Alloying: Understanding the Basics
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# Tool Steels

## Introduction and Overview

A tool steel is any steel used to make tools for cutting, forming, or otherwise shaping a material into a part or component adapted to a definite use. The earliest tool steels were simple, plain carbon steels, but by 1868 and increasingly in the early 20th century, many complex, highly alloyed tool steels were developed. These tool steels contain, among other elements, relatively large amounts of tungsten, molybdenum, vanadium, manganese, and chromium, and they make it possible to meet increasingly severe service demands and to provide greater dimensional control and freedom from cracking during heat treatment. Many alloy tool steels are also widely used for machinery components and structural applications in which particularly stringent requirements must be met, such as high-temperature springs, ultrahigh-strength fasteners, special-purpose valves, and bearings of various types for elevated-temperature service.

In service, most tools are subjected to extremely high loads that are applied rapidly. The tools must withstand these loads a great number of times without breaking and without undergoing excessive wear or deformation. In many applications, tool steels must provide this capability under conditions that produce high temperatures in the tool. No single tool material combines maximum wear resistance, toughness, and resistance to softening at elevated temperatures. Consequently, the selection of the proper tool material for a given application often requires a tradeoff to achieve the optimum combination of properties.

Most tool steels are wrought products, but powder metallurgy (P/M) processing, where gas-atomized powders are consolidated to full density by hot isostatic pressing (HIP), is also used in making tool steels. Powder metallurgy processing provides, first, a more uniform carbide size and distribution in large sections, and, second, special compositions that are difficult or impossible to produce by melting and casting and then mechanically working the cast product.

**Classification and Characteristics.** Table 1 gives composition limits for the wrought tool steels most commonly used. Each group of tool steels of similar composition and properties is identified by a capital letter; within each group, individual tool steel types are assigned code numbers.

**Table 1 Composition limits of principal types of wrought tool steels**

| Designation | | Composition(a), % | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| AISI | UNS | C | Mn | Si | Cr | Ni | Mo | W | V | Co |
| **Molybdenum high-speed steels** | | | | | | | | | | |
| M1 | T11301 | 0.78–0.88 | 0.15–0.40 | 0.20–0.50 | 3.50–4.00 | 0.30 max | 8.20–9.20 | 1.40–2.10 | 1.00–1.35 | … |
| M2 | T11302 | 0.78–0.88 0.95–1.05 | 0.15–0.40 | 0.20–0.45 | 3.75–4.50 | 0.30 max | 4.50–5.50 | 5.50–6.75 | 1.75–2.20 | … |
| M3, class 1 | T11313 | 1.00–1.10 | 0.15–0.40 | 0.20–0.45 | 3.75–4.50 | 0.30 max | 4.75–6.50 | 5.00–6.75 | 2.25–2.75 | … |
| M3, class 2 | T11323 | 1.15–1.25 | 0.15–0.40 | 0.20–0.45 | 3.75–4.50 | 0.30 max | 4.75–6.50 | 5.00–6.75 | 2.75–3.75 | … |
| M4 | T11304 | 1.25–1.40 | 0.15–0.40 | 0.20–0.45 | 3.75–4.75 | 0.30 max | 4.25–5.50 | 5.25–6.50 | 3.75–4.50 | … |
| M7 | T11307 | 0.97–1.05 | 0.15–0.40 | 0.20–0.55 | 3.50–4.00 | 0.30 max | 8.20–9.20 | 1.40–2.10 | 1.75–2.25 | … |
| M10 | T11310 | 0.84–0.94; 0.95–1.05 | 0.10–0.40 | 0.20–0.45 | 3.75–4.50 | 0.30 max | 7.75–8.50 | … | 1.80–2.20 | … |
| M30 | T11330 | 0.75–0.85 | 0.15–0.40 | 0.20–0.45 | 3.50–4.25 | 0.30 max | 7.75–9.00 | 1.30–2.30 | 1.00–1.40 | 4.50–5.50 |
| M33 | T11333 | 0.85–0.92 | 0.15–0.40 | 0.15–0.50 | 3.50–4.00 | 0.30 max | 9.00–10.00 | 1.30–2.10 | 1.00–1.35 | 7.75–8.75 |
| M34 | T11334 | 0.85–0.92 | 0.15–0.40 | 0.20–0.45 | 3.50–4.00 | 0.30 max | 7.75–9.20 | 1.40–2.10 | 1.90–2.30 | 7.75–8.75 |
| M35 | T11335 | 0.82–0.88 | 0.15–0.40 | 0.20–0.45 | 3.75–4.50 | 0.30 max | 4.50–5.50 | 5.50–6.75 | 1.75–2.20 | 4.50–5.50 |
| M36 | T11336 | 0.80–0.90 | 0.15–0.40 | 0.20–0.45 | 3.75–4.50 | 0.30 max | 4.58–5.50 | 5.50–6.50 | 1.75–2.25 | 7.75–8.75 |
| M41 | T11341 | 1.05–1.15 | 0.20–0.60 | 0.15–0.50 | 3.75–4.50 | 0.30 max | 3.25–4.25 | 6.25–7.00 | 1.75–2.25 | 4.75–5.75 |
| M42 | T11342 | 1.05–1.15 | 0.15–0.40 | 0.15–0.65 | 3.50–4.25 | 0.30 max | 9.00–10.00 | 1.15–1.85 | 0.95–1.35 | 7.75–8.75 |
| M43 | T11343 | 1.15–1.25 | 0.20–0.40 | 0.15–0.65 | 3.50–4.25 | 0.30 max | 7.50–8.50 | 2.25–3.00 | 1.50–1.75 | 7.75–8.75 |
| M44 | T11344 | 1.10–1.20 | 0.20–0.40 | 0.30–0.55 | 4.00–4.75 | 0.30 max | 6.00–7.00 | 5.00–5.75 | 1.85–2.20 | 11.00–12.25 |
| M46 | T11346 | 1.22–1.30 | 0.20–0.40 | 0.40–0.65 | 3.70–4.20 | 0.30 max | 8.00–8.50 | 1.90–2.20 | 3.00–3.30 | 7.80–8.80 |
| M47 | T11347 | 1.05–1.15 | 0.15–0.40 | 0.20–0.45 | 3.50–4.00 | 0.30 max | 9.25–10.00 | 1.30–1.80 | 1.15–1.35 | 4.75–5.25 |
| M47 | T11348 | 1.42–1.52 | 0.15–0.40 | 0.15–0.40 | 3.50–4.00 | 0.30 max | 4.75–5.50 | 9.50–10.50 | 2.75–3.25 | 8.00–10.00 |
| M62 | T11362 | 1.25–1.35 | 0.15–0.40 | 0.15–0.40 | 3.50–4.00 | 0.30 max | 10.00–11.00 | 5.75–6.50 | 1.80–2.10 | … |
| **Tungsten high-speed steels** | | | | | | | | | | |
| T1 | T12001 | 0.65–0.80 | 0.10–0.40 | 0.20–0.40 | 3.75–4.50 | 0.30 max | … | 17.25–18.75 | 0.90–1.30 | … |
| T2 | T12002 | 0.80–0.90 | 0.20–0.40 | 0.20–0.40 | 3.75–4.50 | 0.30 max | 1.0 max | 17.50–19.00 | 1.80–2.40 | … |
| T4 | T12004 | 0.70–0.80 | 0.10–0.40 | 0.20–0.40 | 3.75–4.50 | 0.30 max | 0.40–1.00 | 17.50–19.00 | 0.80–1.20 | 4.25–5.75 |
| T5 | T12005 | 0.75–0.85 | 0.20–0.40 | 0.20–0.40 | 3.75–5.00 | 0.30 max | 0.50–1.25 | 17.50–19.00 | 1.80–2.40 | 7.00–9.50 |
| T6 | T12006 | 0.75–0.85 | 0.20–0.40 | 0.20–0.40 | 4.00–4.75 | 0.30 max | 0.40–1.00 | 18.50–21.00 | 1.50–2.10 | 11.00–13.00 |
| T8 | T12008 | 0.75–0.85 | 0.20–0.40 | 0.20–0.40 | 3.75–4.50 | 0.30 max | 0.40–1.00 | 13.25–14.75 | 1.80–2.40 | 4.25–5.75 |
| T15 | T12015 | 1.50–1.60 | 0.15–0.40 | 0.15–0.40 | 3.75–5.00 | 0.30 max | 1.00 max | 11.75–13.00 | 4.50–5.25 | 4.75–5.25 |
| **Intermediate high-speed steels** | | | | | | | | | | |
| M50 | T11350 | 0.78–0.88 | 0.15–0.45 | 0.20–0.60 | 3.75–4.50 | 0.30 max | 3.90–4.75 | … | 0.80–1.25 | … |
| M52 | T11352 | 0.85–0.95 | 0.15–0.45 | 0.20–0.60 | 3.50–4.30 | 0.30 max | 4.00–4.90 | 0.75–1.50 | 1.65–2.25 | … |
| **Chromium hot-work steels** | | | | | | | | | | |
| H10 | T20810 | 0.35–0.45 | 0.25–0.70 | 0.80–1.20 | 3.00–3.75 | 0.30 max | 2.00–3.00 | … | 0.25–0.75 | … |
| H11 | T20811 | 0.33–0.43 | 0.20–0.50 | 0.80–1.20 | 4.75–5.50 | 0.30 max | 1.10–1.60 | … | 0.30–0.60 | … |
| H12 | T20812 | 0.30–0.40 | 0.20–0.50 | 0.80–1.20 | 4.75–5.50 | 0.30 max | 1.25–1.75 | 1.00–1.70 | 0.50 max | … |
| H13 | T20813 | 0.32–0.45 | 0.20–0.50 | 0.80–1.20 | 4.75–5.50 | 0.30 max | 1.10–1.75 | … | 0.80–1.20 | … |
| H14 | T20814 | 0.35–0.45 | 0.20–0.50 | 0.80–1.20 | 4.75–5.50 | 0.30 max | … | 4.00–5.25 | … | … |
| H19 | T20819 | 0.32–0.45 | 0.20–0.50 | 0.20–0.50 | 4.00–4.75 | 0.30 max | 0.30–0.55 | 3.75–4.50 | 1.75–2.20 | 4.00–4.50 |
| **Tungsten hot-work steels** | | | | | | | | | | |
| H21 | T20821 | 0.28–0.36 | 0.15–0.40 | 0.15–0.50 | 3.00–3.75 | 0.30 max | … | 8.50–10.00 | 0.30–0.60 | … |
| H22 | T20822 | 0.30–0.40 | 0.15–0.40 | 0.15–0.40 | 1.75–3.75 | 0.30 max | … | 10.00–11.75 | 0.25–0.50 | … |
| H23 | T20823 | 0.25–0.35 | 0.15–0.40 | 0.15–0.60 | 11.00–12.75 | 0.30 max | … | 11.00–12.75 | 0.75–1.25 | … |

