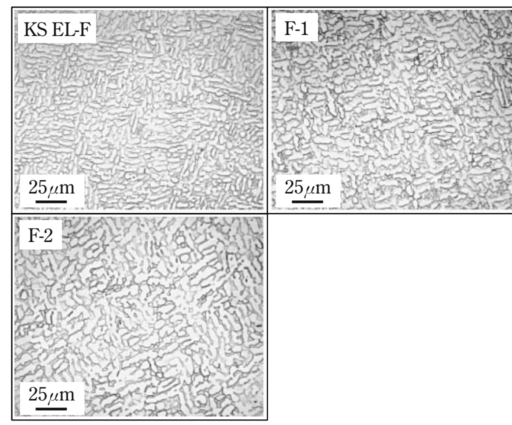

Fig. 6 Microstructure of high Fe system test alloys

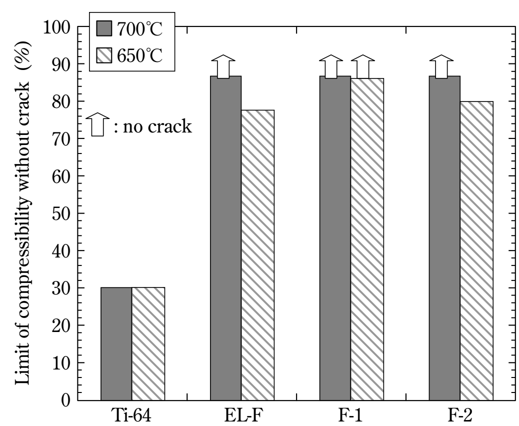

Fig. 7 Limit of compressibility of conventional and high Fe system alloys

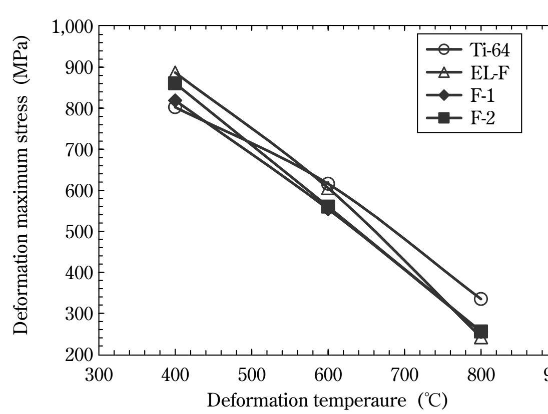

Fig. 8 Deformation stress of conventional and high Fe system alloys

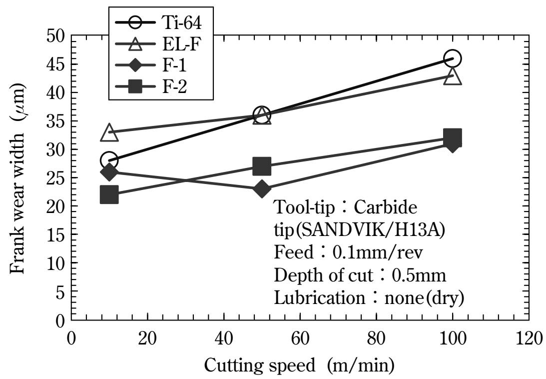

Fig. 9 Frank wear of conventional and high Fe system alloys

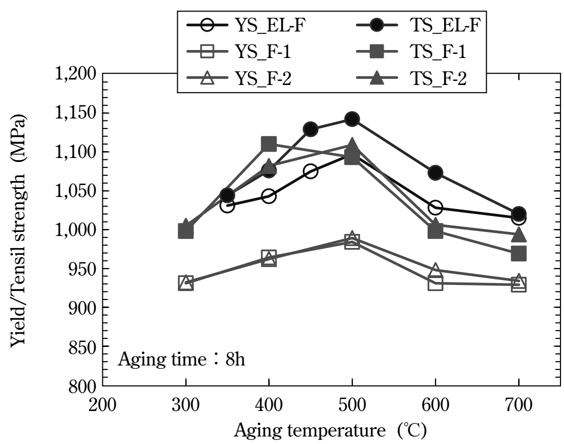

Fig.10 Strength after aging on high Fe system alloys (KS EL-F data : ref. 5))

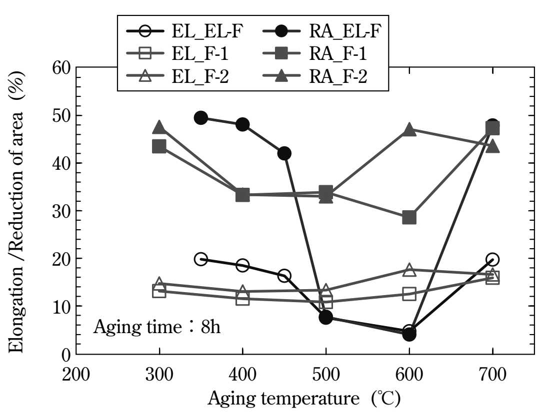

Fig.11 Ductility after aging on high Fe system alloys (KS EL-F data : ref. 5))

2.3 Aging behavior of α-β type titanium alloy having high Fe content

The EL-F alloy and high-Fe alloys shown in Table 2 were aged and subjected to tensile testing. **Fig.10** and **Fig.11** show their tensile properties after the aging. Each alloy has a high strength at around 500℃ with decreased ductility. Compared with the EL-F, the F-1 and F-2 exhibit a much smaller reduction of ductility. Aging embrittlement is known to occur in the EL-F alloy by the precipitation of $TiCr_2$[6], and the decreased Cr content in F-1 and F-2 is considered to inhibit the aging embrittlement. It should be noted that the F-1 and F-2 alloys have a slight difference in the temperature range where the changes in strength and ductility occur. This may be attributable to other precipitates, such as TiFe and $TiCr_2$, as well as to TiC, the details of which are to be the subject of future study.

Conclusions

A study was conducted on machinability and hot workability, using KS EL-F alloy as a reference. The results are as follows:

1) Using the KS EL-F composition (Ti-4.5Al-4Cr-0.5Fe-0.15C) as a base, alloys were prepared with decreased Cr and Al content. These elements were substituted with other alloying elements (i.e., Mo, V, Fe, Ni, Mn, Co, Sn). Each alloy was evaluated for its machinability. It has turned out that substituting Cr with Mo and/or Fe effectively improves the machinability.
2) In an equiaxial α structure, the alloys (1 to 2.5Cr-1.25 to 2Fe), which has a higher Fe content compared with Ti-6Al-4V, or with KS EL-F, exhibit tool wear decreased by about 30%. The alloys have an approximately 10% lower hot deformation resistance at 600℃ and crack limit compression rates no less than 5% higher.
3) Thermodynamic equilibrium calculation shows that the alloys containing high Fe have large solid solubility limits of carbon near the beta-transus. This makes the alloys less prone, compared with KS EL-F, to the precipitation of coarse TiC, which can adversely affect the machinability.
4) The alloys with compositions of decreased Cr and increased Fe have limited precipitation of $TiCr_2$, which prevents the aging embrittlement that occurs in KS EL at around 500℃.

A study is currently in progress to commercialize a modified alloy, KS 531C, which reflects the knowledge described in this paper. This work has been conducted as a part of the project, "Aerospace Industry Innovation Program-Advanced Materials & Process Development for Next-Generation Aircraft Structures" under the contract with RIMCOF Research Center of Materials Process Technology Center, founded by Ministry of Economy, Trade and Industry (METI) of Japan. We would like to express our sincere gratitude to all who were involved in this project.

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