the moving "indenter", thereby damaging the edges of the final cut. Clearly, the need here is for a means of suppressing the chipping mode.

(iii) *Surface removal processes.* Individual chipping events in the machining, drilling, grinding, abrasion, erosion and wear of brittle surfaces in general (e.g. ceramics, gemstones, rocks) are of the type depicted in Fig. 1 [1]. By summing over an appropriate distribution of such microscopic events, it should be possible to describe macroscopic surface removal parameters at a fundamental level.

(iv) *Geophysical impact phenomena.* Meteorite-induced craters ranging in scale from geological land masses [16] to lunar fines [17] bear a resemblance to the damage pattern in Fig. 1 which can only be described as striking. While thermal and stress-wave effects associated with the high-velocity impacts are undoubtedly important factors in these cases [18], the possible role of residual stresses about the central "deformation zone" in determining crater morphology may warrant further attention.

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Using electron/atom ratio in titanium alloy design

A correlation between beta phase stability in titanium and zirconium-base alloys and solute valence has been noted [1, 2]. Such a correlation, if sufficiently precise, could prove quite valuable in the design of strain transformable beta titanium alloys, since these alloys show optimum properties at alloy contents just adequate to insure complete retention of a metastable beta phase on quenching from above the beta transus [3]. Information on the microstructural characteristics of a series of beta titanium alloys quenched from above the beta transus, available from a prior investigation [3], was used to determine how well the observed microstructural characteristics of these alloys correlated with the computed electron/atom ratio.

An initial question which arose in performing this analysis was the proper choice of valence for

TABLE I Valence of metallic elements

Metallic element	Location in Periodic Table	Common chemical valences	Pauling alloying valence	Valence selected in this study
Cu	1b	1,2	5.56	5.6
Al	3	3	3	3
Ti	4a	3,4	4	4
Zr	4a	4	4	4
Sn	4b	2,4	2.56	4
V	5a	2-5	5	4.8
Cr	6a	2,3,6	6	6
Mo	6a	3-6	6	6
Mn	7a	2-4,6,7	6	6
Fe	8a	2,3	6	8
Co	8a	2,3	6	6
Ni	8a	2,3	6	6

use in computing the electron/atom ratio. Russian workers selected valences based upon position in the Periodic Table [1]. Alternately, one might select one of the common chemical valences [2] or the alloying valences derived by Pauling [4]. These values are compared in Table I for the elements of interest in the present study. The final column in Table I shows the valence which appeared to provide the best correlation between electron/atom ratio and microstructural characteristics for the strain transformable beta alloys analysed in this study. These valences were selected on an empirical basis as discussed below.

In Table II, the electron/atom ratios for 42 strain transformable beta titanium alloys, computed using the valences given in the last column of Table I, are compared with the optically observed microstructural characteristics reported in the previous paper [3]. A critical electron/atom ratio of 4.115 was suggested by these data, alloys having a higher electron/atom ratio showing no martensitic alpha as quenched from above the beta transus. If an uncertainty in the computed electron/atom ratio of ± 0.002 is assumed – which could readily be attributed to differences between the nominal and actual alloy composition – only six alloys failed to show the microstructural characteristics anticipated from their electron/atom ratios. Four of these, Ti–6Mo–3Co, Ti–3Mo–9Cu, Ti–6Mo–6Cu, and Ti–4Sn–2Mo–9Cu, contained a compound phase in the microstructure which was not considered in computing the electron/atom ratio. The presence of martensitic alpha in the three copper-containing alloys in which none was predicted based upon the electron/atom ratio can be attributed to the presence of Ti_2Cu compound; Ti_2Cu precipitation would reduce the stability (electron/atom ratio) of the beta matrix. Two alloys were more stable than predicted from the electron/atom ratio, Ti–8Sn–13V and Ti–2.6Al–14Mo. Both contained appreciable amounts of alpha stabilizing additions (aluminium and tin) which may have been a factor in their behaviour.

Assuming a critical electron/atom ratio of 4.115 demanded that the alloying valence of tin in strain transformable beta alloys be 4, not 2.56 as suggested by Pauling. This is shown for three selected examples below.