(continued)

(a) All steels except group W contain 0.25 max Cu, 0.30 max P, and 0.03 max S; group W contains 0.20 max Cu, 0.025 max P, and 0.025 max S. Where specified, sulfur may be increased to 0.06 to 0.15% to improve machinability of group A, D, H, M, and T steels. (b) Available in several carbon ranges. (c) Contains free graphite in the microstructure. (d) Optional. (e) Specified carbon ranges are designated by suffix numbers.

**Table 1 (continued)**

| Designation | | Composition(a), % | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| AISI | UNS | C | Mn | Si | Cr | Ni | Mo | W | V | Co |
| H24 | T20824 | 0.42–0.53 | 0.15–0.40 | 0.15–0.40 | 2.50–3.50 | 0.30 max | … | 14.00–16.00 | 0.40–0.60 | … |
| H25 | T20825 | 0.22–0.32 | 0.15–0.40 | 0.15–0.40 | 3.75–4.50 | 0.30 max | … | 14.00–16.00 | 0.40–0.60 | … |
| H26 | T20826 | 0.45–0.55(b) | 0.15–0.40 | 0.15–0.40 | 3.75–4.50 | 0.30 max | … | 17.25–19.00 | 0.75–1.25 | … |
| **Molybdenum hot-work steels** | | | | | | | | | | |
| H42 | T20842 | 0.55–0.70(b) | 0.15–0.40 | … | 3.75–4.50 | 0.30 max | 4.50–5.50 | 5.50–6.75 | 1.75–2.20 | … |
| **Air-hardening, medium-alloy, cold-work steels** | | | | | | | | | | |
| A2 | T30102 | 0.95–1.05 | 1.00 max | 0.50 max | 4.75–5.50 | 0.30 max | 0.90–1.40 | … | 0.15–0.50 | … |
| A3 | T30103 | 1.20–1.30 | 0.40–0.60 | 0.50 max | 4.75–5.50 | 0.30 max | 0.90–1.40 | … | 0.80–1.40 | … |
| A4 | T30104 | 0.95–1.05 | 1.80–2.20 | 0.50 max | 0.90–2.20 | 0.30 max | 0.90–1.40 | … | … | … |
| A6 | T30106 | 0.65–0.75 | 1.80–2.50 | 0.50 max | 0.90–1.20 | 0.30 max | 0.90–1.40 | … | … | … |
| A7 | T30107 | 2.00–2.85 | 0.80 max | 0.50 max | 5.00–5.75 | 0.30 max | 0.90–1.40 | 0.50–1.50 | 3.90–5.15 | … |
| A8 | T30108 | 0.50–0.60 | 0.50 max | 0.75–1.10 | 4.75–5.50 | 0.30 max | 1.15–1.65 | 1.00–1.50 | … | … |
| A9 | T30109 | 0.45–0.55 | 0.50 max | 0.95–1.15 | 4.75–5.50 | 1.25–1.75 | 1.30–1.80 | … | 0.80–1.40 | … |
| A10 | T30110 | 1.25–1.50(c) | 1.60–2.10 | 1.00–1.50 | … | 1.55–2.05 | 1.25–1.75 | … | … | … |
| **High-carbon, high-chromium, cold-work steels** | | | | | | | | | | |
| D2 | T30402 | 1.40–1.60 | 0.60 max | 0.60 max | 11.00–13.00 | 0.30 max | 0.70–1.20 | … | 1.10 max | … |
| D3 | T30403 | 2.00–2.35 | 0.60 max | 0.60 max | 11.00–13.50 | 0.30 max | … | 1.00 max | 1.00 max | … |
| D4 | T30404 | 2.05–2.40 | 0.60 max | 0.60 max | 11.00–13.00 | 0.30 max | 0.70–1.20 | … | 1.00 max | … |
| D5 | T30405 | 1.40–1.60 | 0.60 max | 0.60 max | 11.00–13.00 | 0.30 max | 0.70–1.20 | … | 1.00 max | 2.50–3.50 |
| D7 | T30407 | 2.15–2.50 | 0.60 max | 0.60 max | 11.50–13.50 | 0.30 max | 0.70–1.20 | … | 3.80–4.40 | … |
| **Oil-hardening cold-work steels** | | | | | | | | | | |
| O1 | T31501 | 0.85–1.00 | 1.00–1.40 | 0.50 max | 0.40–0.60 | 0.30 max | … | 0.40–0.60 | 0.30 max | … |
| O2 | T31502 | 0.85–0.95 | 1.40–1.80 | 0.50 max | 0.50 max | 0.30 max | 0.30 max | … | 0.30 max | … |
| O6 | T31506 | 1.25–1.55(c) | 0.30–1.10 | 0.55–1.50 | 0.30 max | 0.30 max | 0.20–0.30 | … | … | … |
| O7 | T31507 | 1.10–1.30 | 1.00 max | 0.60 max | 0.35–0.85 | 0.30 max | 0.30 max | 1.00–2.00 | 0.40 max | … |
| **Shock-resisting steels** | | | | | | | | | | |
| S1 | T41901 | 0.40–0.55 | 0.10–0.40 | 0.15–1.20 | 1.00–1.80 | 0.30 max | 0.50 max | 1.50–3.00 | 0.15–0.30 | … |
| S2 | T41902 | 0.40–0.55 | 0.30–0.50 | 0.90–1.20 | … | 0.30 max | 0.30–0.60 | … | 0.50 max | … |
| S5 | T41905 | 0.50–0.65 | 0.60–1.00 | 1.75–2.25 | 0.50 max | … | 0.20–1.35 | … | 0.35 max | … |
| S6 | T41906 | 0.40–0.50 | 1.20–1.50 | 2.00–2.50 | 1.20–1.50 | … | 0.30–0.50 | … | 0.20–0.40 | … |
| S7 | T41907 | 0.45–0.55 | 0.20–0.90 | 0.20–1.00 | 3.00–3.50 | … | 1.30–1.80 | … | 0.20–0.30(d) | … |
| **Low-alloy special-purpose tool steels** | | | | | | | | | | |
| L2 | T61202 | 0.45–1.00(b) | 0.10–0.90 | 0.50 max | 0.70–1.20 | … | 0.25 max | … | 0.10–0.30 | … |
| L6 | T61206 | 0.65–0.75 | 0.25–0.80 | 0.50 max | 0.60–1.20 | 1.25–2.00 | 0.50 max | … | 0.20–0.30(d) | … |
| **Low-carbon mold steels** | | | | | | | | | | |
| P2 | T51602 | 0.10 max | 0.10–0.40 | 0.10–0.40 | 0.75–1.25 | 0.10–0.50 | 0.15–0.40 | … | … | … |
| P3 | T51603 | 0.10 max | 0.20–0.60 | 0.40 max | 0.40–0.75 | 1.00–1.50 | … | … | … | … |
| P4 | T51604 | 0.12 max | 0.20–0.60 | 0.10–0.40 | 4.00–5.25 | … | 0.40–1.00 | … | … | … |
| P5 | T51605 | 0.10 max | 0.20–0.60 | 0.40 max | 2.00–2.50 | 0.35 max | … | … | … | … |
| P6 | T51606 | 0.05–0.15 | 0.35–0.70 | 0.10–0.40 | 1.25–1.75 | 3.25–3.75 | … | … | … | … |
| P20 | T51620 | 0.28–0.40 | 0.60–1.00 | 0.20–0.80 | 0.40–2.00 | … | 0.30–0.55 | … | … | … |
| P21 | T51621 | 0.18–0.22 | 0.20–0.40 | 0.20–0.40 | 0.50 max | 3.90–4.25 | … | … | 0.15–0.25 | 1.05–1.25A1 |
| **Water-hardening tool steels** | | | | | | | | | | |
| W1 | T72301 | 0.70–1.50(e) | 0.10–0.40 | 0.10–0.40 | 0.15 max | 0.20 max | 0.10 max | 0.15 max | 0.10 max | … |
| W2 | T72302 | 0.85–1.50(e) | 0.10–0.40 | 0.10–0.40 | 0.15 max | 0.20 max | 0.10 max | 0.15 max | 0.15–0.35 | … |
| W3 | T72305 | 1.05–1.15 | 0.10–0.40 | 0.10–0.40 | 0.40–0.60 | 0.20 max | 0.10 max | 0.15 max | 0.10 max | … |

(a) All steels except group W contain 0.25 max Cu, 0.30 max P, and 0.03 max S; group W contains 0.20 max Cu, 0.025 max P, and 0.025 max S. Where specified, sulfur may be increased to 0.06 to 0.15% to improve machinability of group A, D, H, M, and T steels. (b) Available in several carbon ranges. (c) Contains free graphite in the microstructure. (d) Optional. (e) Specified carbon ranges are designated by suffix numbers.

