# CHAPTER I

# INTRODUCTION

## 1.1. General

Steels have been the most important engineering materials for many years and will remain so for a long while. This position arises from the versatility of alloys based on iron which cover a broad strength spectrum from the comparatively low-yield strength of mild steel (12-15 tons/in.$^2$) to special alloy steels with strength in excess of 200 tons/in.$^2$ In recent years, attempts have been made to achieve better combination of strength and ductility. In this respect, apart from the use of complex thermo-mechanical treatment, tempering is an important step in the processing of steels to achieve an optimum combination of strength and ductility in hardened steels. The role of carbide forming elements in complex steels in developing high strength and ductility is realized through their carbide forming ability; but the addition of non-carbide forming elements such as silicon to such steels for development of high strengths(1,2) is a subject not fully known. To understand the role of such elements on strengthening and embrittlement, it is important to consider their effects first in simple steels; and the present work is confined to such an investigation.

## 1.2 Strengthening in silicon steels

In plain carbon steels there is a progressive softening accompanied by an increase in ductility as a quenched martensite is tempered in the range 100-700°C. Structurally this is a result of the growth of cementite from a fine widmanstatten array of rodlets to coarse spheroidal particles as the temperature is raised. If however, carbide forming elements are added on to carbon steels, a further strengthening reaction sets in over the range 500-700°C, and as a result of which hardness approaching that of as-quenched alloys are very often achieved(3,4). So far the non-carbide forming elements are concerned, the strengthening effects are generally reported to be due to their influence on solid solution hardening of ferrite, but it is obvious that the phenomenon of retarded softening/secondary hardening associated with the presence of some such elements, in particular Silicon(5), cannot be explained from the same considerations.

In the study of the properties of silicon steels(6) it was found that the alloy did not soften during tempering over the range 150-370°C as other medium alloy steels did. Bain(7) attributed the solid solution strengthening of ferrite as mentioned above but it is not clear as why the silicon steel should show such pronounced retarded softening in the range 150-370°C when other medium alloy steels with the same amount of alloy content do not behave likewise.

Allten and Payson(8) on the basis of physical property measurements, optical metallography, and X-ray diffraction analysis suggested that coherency hardening of $\varepsilon$-carbide may be the cause for the retarded softening. Owen(9) proposed that the technologically important inhibition of the tempering of martensite by the presence of silicon in the steel (8,10,11) was due to the rejection of the element by the growing cementitic carbite particles. The build-up of silicon around the growing particles causes an increase in the activity of carbon in this region, thereby decreasing the flux of carbon to the particle and this in turn inhibits the growth of cementite and decreases the rate of precipitation. This model of silicon diffusion was explained on the basis of the activation energy of the third stage of tempering, and the time exponent(n) as described by him (9) suggests a type of precipitation, particles being spherical tending to be rod like or pearlitic in high silicon steels.

The effects of increasing the silicon content in 4340 and 4325 steels up to 1.5%, have been observed as a function of tempering temperature (10). The softening on tempering has been observed to retard and possibility of obtaining higher strengths without corresponding loss in ductility has also been shown, but neither the mechanism of retarded softening nor the ductility associated with the high strength in the silicon steels is discussed.

The known effects of silicon additions to steel are (a) increasing the hardenability and (b) increasing resistance to softening during tempering, are shown by Vajda, Hauser and Wells (11) but the most interesting point to be noted, is the report of secondary hardening in silicon steels on tempering around 300°C. This secondary hardening has been attributed by the authors(11) to coherency hardening as a result of tempering the martensite, but no specific report is available on the nature of the coherent particle whether it is ε-carbide, $\chi$-carbide, cementite or something else.

Stabilization of ε-carbide and/or martensite (12, 13) has also been attributed to be the cause of the retarded softening but no convincing experimental data have been provided. During the tempering of low-alloy steels (.4%C) with 1.5% Si. Reisdorf(14) has shown the existence of a peak at about 300°C of tempering by hardness, yield strength and line width measurements, and this increase in strength he assigns to the strains resulting from the ε-carbide precipitation. Cox (15) in a study on the tempering characteristics of a .38%C - 1.7% Si has explained the increase in strength at 300°C in terms of large volume fraction and increased coherency of ε-carbide. In a latter investigation Cox (16) has suggested that ε-carbide is stabilized by the presence of silicon, and the increased stability of ε-carbide was considered to arise from silicon concentrating at the ferrite/carbide interface and thus reducing the surface energy.

Recently, Gordine and Codd (17) have studied the tempering characteristics of a chromium-silicon spring steel using electron microscopy. It has been shown there that the first stage of tempering persists to higher temperature in steels containing 1.5% silicon as alloying element. Epsilon carbide is shown to be stabilized to much higher temperatures than in a comparable low-silicon steel. The stabilization of ε-carbide is reported to be associated with the presence of silicon in this carbide (ε-carbide).

## 1.3 Embrittlement of Tempered Martensite

Although the embrittlement of hardened steel tempered at 260-315°C has been recognized for years, the first systematic study of its characteristics was that by Grossmann (18), followed by the investigations of Schrader, Wiester and Siepmann (19), and others (8,20,21). Theories have been advanced to explain the cause of 260°C embrittlement, such as (a) transformation of retained austenite, and (b) formation of martensite spines at prior austenic grain boundaries (18), precipitation of nitride(22), formation of cementite (23), cementite platelets on martensitic boundary (24), thin ferrite networks (25), continuous carbide films (26), and dislocation locking through precipitation on dislocation intersection and jogs (27). The last mentioned theory with certain amount of modification is now gradually being accepted.

The effect of alloying elements on the embrittlement phenomenon is an other interesting feature. In this respect addition of silicon ( 2%) to carbon steel has been reported to raise the 260°C embrittlement to elevated temperature, but the manner in which it does so, is not clearly known as yet.

## 1.4 Object of the present study

It is evident from the summary of the results presented above in the Sections 1.2 and 1.3, that there is a large amount of confusion regarding (i) the mechanism of strengthening in silicon steels, and (ii) the mechanism of embrittlement. The present study was taken up with a view to investigate these aspects, in detail, and to suggest a mechanism which may explain the relevant data on the tempering behaviour of silicon and other steels.