NICKEL ALLOY TOOL STEELS

A PRACTICAL GUIDE TO THE USE OF NICKEL-CONTAINING ALLOYS

Nº 472

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The Nickel Institute republished the handbook in 2021. Despite the age of this publication the information herein is considered to be generally valid.

Nickel Institute

communications@nickelinstitute.org
www.nickelinstitute.org

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Location of Data

[a] Three systems of classification are used for the nickel alloy tool steels:
- AISI method, "Tool Steels," 1963.[1]
- ASM designations for tool steels.[2]
- Nominal alloy content in weight per cent.

[b] Molybdenum (0.15 per cent) is optional.

[c] Molybdenum (0.25 per cent) and vanadium (0.30 per cent) are optional.

Nickel Alloy Tool Steels

INTRODUCTION

This bulletin is confined to the discussion of steel compositions developed primarily for tool and die purposes; that is, the cutting and shaping of other metallic and nonmetallic materials. It should be recognized that tools may be manufactured from steels developed primarily for other applications, and conversely, that sometimes tool steel compositions may be applied for mechanical or constructional purposes.

Approximately 180 tool steel compositions are manufactured in the United States. Most of these compositions can be classified according to the system designed by the American Iron and Steel Institute (AISI)[1] or designations used by American Society for Metals (ASM).[2] Table I shows the compositions, heat treatments, and characteristics of the nickel-containing tool steels listed by AISI.* Table II lists the compo-

* The AISI method of identification and type classification of tool steels was designed to follow the most commonly used and generally accepted terminology of tool steel types or classes. It includes such basic principles as method of quenching, applications, special characteristics, steels for particular industries, etc.

TABLE I

Identifying Compositions, Treatments and Properties of AISI Tool Steels Containing Nickel[a]

AISI TOOL STEEL DESIGNATIONS	A9	A10	L6	P2	P3	P6	P21
COMPOSITION							
Carbon, %	0.50	1.35	0.70	.07	0.10	0.10	0.20
Manganese, %	—	1.80	—	—	—	—	—
Silicon, %	—	1.25	—	—	—	—	—
Nickel, %	1.50	1.80	1.50	0.50	1.25	3.50	4.00
Chromium, %	5.00	—	0.75	2.00	0.60	1.50	—
Molybdenum, %	1.40	1.50	0.25[b]	0.20	—	—	—
Vanadium, %	1.00	—	—	—	—	—	—
Aluminum, %	—	—	—	—	—	—	1.20
TREATMENTS							
Forging							
Start Forging at, F	1950-2100	1800-1925	1800-2000	1850-2050	1850-2050	1950-2150	2000-2100
Do not Forge below, F	1700	1600	1550	1550	—	1700	1750
Normalizing, F[c]	Not required	1450	1600	Not required	Not required	Not required	1650
Annealing[d]	—	—	—	—	—	—	Not required
Temperature, F	1550-1600	1410-1460	1400-1450	1350-1500	1350-1500	1550	—
Rate of Cooling, °F max/hr	25	15	50	50	Slowly in furnace	30	—
Brinell Hardness (approx)	212-218	235-269	182-212	103-123	109-137	207	—
Hardening	—	—	—	—	—	—	Solution treat[e]
Rate of Heating	Slowly	Slowly	Slowly	—	—	—	Slowly
Carburizing Temperature, F	—	—	—	1650-1700	1650-1700	1650-1700	—
Preheat Temperature, F	1450	1200	—	—	—	—	Do not preheat
Hardening Temperature, F	1800-1875	1450-1500	1450-1550	1525-1550[f]	1475-1525[f]	1450-1500[f]	—
Solution Temperature, F	—	—	—	—	—	—	1300-1350
Time at Temperature, min	20-45	30-60	10-30	15	15	15	60-180
Quenching Medium	Air	Air	Oil	Oil	Oil	Oil	Air or Oil
Tempering Temperature, F	950-1150	350-800	300-1000	300-500	300-500	300-450	—
Aging Temperature, F	—	—	—	—	—	—	950-1025
Rockwell Hardness (approx)	56-35	62-55	62-45	64-58[g]	64-58[g]	61-58[g]	40-30
PROPERTIES							
Depth of Hardening	Deep	Deep	Medium	Shallow	Shallow	Deep	Deep
Nondeforming Properties	Very Good	Very Good	Good	Good	Good	Good	Very Good
Safety in Hardening	Very Good	Very Good	Good	Good	Good	Good	Very Good
Toughness	Good	Fair	Very Good	Good	Good	Good	Fair
Resistance to Softening on Heating	Good	Fair	Poor	Poor	Poor	Fair	Fair
Wear Resistance	Good	Good	Fair	Good	Good	Good	Fair
Machinability	Fair	Good	Fair	Good	Fair	Fair	Fair
Resistance to Decarburization	Fair	Good	Good	Good	Good	Good	Good

[a] American Iron and Steel Institute.[1] Percentages listed are only for identification and are not the means of the composition ranges of the elements. Steels of the same type may differ in mean analysis and may contain elements not listed.

[b] At producer's option.

[c] Length of time steel is held, after being uniformly heated at the normalizing temperature, varies from about 15 min for small sections to 1 hr for large sizes. Steel is cooled in still air.