Tool steels are produced to various standards, including several ASTM specifications. The *Steel Products Manual* covering tool steels, which is published by the Iron and Steel Society, Inc. (Ref 1), contains much useful information that essentially represents the normal manufacturing practices of most tool steel producers. Frequently, more stringent chemical and/or metallurgical standards are invoked by the individual producers or consumers to achieve certain commercial goals. Where appropriate, standard specifications for tool steels, ASTM A600, A681, and A686, may be used as a basis for procurement. ASTM A600 sets forth standard requirements for tungsten and molybdenum high-speed steels; A681 applies to hot-work, cold-work, shock-resisting, special-purpose, and mold steels; and A686 covers water-hardening tool steels. In many instances, however, tool steels are purchased by tradename because the user has found that a particular tool steel from a certain producer gives better performance in a specific application than does a tool steel of the same AISI type classification purchased from another source.

## Wrought High-Speed Tool Steels

High-speed tool steels are so named primarily because of their ability to machine materials at high cutting speeds. They are complex iron-base alloys of carbon, chromium, vanadium, molybdenum, or tungsten, or combinations thereof, and, in some cases, substantial amounts of cobalt. The carbon and alloy contents are balanced at levels to give high attainable hardening response, high wear resistance, high resistance to the softening effect of heat, and good toughness for effective use in industrial cutting operations.

### *M and T Classification*

There are presently more than 40 classifications of high-speed tool steels, according to the American Iron and Steel Institute (AISI). When these are compounded by the number of domestic manufacturers, the total number of individual steels in the high-speed tool steels category exceeds 150.

The AISI established its own classification system for high-speed tool steels many years ago. It designates with a T those steels that have tungsten as one of their primary alloying elements and with an M those steels that have molybdenum additions as one of their primary alloying elements. A number follows either the M or the T (e.g., M1, M2, M41, T1, T15), but it has no significance other than to distinguish one high-speed tool steel from another. For example, M1 is not more highly alloyed than M2, or more hardenable, or more wear resistant and so on. Table 1 lists composition limits for M and T types.

## *Effects of Alloying Elements*

The T-series contains 12 to 20% W with chromium, vanadium, and cobalt as the other major alloying elements. The M-series contains approximately 3.5 to 10% Mo, with chromium, vanadium, tungsten, and cobalt as the other alloying elements. All types, whether molybdenum or tungsten, contain about 4% Cr; the carbon and vanadium contents vary. As a general rule, when the vanadium content is increased, the carbon content is usually increased (Ref 1).

Type T1 does not contain molybdenum or cobalt. Cobalt-base tungsten types range from T4 through T15 and contain from 5 to 12% Co.

Types M1 through M10 (except M6) contain no cobalt, but most contain some tungsten. The cobalt-base, molybdenum-tungsten, premium types are generally classified in the M30 and M40 series. Super high-speed steels normally range from M40 upward; they are capable of being heat treated to high hardnesses.

Compared to the T-type steels, the M-type steels generally have higher abrasion resistance, are less prone to distortion in heat treatment, and are less expensive (Ref 2). Tools made of high-speed tool steels can also be coated with titanium nitride, titanium carbide, and numerous other coatings by physical vapor deposition for improved performance and increased tool life.

Various elements are added to M- and T-type steels to impart certain properties. These elements and their effects are discussed in the following paragraphs.

**Carbon** is by far the most important of the elements and is very closely controlled. The carbon content of any one high-speed tool steel is usually fixed within narrow limits, but variations within these limits can cause important changes in the mechanical properties and the cutting ability. As the carbon concentration is increased, the working hardness rises, the elevated temperature hardness rises, and the number of hard, stable, complex carbides rises. The latter contribute much to the wear resistance and other properties of the high-speed tool steels.

**Silicon.** Up to about 1.00%, the influence of silicon on high-speed tool steels is slight. Increasing the silicon content from 0.15 to 0.45% gives a slight increase in maximum attainable tempered hardness and has some influence on carbide morphology, although there seems to be a concurrent slight decrease in toughness. Some manufacturers produce at least one grade with silicon up to 0.65%, but this level requires a lower maximum austenitizing temperature than a lower silicon level in the same grade, to prevent overheating. In general, the silicon content is kept below 0.45% on most grades.

**Manganese** concentration is generally not high in high-speed tool steels because of its marked effect in increasing brittleness and the danger of cracking upon quenching.

**Phosphorus** has no effect on any of the desired properties of high-speed tool steels. However, because of its well-known effect in causing cold shortness, or room-temperature brittleness, the concentration of phosphorus is kept to a minimum.

**Chromium** is always present in high-speed tool steels in amounts ranging from 3 to 5%. It is mainly responsible for the hardenability. Generally, the addition is 4%, because it appears that this concentration gives the best compromise between hardness and toughness. In addition, chromium reduces oxidation and scaling during heat treatment.

**Tungsten.** In the high-speed tool steels, tungsten is of vital importance. It is found in all T-type steels and in all but two of the M-type steels. The complex carbide of iron, tungsten, and carbon that is found in high-speed tool steels is very hard and significantly contributes to wear resistance. Tungsten improves hot hardness, causes secondary hardening, and imparts marked resistance to tempering. When the tungsten concentration is lowered in high-speed tool steels, molybdenum is usually added to make up for its loss.

**Molybdenum** forms the same double carbide with iron and carbon as tungsten does, but it has half the atomic weight of tungsten. As a consequence, molybdenum can be substituted for tungsten on the basis of approximately one part of molybdenum, by weight, for two parts of tungsten.

The melting point of M-type steels is somewhat lower than that of T-type steels, and they thus require a lower hardening temperature and have a narrower hardening range. The M-type steels are tougher than the T-type steels, but the hot hardness is slightly lower. Compensation for this reduced hot hardness is partially accomplished by the addition of tungsten (and, to a lesser extent, vanadium) to the plain molybdenum grades. This is one important reason for the popularity of the tungsten-molybdenum grades, such as M2, M3, and M4: they afford good hot hardness, which is so desirable in high-speed tool steels.

**Vanadium** was first added to high-speed tool steels as a scavenger to remove slag impurities and to reduce nitrogen levels in the melting operation. It was soon found that this element materially increases the cutting efficiency of tools. The addition of vanadium promotes the formation of very hard, stable carbides, which significantly increase wear resistance and, to a lesser extent, hot hardness. When properly balanced by carbon additions, an increase in vanadium has relatively little effect on the toughness. For this reason, vanadium-bearing grades are a very good choice when very fast cutting operations are demanded, as in finishing cuts, or when the surface of the material is hard and scaly.

Several specially developed steels with high vanadium additions have been developed for very severe service requiring high toughness, as well as exceptional hot hardness and wear resistance. The T15, M4, and M15 grades are in this category; their vanadium contents are 4.88, 4.13, and 5.00%, respectively.

**Cobalt.** The main effect of cobalt in high-speed tool steels is to increase the hot hardness (Fig. 1 and 2) and thus increase the cutting efficiency when high tool temperatures are attained during the cutting operation. Cobalt raises the heat-treating temperatures because it elevates the melting point. Hardening temperatures for cobalt high-speed tool steels can be 14 to 28 °C (25 to 50 °F) higher than would be normal for similar grades without cobalt. Cobalt additions slightly increase the brittleness of high-speed tool steels.

Cobalt steels are especially effective on rough or hogging cuts, but they are not usually suited to finishing cuts that do not involve high temperatures. They usually perform quite well for operations involving deep cuts and fast speeds, hard and scaly materials, or materials that have discontinuous chips, such as cast iron or nonferrous metals.

**Sulfur,** in normal concentrations of 0.03% or less, has no effect on the properties of high-speed tool steels. However, sulfur is added to certain high-speed tool steels to contribute free-machining qualities, as it does in low-alloy steels. The consumption of free-machining high-speed tool steels is a small but significant percentage of the total consumption of high-speed tool steels. One of the major applications for free-machining high-speed tool steels is in larger-diameter tools such as hobs, broaches, and so on.

Sulfur forms complex sulfides, containing chromium, vanadium, and manganese, that are distributed throughout the steel as stringer-type inclusions, interrupting the steel structure and acting as notches. These notches aid the metal-removing action of a cutting tool when a high-speed steel is machined, because the resulting chip is discontinuous, a characteristic of free-machining steels. Very high sulfur additions (up to 0.30%) are made to some P/M high-speed tool steels for improved machinability/ grindability by forming globular sulfides rather than stringers. (See the section “P/M High-Speed Tool Steels” in this article.)

**Nitrogen** is generally present in air-melted high-speed tool steels in amounts varying from approximately 0.02 to 0.03%. The nitrogen content of some high-speed tool steels is deliberately increased to about 0.04 to 0.05%. This addition, when combined with higher-than-usual amounts of silicon, results in a slight increase of maximum attainable tempered hardness and some change in carbide morphology.

