be heated or cooled at any rate without danger of rupture. Hot working can be done at any temperature below 1,260°C (2,300°F). Exposure at high temperature to sulphur-bearing gases causes poor hot working qualities. Cold working hardens the alloy to a maximum of about Rockwell C32. Normally a 1150–1170°C (2100–2140°F) forging temperature is employed.

Weldability May be successully welded by any of the methods in common use. When welding with rod, it is essential that the rod be of the same composition if similar properties in the weld are desired; otherwise mild steel rods or 18–8 stainless steel rods may be employed. The rods should be heavily coated. In oxyacetylene welding, the flame is maintained slightly on the reducing side. An Invar welding wire with a higher titanium and manganese content minimizes weld hot-cracking in heavy gages. Either the gas metal arc (MIG) or gas tungsten arc (TIG) process can be used with this wire. Brazing and silver soldering of Invar have been fairly common. If silver soldering is done manually, the parts should be preheated to 425°C (800°F) and slowly cooled.

Corrosion resistance Resists atomospheric corrosion and fresh or salt water.

Pickling Pickling is best done in hydrochloric acid solutions. A 25% solution at 70°C (160°F) is particularly effective.

22.2.3 Fe–Ni–Co– Alloy

(a) Scott's Investigation and Low Expansion Alloys H. Scott reported that the addition of Co to Fe–Ni alloys was first attempted by P.H. Brace, but it was Scott himself who made a systematic study of Co additions.[24] He investigated the effects of additions of Co, Mn, and C on the value of α in the annealed state and on the inflection point θ (°C) in the thermal expansion curves (See Fig. 22.18), for FCC phase alloys in the Fe–Ni system.

Figures 22.18 and 22.19 show several examples of the thermal expansion curves for ternary Fe–Ni–Co alloys in which the Co concentration Y, is changed while keeping the Ni composition X, and the Mn composition Z, approximately constant (constant nickel, variable cobalt series). It is evident from the figure that Co has a remarkable influence on θ and α. Scott further obtained the relationship between X, Y, W, Z, and θ while changing C concentration W:

$$\theta = 19.5\,(X + Y) - 22\,Z - (0\,W) - 465.$$

Also, he proposed the following formulae for X and Y in which the FCC $\rightleftharpoons$ BCC transformation point is maintained near −100°C and θ is in the range 200–600°C:

$$Y = 0.0795\,\theta + 4.8\,Z + 19\,W - 18.1,$$

$$X = 41.9 - 0.0282\,\theta - 3.7\,Z - 19\,W.$$

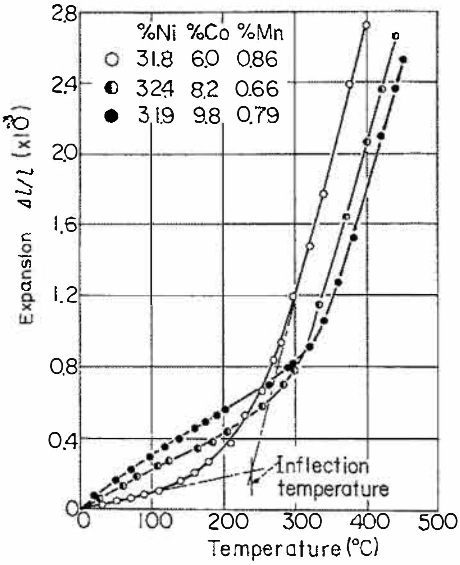

Fig. 22.18 Thermal expansion curves of some Fe–Ni–Co alloys.[24]

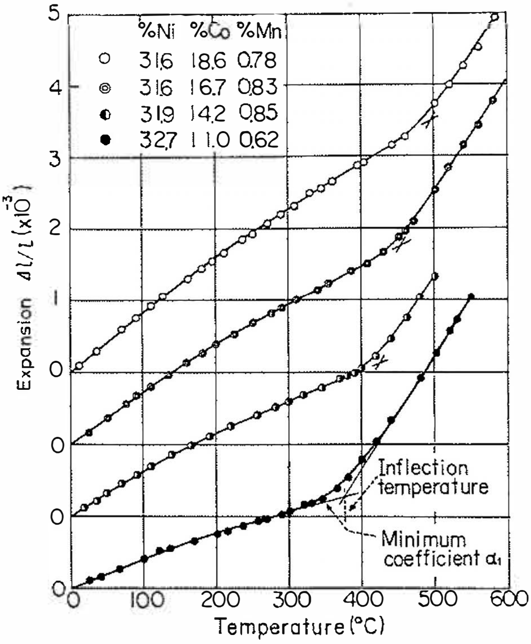

Fig. 22.19 Thermal expansion curves of some Fe–Ni–Co alloys.[24]