Composition (wt %)	Electron/atom ratio	
	Sn = 2.56	Sn = 4
Ti–4Sn–12Mo	4.104	4.130
Ti–6Sn–11Mo	4.081	4.120
Ti–4Sn–7Cr	4.112	4.132

None of these alloys contained martensitic alpha as quenched. A similar argument indicated that the effective alloying valence of vanadium was less than 5, 4.8 giving the best agreement with observed stability:

Composition (wt %)	Electron/atom ratio	
	V = 5	V = 4.8
Ti–15V	4.140	4.114
Ti–1.3Al–17V	4.137	4.105
Ti–1Al–S2n-6Mo–8V	4.126	4.106

All three of these alloys showed martensitic alpha as quenched. A fractional valence for vanadium might be attributed to significant

TABLE II Correlation between electron/atom ratio and beta stability

Composition (wt %) balance Ti	Electron/atom ratio	Microstructure, as beta quenched*
A. Beta-isomorphous additions (Mo and V)		
11 Mo	4.116	a′ + B
13 Mo	4.138	B
1.3Al–12Mo	4.102	a′ + B
2.6Al–12Mo	4.076	a′ + B
2.6Al–14Mo	4.099	B
2Sn–10Mo	4.106	a′ + B
4Sn–12Mo	4.130	B
6Sn–11Mo	4.120	B
5Zr–12Mo	4.130	B
15V	4.114	a′ + B
17V	4.130	B
1.3Al–17V	4.105	a′ + B
1.3Al–19V	4.130	B
2.6Al–17V	4.080	a′ + B
4Sn–13V	4.101	a′ + B
4Sn–15V	4.117	B
8Sn–11V	4.087	a′ + B
8Sn–13V	4.103	B
5Zr–15V	4.117	B
1Al–2Sn–6Mo–8V	4.106	a′ + B
B. Sluggish beta-eutectoid additons (Cr, Mn and Fe)		
4Sn–7Cr	4.132	B
1.3Al–7Cr	4.105	a′ + B
5Zr–7Cr	4.132	B
6Mo–4Cr	4.138	B
3Mo–6Cr	4.142	B
4Sn–2Mo–6Cr	4.136	B
0.5Al–3Sn–3V–6Cr	4.126	B
1Al–3Zr–6V–3Mo–3Cr	4.116	B
1Al–2Sn–3Zr–2.6Mo–6V–3Cr	4.113	B
1.3Al–8.2Mn	4.119	B
4Sn–7Mn	4.126	B
6Mo–4Mn	4.134	B
1.3Al–5Fe	4.149	B + C
4Sn–4Fe	4.140	B
6Mo–2Fe	4.134	B + C
C. Active beta-eutectoid additions (Cu, Ni and Co)		
4Sn–12Cu	4.154	B + C
6Mo–6Cu	4.139	a′ + B + C
3Mo–9Cu	4.144	a′ + B + C
4Sn–2Mo–9Cu	4.137	a′ + B + C
6Mo–4Ni	4.124	B + C
4Sn–7Co	4.118	B
6Mo–3Co	4.112	B + C

*Determined by optical metallography. a′ = martensitic alpha, B = beta (and perhaps omega), C = intermetallic compound.

losses of this element during fabrication to sheet as a result of preferential oxidation. Additional study is needed to determine whether the empirically determined fractional valence of vanadium has a rational explanation. The high stability of iron-containing alloys, although possibly the result of omega formation during quenching, suggested that the valence of iron in beta-stabilized alloys was probably 8 even though the alloying valence of manganese was almost certainly 6 rather than 7. Since very little information was available from which to select valences for the compound forming elements, nickel, cobalt, and copper, Pauling's alloying valences were chosen. The computed electron/atom ratios for copper-containing alloys, taking into account the probable effects of compound precipitation on alloy stability, appeared reasonable. However, the microstructures observed in the cobalt- and nickel-containing alloys suggested that the valences of these elements may be higher than 6.

It is concluded that the electron/atom ratio dominates beta titanium alloy stability to a large degree. However, to achieve a satisfactory correlation between electron/atom ratio and microstructure as quenched from above the beta transus, assuming a single value for the critical electron/atom ratio, it is necessary to select valences for several of the solute elements on a largely empirical basis. Nevertheless, once appropriate valences are selected, it is concluded that quite complex beta titanium alloys can be formulated having desired microstructural characteristics based upon consideration of the electron/atom ratio.

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