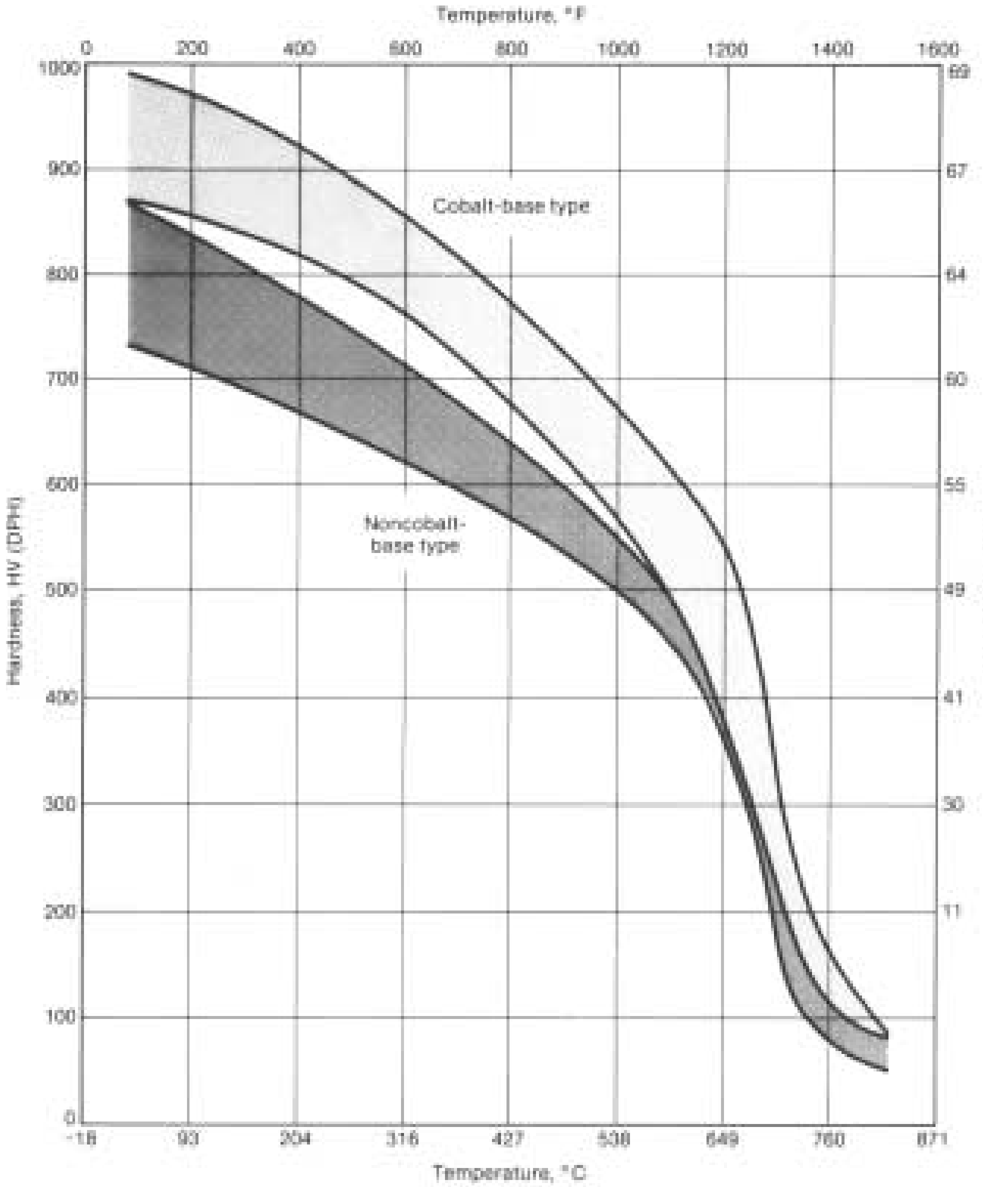



**Fig. 1** Comparison of the hot hardness of cobalt-bearing (M4, M33, M36, and T15)vs. that of noncobalt-bearing (M1, M2, M4, M7, and T1) high-speed tool steels

## *Effects of Alloying and Alloy Carbides on Wear Resistance*

Wear resistance of high-speed tool steels is affected by the matrix hardness and composition, precipitated $M_2C$ and MC carbides responsible for secondary hardness, the volume of excess alloy carbides, and the nature of these excess carbides. Table 2 lists the types of carbides, the crystal lattice types, and some characteristics of each of the various carbides found in tool steels. The wear resistance of tool steels increases with increasing carbide volume fraction and carbide hardness.

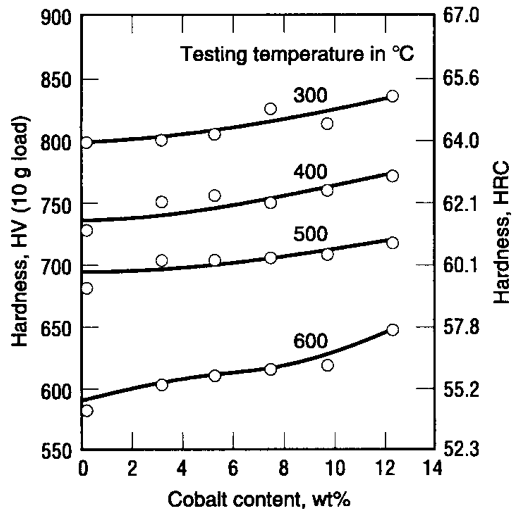



**Fig. 2** Effect of cobalt content on the hot hardness of T1 high-speed steel. Initial hardness of 66 HRC at different testing temperatures. Source: Ref 3

Figure 3 is a graphical comparison of the hardness of various alloy carbides relative to the hardness of martensite and cementite ($Fe_3C$), the carbide typically found in plain carbon and low-alloy carbon steels. As shown, the precipitated metal carbides such as MC and $M_2C$ attain very high hardness, and they contribute significant wear resistance to tool steels that are alloyed to contain large volume fractions of carbides. For example, high-speed tool steels may contain as much as 30 vol% of carbides, consisting of a mixture of MC, $M_{23}C_6$ and $M_6C$ (Ref 6).

In practically any given high-speed tool steels, wear resistance strongly depends on the hardness of the steel. Higher hardness, however achieved, is an aim when highly abrasive cutting conditions will be encountered.

For the ultimate in wear resistance, carbon content can be increased simultaneously with vanadium content, introducing a greater quantity of total carbide and a greater percentage of extremely hard vanadium carbide. Steels T15, M3 (class 2), M4, and M15 are in this category, and all have extremely high wear resistance.

**Table 2 Characteristics of alloy carbides found in tool steels**

| Type of carbide | Lattice type | Remarks |
|---|---|---|
| $M_3C$ | Orthorhombic | This is a carbide of the cementite ($Fe_3C$) type, M, maybe Fe, Mn, Cr with a little W, Mo, V. |
| $M_7C_3$ | Hexagonal | Mostly found in Cr alloy steels. Resistant to dissolution at higher temperatures. Hard and abrasion resistant. Found as a product of tempering high-speed steels. |
| $M_{23}C_6$ | Face-centered cubic | Present in high-Cr steels and all high-speed steels. The Cr can be replaced with Fe to yield carbides with W and Mo. |
| $M_6C$ | Face-centered cubic | Is a W- or Mo-rich carbide. May contain moderate amounts of Cr, V, Co. Present in all high-speed steels. Extremely abrasion resistant. |
| $M_2C$ | Hexagonal | W- or Mo-rich carbide of the $W_2C$ type. Appears after temper. Can dissolve a considerable amount of Cr. |
| MC | Face-centered cubic | V-rich carbide. Resists dissolution. Small amount that does dissolve reprecipitates on secondary hardening. |

Source: Ref 4

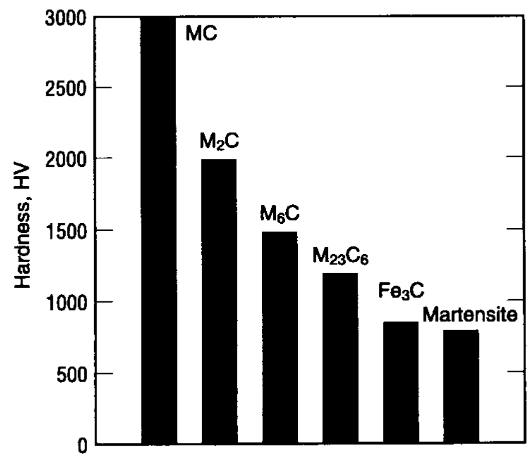



**Fig. 3** Relative hardness of alloy carbides, cementite, and martensite in high-speed steels. Source: Ref 5

## Wrought Hot-Work Tool Steels

Many manufacturing operations involve punching, shearing, or forming of metals at high temperatures. Hot-work steels (group H) have been developed to withstand the combinations of heat, pressure, and abrasion associated with such operations.

Group H tool steels usually have medium carbon contents (0.35 to 0.45%) and chromium, tungsten, molybdenum, and vanadium contents of 6 to 25%. These steels are divided into three subgroups: chromium hot-work steels (types H10 to H19), tungsten hot-work steels (types H21 to H26), and molybdenum hot-work steels (types H42 and H43). Composition limits for hot-work steels are listed in Table 1.

### *Effects of Alloying Elements*

**Chromium hot-work steels** (types H10 to H19) have good resistance to heat softening because of their medium chromium content and the addition of carbide-forming elements such as molybdenum, tungsten, and vanadium. The low carbon and low total alloy contents promote toughness at the normal working hardnesses of 40 to 55 HRC. Higher tungsten and molybdenum contents increase hot strength but slightly reduce toughness. Vanadium is added to increase resistance to washing (erosive wear) at high temperatures. An increase in silicon content improves oxidation resistance at temperatures up to 800 °C (1475 °F). The most widely used types in this group are H11, H12, H13, and, to a lesser extent, H19.

**Tungsten Hot-Work Steels.** The principal alloying elements of tungsten hot-work steels (types H21 to H26) are carbon, tungsten, chromium, and vanadium. The higher alloy contents of these steels make them more resistant to high-temperature softening and washing than H11 and H13 hot-work steels. However, high alloy content also makes them more prone to brittleness at normal working hardnesses (45 to 55 HRC) and makes it difficult for them to be safely water cooled in service.