From these formula it is clear that among the above four elements only Co can contribute to an increase in θ. The minimum expansivity α_1 (Fig. 22.20) and the mean expansivity α_2 up to θ can be given by the following formulae, when θ is

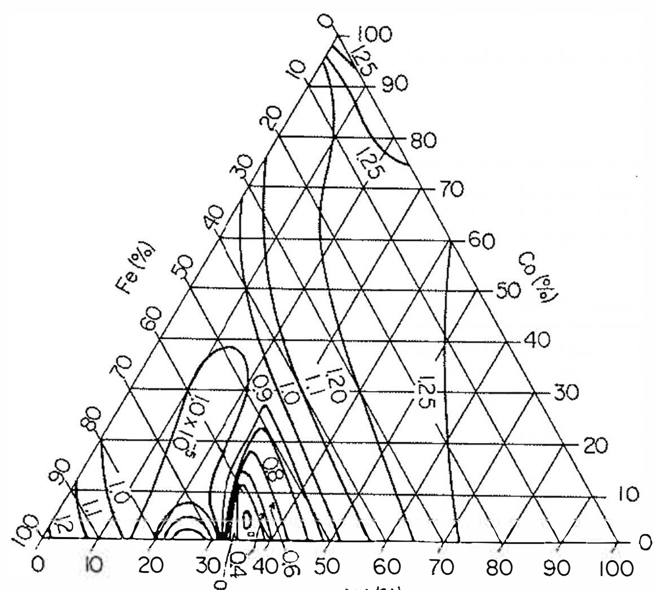

Fig. 22.20 Equi-expansion coefficient curves in the Fe–Ni–Co system.[5]

between 350 and 600°C:

$$\alpha_1 \times 10^6 = 0.024\,\theta + 0.38\,Z - 1.2\,W - 6.65,$$
$$\alpha_2 \times 10^6 = 0.024\,\theta + 0.38\,Z - 1.2\,W - 5.6.$$

For wire to be sealed in glass, the mean expansion coefficient α_2 should be equal to that of glass ($3\text{–}11 \times 10^{-6}$), and θ must be higher than the softening temperature of glass. Although α in the above alloys containing Co is larger than that of Invar, the value is small compared to conventional metals and alloys, and θ can be controlled within a wide range. These alloys are used as low expansion alloys for glass-to-metal seal materials, together with 42 alloy (Fe–42 wt.% Ni) and 52 alloy (Fe–52 wt.% Ni). Among these alloys, Kovar[24] and Fernico,[25] with 25–31 wt.% Ni, 15–18 wt.% Co, balance Fe, are most widely known. They have a mean α of 6.3×10^{-6} in the range of 20–500°C, and θ of 425°C. Konel[26] is an alloy used for filaments of vacuum tubes, and contains about 20 wt.% Co, 70 wt.% Ni 2.8 wt.% Ti, balance Fe.

The minimum value of α observed in the studies outlined above is 0.6×10^{-6}, which is lower than standard Invar (1.26×10^{-6}).

(b) Super Invar[5] H. Masumoto measured the thermal expansion coefficients α, over the whole compositional range of the ternary system of iron, nickel, and cobalt in the annealed state. His work was evidently in progress at about the same time that H. Scott undertook similar experiments as mentioned in the previous section.[27]

In June 1921 Masumoto obtained alloys having a much smaller α than that of fused silica. Figure 1.8 shows a solid model which represents the relation between α and the composition of the ternary alloys, and Fig. 22.21 is a projection of the equiexpansion coefficient curves onto the ternary composition diagram. As seen in Fig. 1.8 and Fig. 22.2, the small coefficient of expansion of Invar containing 36.5% of nickel rapidly diminishes as cobalt is added, reaches a minimum at about 5% cobalt, and afterwards rapidly increases, forming a deep valley on the space diagram.

Figure 22.21 shows some examples of thermal expansion curves of alloys in the concentration range having small expansivity. In the figure, an arrow shows the transformation temperature of γ-(FCC) phase to α-(BCC) phase on cooling (A_{r3}). In some alloys this temperature is below that of liquid air, as seen in the figure. The value of α at 20°C taken from the curves in Fig. 22.21 are given in Table 22.8. The value of the smallest coefficient obtained here is less than 10^{-7}. The alloys with these very small coefficients were named Super Invar.

Masumoto investigated the influence of Mn on the expansivity of Super Invar, and found that the addition of a small amount of Mn is beneficial; that is, as seen in Fig. 22.21 or Table 22.8, a small content of Mn lowers the A_{r3} of Super Invar.

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