**Molybdenum Hot-Work Steel.** There are only two active molybdenum hot-work steels: type H42 and type H43. These alloys contain molybdenum, chromium, vanadium, carbon, and varying amounts of tungsten. They are similar to tungsten hot-work steels, having almost identical characteristics and uses. Although their compositions resemble those of various molybdenum high-speed steels, they have a low carbon content and greater toughness. The principal advantage of types H42 and H43 over tungsten hot-work steels is their lower initial cost. They are more resistant to heat checking than are tungsten hot-work steels, but in common with all high-molybdenum steels, they require greater care in heat treatment, particularly with regard to decarburization and control of austenitizing temperature.

## Wrought Cold-Work Tool Steels

Cold-work tool steels, because they do not have the alloy content necessary to make them resistant to softening at elevated temperature, are restricted in application to those uses that do not involve prolonged or repeated heating above 205 to 260 °C (400 to 500 °F). There are three categories of cold-work steels: air-hardening steels, also called group A; high-carbon, high-chromium steels, also called group D; and oil-hardening steels, also called group O. Composition limits for cold-work steels are listed in Table 1.

### *Effects of Alloying Elements*

**Air-hardening, medium-alloy, cold-work steels** (group A) contain enough alloying elements to enable them to achieve full hardness in sections up to about 100 mm (4 in.) in diameter upon air cooling from the austenitizing temperature. (Type A6 through-hardens in sections as large as a cube 175 mm, or 7 in., on a side.) Because they are air hardening, group A tool steels exhibit minimum distortion and the highest safety (least tendency to crack) in hardening. Manganese, chromium, and molybdenum are the principal alloying elements used to provide this deep hardening. Types A2, A3, A7, A8, and A9 contain a high percentage of chromium (5%), which provides moderate resistance to softening at elevated temperatures.

Types A4, A6, and A10 are lower in chromium content (1%) and higher in manganese content (2%). They can be hardened from temperatures about 110 °C (200 °F) lower than those required for the high-chromium types, further reducing distortion and undesirable surface reactions during heat treatment.

To improve toughness, silicon is added to type A8, and both silicon and nickel are added to types A9 and A10. Because of the high carbon and silicon contents of type A10, graphite is formed in the microstructure. As a result, A10 has much better machinability in the annealed condition, and somewhat better resistance to galling and seizing in the fully hardened condition, than other group A tool steels.

Typical applications for group A tool steels include shear knives, punches, blanking and trimming dies, forming dies, and coining dies. The inherent dimensional stability of these steels makes them suitable for gages and precision measuring tools. In addition, the extreme abrasion resistance of type A7 makes it suitable for brick molds, ceramic molds, and other highly abrasive applications.

The complex chromium or chromium-vanadium carbides in group A tool steels enhance the wear resistance provided by the martensitic matrix. Therefore, these steels perform well under abrasive conditions at less than full hardness. Although cooling in still air is adequate for producing full hardness in most tools, massive sections should be hardened by cooling in an air blast or by interrupted quenching in hot oil.

**High-carbon, high-chromium, cold-work steels** (group D) contain 1.50 to 2.35% C and 12% Cr. With the exception of type D3, they also contain 1% Mo. All group D tool steels except type D3 are air hardening and attain full hardness when cooled in still air. Type D3 is almost always quenched in oil (small parts can be austenitized in vacuum and then gas quenched). Therefore, tools made of D3 are more susceptible to distortion and are more likely to crack during hardening.

Group D steels have high resistance to softening at elevated temperatures. These steels also exhibit excellent resistance to wear, especially type D7, which has the highest carbon and vanadium contents. All group D steels, particularly the higher-carbon types D3, D4, and D7, contain massive amounts of carbides, which make them susceptible to edge brittleness.

Typical applications of group D steels include long-run dies for blanking, forming, thread rolling, and deep drawing; dies for cutting laminations; brick molds; gages; burnishing tools; rolls; and shear and slitter knives.

**Oil-hardening cold-work steels** (group O) have high carbon contents, plus enough other alloying elements that small-to-moderate sections can attain full hardness when quenched in oil from the austenitizing temperature. Group O tool steels vary in type of alloy, as well as in alloy content, even though they are similar in general characteristics and are used for similar applications. Type O1 contains manganese, chromium, and tungsten. Type O2 is alloyed primarily with manganese. Type O6 contains silicon, manganese, and molybdenum. It has a high total carbon content that includes free carbon, as well as sufficient combined carbon to enable the steel to achieve maximum as-quenched hardness. Type O7 contains manganese and chromium and has a tungsten content higher than that of type O1.

The most important service-related property of group O steels is high resistance to wear at normal temperatures, a result of high carbon content. On the other hand, group O steels have a low resistance to softening at elevated temperatures.

The ability of group O steels to harden fully upon relatively slow quenching yields lower distortion and greater safety (less tendency to crack) in hardening than is characteristic of the water-hardening tool steels. Tools made from these steels can be successfully repaired or renovated by welding if proper procedures are followed. In addition, graphite in the microstructure of type O6 greatly improves the machinability of annealed stock and helps reduce galling and seizing of fully hardened steel.

Group O steels are used extensively in dies and punches for blanking, trimming, drawing, flanging, and forming. Surface hardnesses of 56 to 62 HRC, obtained through oil quenching followed by tempering at 175 to 315 °C (350 to 600 °F), provide a suitable combination of mechanical properties for most dies made from type O1, O2, or O6. Type O7 has lower hardenability but better general wear resistance than any other group O tool steel, and it is more often used for tools requiring keen cutting edges. Oil-hardening tool steels are also used for machinery components (e.g., cams, bushings, and guides) and for gages, where good dimensional stability and wear resistance properties are needed.

## Effects of Alloying on the Characteristics of Other Non-Machining Wrought Tool Steel Grades

In addition to the hot- and cold-work steels described previously, shock-resisting steels, low-alloy special-purpose steels, mold steels, and water-hardening steels are also used for non-machining applications. Table 1 lists composition limits for these steels.

**Shock-Resisting Steels.** The principal alloying elements in shock-resisting steels, also called group S steels, are manganese, silicon, chromium, tungsten, and molybdenum, in various combinations. Carbon content is about 0.50% for all group S steels, which produces a combination of high strength, high toughness, and low-to-medium wear resistance. Group S steels are used primarily for chisels, rivet sets, punches, driver bits, and other applications requiring high toughness and resistance to shock loading. Types S1 and S7 are also used for hot punching and shearing, which require some heat resistance.

**Low-alloy special-purpose steels,** also called group L steels, contain small amounts of chromium, vanadium, nickel, and molybdenum. At one time, seven steels were listed in this group, but because of falling demand, only types L2 and L6 remain. Type L2 is available in several carbon contents, from 0.50 to 1.10%. Its principal alloying elements are chromium and vanadium, which make it an oil-hardening steel of fine grain size. Type L6 contains small amounts of chromium and molybdenum, as well as 1.50% Ni for increased toughness. Group L steels are generally used for machine parts, such as arbors, cams, chucks, and collets, and for other special applications requiring good strength and toughness.

**Mold steels,** also called group P steels, contain chromium and nickel as principal alloying elements. Their low-carbon content facilitates mold impression by cold hubbing. Group P steels are used for low-temperature die casting dies and in molds for the injection of compression molding of plastics.

**Water-hardening** steels, also called group W steels, contain carbon as the principal alloying element. Small amounts of chromium are added to most of the group W steels to increase hardenability and wear resistance, and small amounts of vanadium are added to maintain fine grain size and thus enhance toughness. Group W tool steels are made with various nominal carbon contents (~0.60 to 1.40%); the most popular grades contain approximately 1.00% C.

Group W steels have low resistance to softening at elevated temperatures. They are suitable for cold heading, striking, coining, and embossing tools; woodworking tools; hard metal-cutting tools, such as taps and reamers; wear-resistant machine tool components; and cutlery.

## P/M High-Speed Tool Steels

Powder metallurgy tool steels used in the cutting tool industry are high-speed steel compositions capable of both achieving high room-temperature hardness for wear resistance (at least 64 HRC after heat treatment) and maintaining high hardness when exposed to the frictional heating encountered at the tool/workpiece interface during the cutting operation (commonly referred to as hot hardness or "red hardness").

### *Effects of Alloying and Alloy Carbides on Properties*

The relative performance of the P/M high-speed steels is strongly influenced by the alloy composition and heat treatment. The principal alloying elements found in varying amounts in high-speed steels are carbon, tungsten, molybdenum, vanadium, and cobalt. All high-speed steels also contain about 4% Cr to provide good hardenability in larger cross sections during heat treatment. Carbon is necessary for heat treat response, and it combines with the carbide-forming elements to form wear-resistant primary carbides. Tungsten and/or molybdenum are essential alloying elements for developing sufficient temper resistance to enable these materials to perform at high speeds in cutting operations. Both elements form wear-resistant $M_6C$ primary carbides that partially dissolve during heat treatment to provide a strong precipitation or "secondary" hardening response on tempering. In high molybdenum compositions (e.g., containing 9 to 10% Mo), it is also possible to form some $M_2C$ carbides. Recognizing that tungsten and molybdenum can often be used interchangeably for alloying on an atomic basis and that their atomic weights differ by a factor of two, the combined effects of tungsten and molybdenum are often compared by calculating a "tungsten equivalency" ($W_{eq}$) equal to the tungsten content plus twice the molybdenum content (W + 2 Mo). Vanadium also contributes to secondary hardening during heat treatment, but its main function is to form primary MC carbides for wear resistance. Niobium would be expected to have an effect similar to that of vanadium, but it is not a commonly used alloying element for high-speed steels. Cobalt does not form carbides in tool steels, but significantly contributes to the hot hardness and tempering resistance of the matrix in compositions containing 5 to 8% Co and higher.

Table 3 lists a number of the commonly recognized P/M high-speed steel compositions that are currently produced internationally. The table also includes the calculated $W_{eq}$ and the attainable hardness capability for each alloy. Some of the compositions listed are P/M modifications of traditional high-speed-steel grades (e.g., M3, M4, and T15) that are also produced conventionally. Notably absent from this table are the 1 to 2% V commodity high-speed steels such as M1, M2, M7, and M42. Although several of the latter materials have been periodically produced in P/M form for specialized applications, the general trend in the cutting tool industry has been to take advantage of the grindability and toughness properties resulting from P/M processing to upgrade to higher-performance higher-vanadium alloy compositions. Thus, the base alloy compositions listed are P/M M3 and P/M M4, which are essentially high-carbon and high-vanadium modifications of M2. With the exception of P/M M35 (M2 + 5 Co), the balance of the compositions listed are generally classified as "super-high-speed" steels, which have high attainable hardness capability (66 HRC minimum) and excellent temper resistance for a combination of good wear resistance and high red hardness properties.

**The wear resistance** of a P/M high-speed steel is determined by the heat treated hardness and by the amount and type (hardness) of primary carbide present in the heat treated microstructure. As discussed earlier, all

**Table 3 Nominal compositions of P/M high-speed steels**

| Tradename(s) | Designation: AISI | UNS | JIS | Werk. No. | Composition, wt%: C | W | Mo | V | Co | $W_{eq}$ | Hardness, HRC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Wear-resistant high-speed steels containing 3 to 4% V** | | | | | | | | | | | |
| ASP23, APM 23, CPM M3, Micromelt M3, FAX 31, DEX 20, KHA 32 | M3 | T11323 | SKH53 | 1.3344 | 1.3 | 6.25 | 5 | 3 | … | 16.25 | 65–67 |
| CPM M4, Micromelt M4, Isomatrix S690, HAP M4 | M4 | T11304 | SKH54 | … | 1.4 | 5.75 | 5 | 4 | … | 15.75 | 65–67 |
| **Heat-resistant and super-high-speed steels containing 5 to 12% Co and 2 to 6.5% V** | | | | | | | | | | | |
| CPM M35 | M35 | … | SKH 55 | 1.3243 | 1 | 6 | 5 | 2 | 5 | 16 | 65–67 |
| CPM Rex 54 | … | … | … | … | 1.5 | 5.75 | 5 | 4 | 5 | 15.75 | 66–68 |
| ASP30, APM30, CPM Rex 45, Micromelt HS 30, Isomatrix S790, FAX 38, DEX 40, HAP 40, KHA 30 | … | … | … | … | 1.3 | 6.25 | 5 | 3 | 8 | 16.25 | 66–68 |
| CPM T15, Micromelt T15, FAX 55, DEX 61, HAPT15, KHA 50 | T15 | T12015 | SKH10 | 1.3202 | 1.6 | 12 | … | 5 | 5 | 12 | 66–68 |
| CPM Rex 76, Micromelt HS 76 | M48 | T11348 | … | … | 1.5 | 10 | 5.25 | 3 | 8.5 | 20.5 | 67–69 |
| HAP 50, DEX 62 | … | … | … | … | 1.5 | 8 | 6 | 4 | 8 | 20 | 67–69 |
| Isomatrix S390 | … | … | … | … | 1.6 | 11 | 2 | 5 | 8 | 15 | 66–68 |
| ASP60, APM60, KHA 60 | … | … | … | 1.3241 | 2.3 | 6.5 | 7 | 6.5 | 10.5 | 20.5 | 67–69 |
| DEX 80 | … | … | … | … | 2.1 | 14 | 6 | 5.5 | 12 | 26 | 68–70 |
| HAP 70 | … | … | … | … | 2.2 | 12 | 9 | 5 | 12 | 30 | 69–71 |
| **Cobalt-free super-high-speed steels** | | | | | | | | | | | |
| CPM Rex 20 | M62 | T11362 | … | … | 1.3 | 6.25 | 10.5 | 2 | … | 27.25 | 66–68 |
| CPM Rex 25 | M61 | T11361 | … | … | 1.8 | 12.5 | 6.5 | 5 | … | 25.5 | 67–69 |

Note: All of the P/M high-speed steels contain about 4% Cr for hardenability in large sections. Silicon, manganese, and sulfur contents are typically 0.50%, 0.30%, and 0.03% maximum, respectively. For select applications requiring improved machinability, sulfur contents are increased to 0.10 or 0.22% with corresponding increases in the manganese contents.

of the P/M high-speed steels contain significant amounts of tungsten and/or molybdenum as well as vanadium, which combine with carbon to form tungsten or molybdenum-rich $M_6C$ (occasionally some $M_2C$) and vanadium-rich MC primary carbides, respectively. The approximate microhardnesses of these complex carbides, as well as the chromium-rich $M_7C_3$-type primary carbide found in some cold-work die steels, which are discussed later, are given in Table 4. It follows that for a given heat treated hardness and a similar total primary carbide volume fraction, a high-speed steel with a higher percentage of the harder vanadium-rich (or niobium-rich) MC carbide exhibits better wear resistance. It is therefore very often possible to rank the P/M high-speed steels in Table 3 in order of increasing wear resistance by simply looking at the relative vanadium contents. Thus, the P/M high speed steels with 4% V generally outwear P/M or con-

**Table 4 Microhardness of primary carbides in P/M tool steels**

| Carbide type | Knoop hardness |
|---|---|
| M(V,Nb)C | 2200–2800 |
| $M(W,Mo)_6C$ | 1550–1750 |
| $M(Cr)_7C_3$ | 1300–1600 |

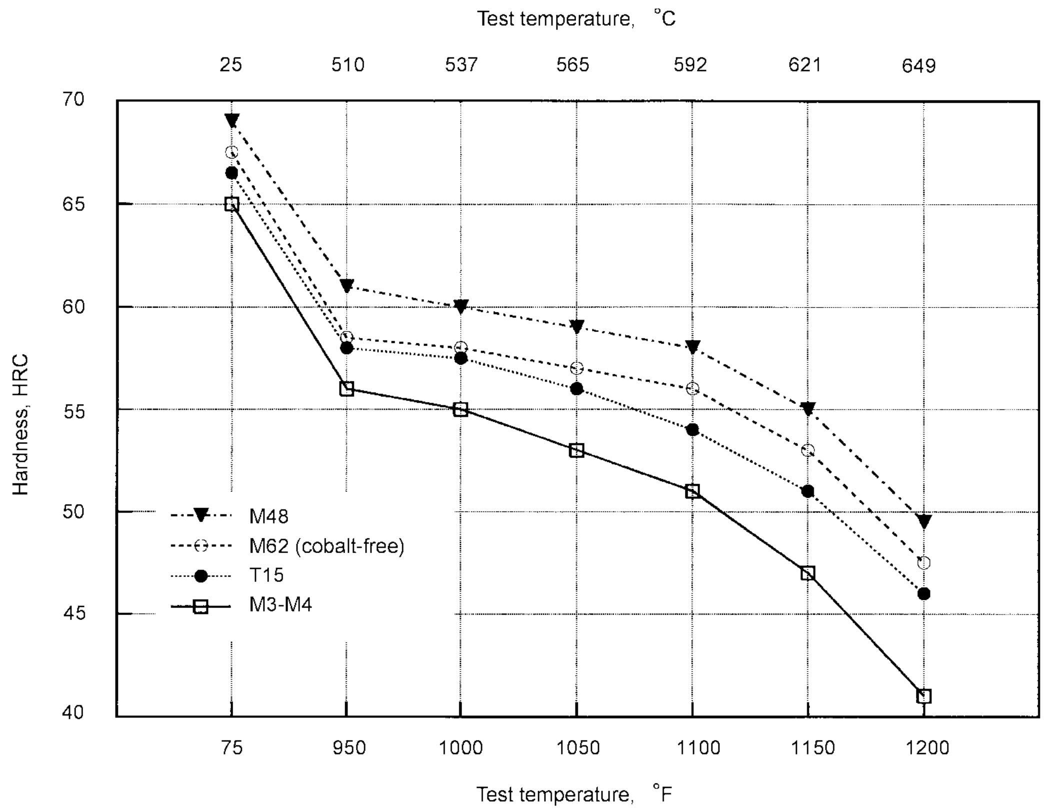



**Fig. 4** Hot hardness of P/M high-speed steels

ventional high-speed steels with 2 to 3% V, and steels with 5 to 6% V generally outwear the materials with 4% V. Exceptions to this vanadium content "rule of thumb" are special cases where the alloying results in a significant increase in the total volume fraction of primary carbides as well as the attainable hardness capability. An example of the latter is P/M M48 (1.5C-10W-5Mo-3V-8.5Co), which contains about 33% total alloy content. This material is capable of attaining 67 to 69 HRC and also has a significantly greater volume fraction of primary carbides than the lower alloyed P/M M3, P/M M4, and P/M M3 + 8Co grades. Other exceptions to this rule are the cobalt-free P/M super high-speed steels, which by design also have significantly increased volume fractions of the $M_6C$ primary carbide compared to the cobalt-bearing materials they were designed to replace. These materials are discussed in a later section.

**The red hardness** characteristic of a high-speed steel is dependent on the effect of alloying on the initial attainable hardness as well as on resistance to softening as the tempering or exposure temperature is increased. A measure of the relative red hardness capability is laboratory hot hardness, which is shown in Fig. 4 for a number of the P/M high-speed steels. Note that the materials that exhibit higher initial attainable hardness also exhibit higher hot hardness as the testing temperature is increased. These same materials also exhibit greater resistance to tempering during heat treatment.

**Cobalt-Free High-Speed Steels.** A unique class of materials are the cobalt-free P/M super-high-speed steels that were first developed by the Crucible Materials Corporation in the late 1970s in direct response to a serious curtailment in the worldwide availability of cobalt raw materials. P/M M61 (1.8C-12.5W-6.5Mo-5V) and P/M M62 (1.3C-6.25W-10.5Mo-2V) were simultaneously designed as cobalt-free substitutes for T15 (1.5C-12W-5V-5Co) and M42 (1.1C-1.5W-9.5Mo-1V-8Co), which have historically been two of the more important cobalt-bearing cutting tool materials used in the aerospace industry and elsewhere. Replacing the solid-solution effects of cobalt on heat treating response and elevated-temperature properties was accomplished primarily by alloying with tungsten and/or molybdenum to form a significantly greater number of alloy carbides in the annealed microstructure, which partially dissolve during austenitizing for heat treatment to provide a strong secondary or precipitation hardening response on tempering. Thus, the P/M M61 composition with a $W_{eq}$ = 25.5 and no cobalt has heat treat response and temper-resistance characteristics comparable to T15 with 5% Co, and also better wear resistance due to a greater volume fraction of primary carbides in the heat treated microstructure. Similarly, the P/M M62 composition with a $W_{eq}$ = 27.25 and no cobalt has about the same attainable hardness, somewhat better temper resistance, and significantly better wear resistance compared to M42 with 8% Co. These highly alloyed cobalt-free compositions could not be economically produced or fabricated into tools without the benefits of P/M processing.

**Property Comparisons.** The relative effects of attainable hardness, vanadium carbide content, and total alloying on the properties of the P/M high-speed steels are summarized in the qualitative comparison chart shown in Fig. 5. As illustrated in the graph, red hardness increases as the total alloy content and corresponding attainable hardness capability increase. Wear resistance also generally increases with total alloy content and attainable hardness, but the most wear-resistant materials in each classification of high-speed steels are the higher vanadium compositions, for example, P/M M4 and P/M T15. The graph also shows that as the alloy content increases, the relative toughness decreases. The generally improved toughness of the P/M materials compared to conventionally produced high-speed steels often enables upgrading without serious concerns about the actual toughness in service.

## P/M Cold-Work Tool Steels

**Effects of Alloying and Alloy Carbides.** Several of the international tool steel producers have also taken advantage of P/M processing to develop new cold-work tooling materials alloyed primarily with high vanadium to maximize wear resistance. The first such material designed specifical-

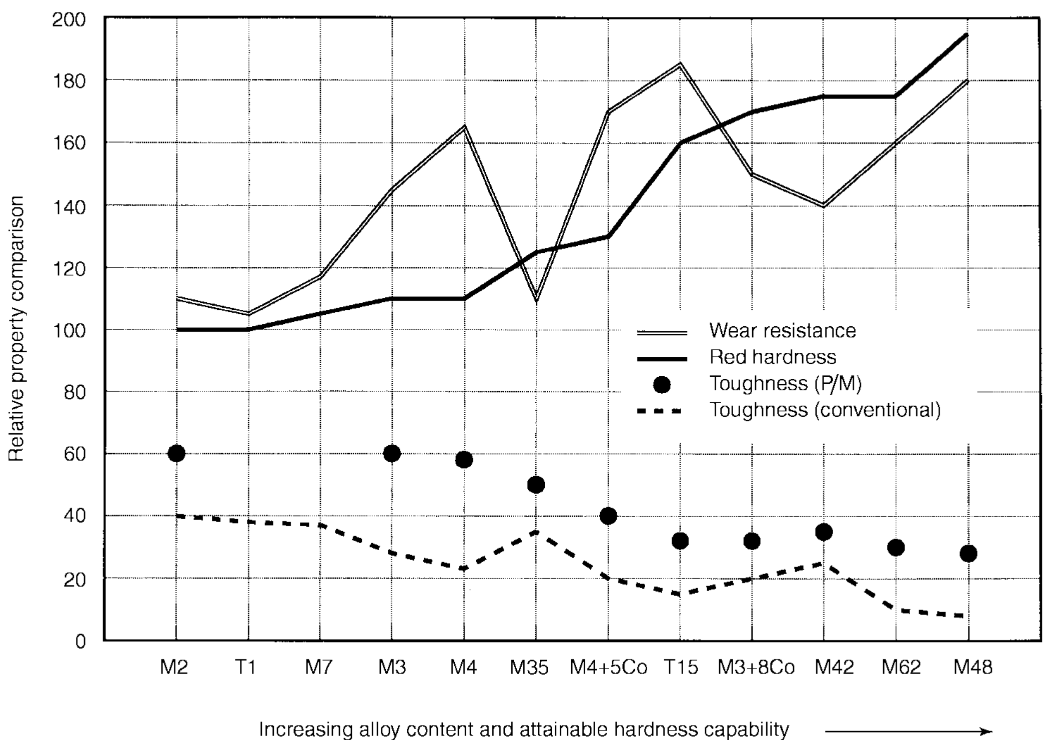



**Fig. 5** Graphical comparison of high-speed steel properties

ly for high-performance wear applications was Crucible particle metallurgy CPM 10V (hereafter referred to as P/M 10V), which was introduced commercially in 1978. Also developed at about the same time was a lower-matrix carbon and slightly lower vanadium modification of P/M 10V, called CPM 9V (hereafter referred to as P/M 9V), which has lower attainable hardness but better toughness than P/M 10V and can also be used in warm-working applications requiring resistance to heat checking. More recent P/M tool steel development work has focused on the following: (a) even more wear-resistant ultrahigh vanadium compositions containing 15 to 18% V with up to 30% by volume of primary MC-type carbides, (b) low-to-intermediate carbide volume fraction materials moderately alloyed with vanadium and chromium to optimize the toughness properties while still maintaining good wear resistance, and (c) high-vanadium high-chromium compositions for wear applications that also require good corrosion resistance. The wear/corrosion-resistant P/M tool steels are discussed in a later section.

Table 5 lists the nominal compositions for several of the commercially available P/M cold-work tool steels as well as the P/M M4 high-speed steel discussed previously. Also included are the compositions of conventionally produced A2, D2, and D7 cold-work tool steels. With the exception of P/M 9V, all of the tool steels listed in the table are capable of attaining 58 to 62 HRC during heat treatment, which is the typical application hardness range for cold-work tooling.

**Table 5 Nominal compositions of P/M cold-work tool steels**

| Steel | AISI designation | Commercial equivalent | Composition, wt% | | | | |
|---|---|---|---|---|---|---|---|
| | | | C | Cr | Mo | W | V |
| **P/M cold-work tool steels** | | | | | | | |
| P/M 3V | … | CPM 3V | 0.80 | 7.50 | 1.00 | … | 2.75 |
| P/M M4 | M4 | CPM M4HC | 1.40 | 4.00 | 5.25 | 5.75 | 4.00 |
| P/M 8Cr4V | … | Vanadis 4 | 1.50 | 8.00 | 1.00 | … | 4.00 |
| P/M 12Cr4V | D2 | K190 P/M | 2.30 | 12.00 | 1.00 | … | 4.00 |
| P/M 9V | … | CPM 9V | 1.80 | 5.25 | 1.30 | … | 9.00 |
| P/M 10V | A11 | CPM 10V | 2.45 | 5.25 | 1.30 | … | 9.75 |
| P/M 8Cr10V | … | Vanadis 10 | 2.90 | 8.00 | 1.50 | … | 9.80 |
| P/M 15V | … | CPM 15V | 3.50 | 5.25 | 1.30 | … | 14.50 |
| P/M 18V | … | CPM 18V | 3.90 | 5.25 | 1.30 | … | 17.50 |
| **Conventionally produced (ingot-cast) cold-work tool steels** | | | | | | | |
| A2 | A2 | … | 1.00 | 5.25 | 1.15 | … | 0.30 |
| D2 | D2 | … | 1.55 | 11.50 | 0.80 | … | 0.90 |
| D7 | D7 | … | 2.35 | 12.00 | 1.00 | … | 4.00 |

For a given hardness, the relative wear resistance of both the P/M and conventional cold-work tool steels is a function of the amount and type (hardness) of primary carbide present in the heat treated microstructure. Carbide size is only a factor under abrasive wear conditions and generally only applies to conventionally produced tool steels that have inherently coarser carbide size compared to the P/M tool steels. Table 6 shows the results of SEM and image analysis of the primary carbides observed in heat treated samples of the alloys listed in Table 5. The total volume percent of primary carbides ranges from approximately 5% in P/M 3V to

**Table 6 SEM image analysis of the primary carbides in P/M cold-work tool steels**

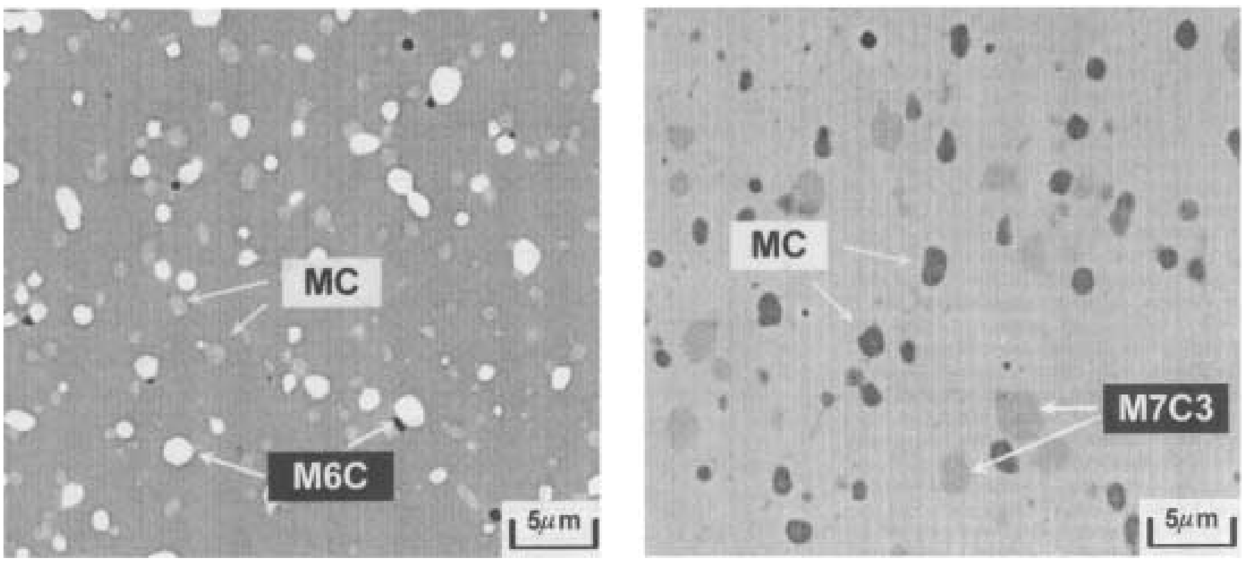
| Steel | Heat treatment | Hardness, HRC | Carbide content, vol% | | | |
|---|---|---|---|---|---|---|
| | | | MC | $M_7C_3$ | $M_6C$ | Total |
| **P/M cold-work tool steels** | | | | | | |
| P/M 3V | 1121 °C (2050 °F)/30 min + air cool + 524 °C (975 °F) temper (3 × 2h) | 60 | 4.7 | 0.4 | … | 5.1 |
| P/M M4 | 1163 °C (2125 °F)/4 min + oil quench + 565 °C (1050 °F) temper (3 × 2h) | 62 | 3.8 | … | 8.8 | 12.6 |
| P/M 8Cr4V | 1021 °C (1870 °F)/30 min + air cool + 524 °C (975 °F) temper (2 × 2h) | 60 | 6.6 | 5.7 | … | 12.3 |
| P/M 12Cr4V | 1121 °C (2050 °F)/30 min + oil quench + 260 °C (500 °F) temper (2 × 2h) | 59 | 3 | 20 | … | 23 |
| P/M 9V | 1121 °C (2050 °F)/30 min + air cool + 565 °C (1050 °F) temper (2 × h) | 54 | 14.4 | … | … | 14.4 |
| P/M 10V | 1121 °C (2050 °F)/30 min + oil quench + 552 °C (1025 °F) temper (2 × 2h) | 61 | 17.4 | … | … | 17.4 |
| P/M 8Cr10V | 1060 °C (1940 °F)/30 min + air cool + 552 °C (1025 °F) temper (2 × 2h) | 60 | 13 | 14 | … | 27 |
| P/M 15V | 1177 °C (2150 °F)/10 min + oil quench + 552 °C (1025 °F) temper (3 × 2h) | 62 | 22.7 | … | … | 22.7 |
| P/M 18V | 1121 °C (2050 °F)/30 min + oil quench + 552 °C (1025 °F) temper (2 × 2h) | 62 | 30.5 | … | … | 30.5 |
| **Conventionally ingot cast cold-work tool steels** | | | | | | |
| A1 | Not reported | 60 | … | 6 | … | 6 |
| D2 | Not reported | 61 | … | 15.5 | … | 15.5 |
| D7 | Not reported | 61 | 3 | 21 | … | 24 |

30% in P/M 18V. The relative percentages of the primary carbide types present (MC, $M_6C$, $M_7C_3$) vary according to the alloying balance, with only P/M 3V, P/M 9V, P/M 10V, P/M 15V, and P/M 18V having essentially all MC carbides. Although P/M M4 and P/M 8Cr4V have similar vanadium contents and total carbide volumes (about 12.5%), about two-thirds of the carbides in P/M M4 are $M_6C$ and about half the carbides in P/M 8Cr4V are $M_7C_3$-type. These microstructural differences are illustrated in the photomicrographs in Fig. 6, where it can be seen that the various carbide types exhibit characteristically different electronic imaging in the SEM. Figure 7 shows a similar SEM metallographic comparison between P/M 12Cr4V and P/M 15V both of which contain about 23% total primary carbide volume. Whereas P/M 15V contains all vanadium-rich MC-type carbides, P/M 12Cr4V has predominantly $M_7C_3$-type due to the high chromium content. Table 6 also lists the approximate total primary carbide volumes for conventionally produced A2, D2, and D7. With less than 1% V, A2 and D2 tool steels contain predominantly $M_7C_3$-type primary carbides. Conventional D7 has essentially the same alloy composition as P/M 12Cr4V and very similar carbide volumes as determined by SEM analysis. More detailed information on the influence of carbide content and total primary carbide volume on the wear resistance of P/M cold-work tool steels can be found in Ref 7.

## P/M Wear/Corrosion-Resistant Tool Steels

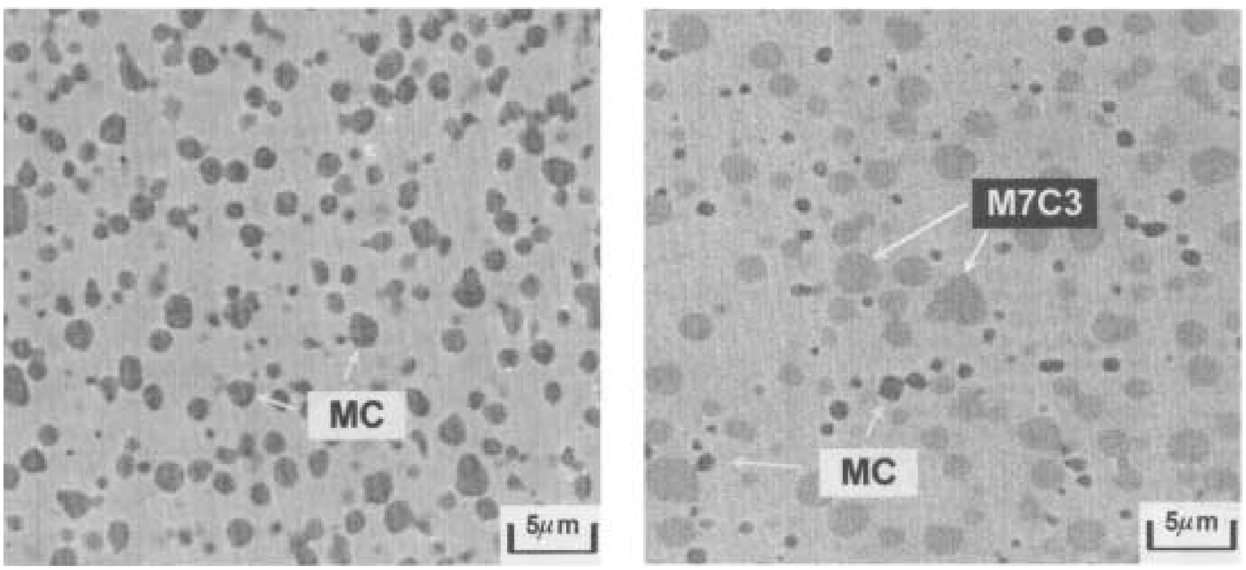
**Effects of Alloying and Alloy Carbides.** A number of high-performance wear/corrosion-resistant P/M tool steels have been developed containing the following: (a) significant amounts of vanadium and chromium to form wear-resistant primary carbides, (b) a minimum of 11% matrix Cr after heat treatment to provide increased corrosion resistance compared to the P/M tool steels containing 5 to 8% total Cr, and (c) an optimal level of carbon and/or nitrogen to form the wear-resistant carbides and to achieve a minimum of 56 to 58 HRC after heat treatment without forming excessive amounts of retained austenite or precipitating additional chromium-rich carbides, which would lower the desired matrix chromium. These materials usually also contain a minimum of 1% Mo to improve hardenability and resistance to pitting corrosion.

Table 7 lists the nominal compositions of several commercially available P/M wear/corrosion-resistant tool steel grades along with the compositions of conventionally produced T440C stainless steel and D2 tool steel. As shown, the P/M wear/corrosion-resistant materials have total chromium contents ranging from about 14 to 24%, vanadium contents ranging from about 3 to 15%, molybdenum contents ranging from about




(a) (b)

**Fig. 6** Primary carbides in (a) heat treated P/M M4 and (b) P/M 8Cr4V wear-resistant tool steels containing approximately 12.5% total carbide volume




(a) (b)

**Fig. 7** Primary carbides in (a) heat treated P/M 15V and (b) P/M 12Cr4V wear-resistant tool steels containing approximately 23% total carbide volume

**Table 7 Nominal compositions of wear/corrosion-resistant tool steels**

| Steel | Commercial equivalent | Composition, wt % | | | | |
|---|---|---|---|---|---|---|
| | | C | Cr | V | Mo | Other |
| **P/M steels** | | | | | | |
| P/M 14Cr-9V | CPM 420V (9V) | 2.30 | 14 | 9 | 1 | … |
| P/M 14Cr-12V | CPM 420V (12V) | 2.85 | 14 | 12 | 1 | … |
| P/M 14Cr-15V | CPM 420V (15V) | 3.25 | 14 | 14.5 | 1 | … |
| P/M 17Cr-6V | CPM 440VM | 1.90 | 17 | 6 | 1 | … |
| P/M 17Cr-3V | Elmax P/M | 1.70 | 17 | 3 | 1 | … |
| P/M 20Cr-4V | Isomatrix M390 | 1.90 | 20 | 4 | 1 | 0.60%W |
| P/M 24Cr-9V | Supracor | 3.75 | 24 | 9 | 3 | … |
| **Conventional steel** | | | | | | |
| T440C | … | 1.05 | 17 | … | 0.5 | … |
| D2 | … | 1.55 | 11.5 | 0.8 | … | … |

1 to 3%, and carbon contents ranging from about 1.7 to 3.75%. The relative wear and corrosion resistance of these materials is strongly influenced by the partitioning of the alloying elements between the matrix and the primary carbides during solidification from the melt, by the volume fraction of primary carbides, and by heat treatment (Ref 7).

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