[d] Annealing temperature is given as a range, the upper limit should be used for large sections and the lower limit for smaller sections. The holding time, after uniform heating at the annealing temperature, varies from about 1 hr for light sections to about 4 hr for heavy sections.

[e] This entry applies to a precipitation hardening steel having a thermal treatment which involves solution treating and aging rather than hardening and tempering.

[f] After carburizing.

[g] Carburized case hardness.

TABLE II

Identifying Composition of ASM Tool Steels Containing Nickel[a]

Tool Steel Designations	Composition, %						
	C	Mn	Si	Ni	Cr	Mo	V
ASM 6F2	0.55	0.75	0.25	1.00	1.00	0.30	0.10[b]
ASM 6F3	0.55	0.60	0.85	1.80	1.00	0.75	0.10[b]
ASM 6F4	0.20	0.70	0.25	3.00	—	3.35	—
ASM 6F5	0.55	1.00	1.00	2.70	0.50	0.50	0.10
ASM 6F7	0.40	0.35	—	4.25	1.50	0.75	—

a American Society for Metals.[2]
b Optional element.

sition of the nickel-containing tool steels designated by ASM. In addition to the basic AISI classes and ASM designations, a number of other nickel-containing grades have been developed for special applications and these are identified in this bulletin by nominal alloy content in weight per cent, such as 2 nickel-0.9 chromium-0.7 molybdenum.

HOT WORK TOOL STEELS

The compositions of 11 nickel-containing grades of hot work tool and die steels are given in Table III. The principal characteristics sought in these grades are improved resistance to softening, cracking, thermal fatigue (heat checking) and wear, when used to make dies for forging materials in the 1100 to 2400 F temperature range. Table IV shows the resistance of six of these grades to softening and Tables V and VI provide some mechanical property data on two of the grades. Figures 1 to 6 furnish additional data on hardness and mechanical properties.

Applications of these steels comprise a wide range of dies and other components for hot forging metals, including die blocks, extrusion dies, hot cut-off tools, hot heading punches, and points for piercing nonferrous billets for tubing.

Die block applications comprise the largest single use of the nickel-containing hot work tool steels. About 1920 alloy hot work tool steels began to replace the carbon hot work tool steels. Because of the low hardenability of the carbon steels, it was necessary to cut the die impression into the die face to provide relatively thin sections before quenching and tempering, this naturally produced much cracking. On the other hand, the alloy tool steels had enough hardenability to allow the die block to be quenched and tempered before machining the die impression.[3]

For general drop forging work where maximum wear resistance and die life are not essential, low-alloy steels such as those comprising the first three in Table III normally are used.[3,4] Their relatively low hardenability limits their use in large sections. During heat treatment, quenching produces martensitic structures to a relatively shallow depth, whereas the center transforms to bainite. Hardness and mechanical property data for a representative member of this group, the 0.5 nickel-1 chromium-0.4 molybdenum-.03 vanadium steel, are given in Table IV and Figure 1. Its short-time elevated temperature tensile properties are presented in Table V.

Increasing the alloy content produced the three compositions with 1.8 to 2.7 per cent nickel, labeled "Intermediate Hardening in Large Sections" in Table III. They have improved mechanical properties throughout a die block and usually are recommended

TABLE III

Representative Compositions of Nickel-Containing Hot Work Tool Steels

Steel Type	Composition, %							
	C	Mn	Si	Ni	Cr	Mo	V	W
Shallow Hardening in Large Sections								
0.5 Ni-1 Cr-0.4 Mo-.03 V	0.55	0.80	0.25	0.53	1.00	0.43	.03	—
ASM 6F2	0.55	0.75	0.25	1.00	1.00	0.30	0.10[a]	—
1.5 Ni-0.95 Cr-0.30 Mo-.08 V	0.55	0.55	0.25	1.50	0.95	0.30	.08	—
Intermediate Hardening in Large Sections								
ASM 6F3	0.55	0.60	0.85	1.80	1.00	0.75	0.10[a]	—
2 Ni-0.9 Cr-0.7 Mo	0.55	0.60	0.60	2.10	0.88	0.73	—	—
2.7 Ni-1.4 Cr-0.6 Mo-0.2 V	0.43	0.70	0.43	2.65	1.40	0.55	0.18	—
Deep Hardening in Large Sections								
AISI A9	0.50	0.40	1.00	1.50	5.00	1.40	1.00	—
4.3 Ni-1.4 Cr-0.8 Mo-0.15 V[b]	0.45	0.45	0.60	4.30	1.45	0.75	0.14	—
Tungsten Steels								
1.8 Ni-2.8 Cr-10 W	0.30	0.30	0.30	1.75	2.75	0.25[a]	0.30[a]	10.0
2.5 Ni-4 Cr-2 Mo-14 W	0.35	0.30	0.30	2.50	4.00	2.00	—	14.0
Age-Hardening Steel								
ASM 6F4	0.21	0.70	0.25	3.00	—	3.35	.08[a]	—

a Optional element.
b Close to ASM 6F7.

for applications too severe for the 0.5 to 1.5 per cent nickel steels.[3] The effect of quenching and tempering on the hardness of relatively large sections of two of these steels is shown in Table IV.

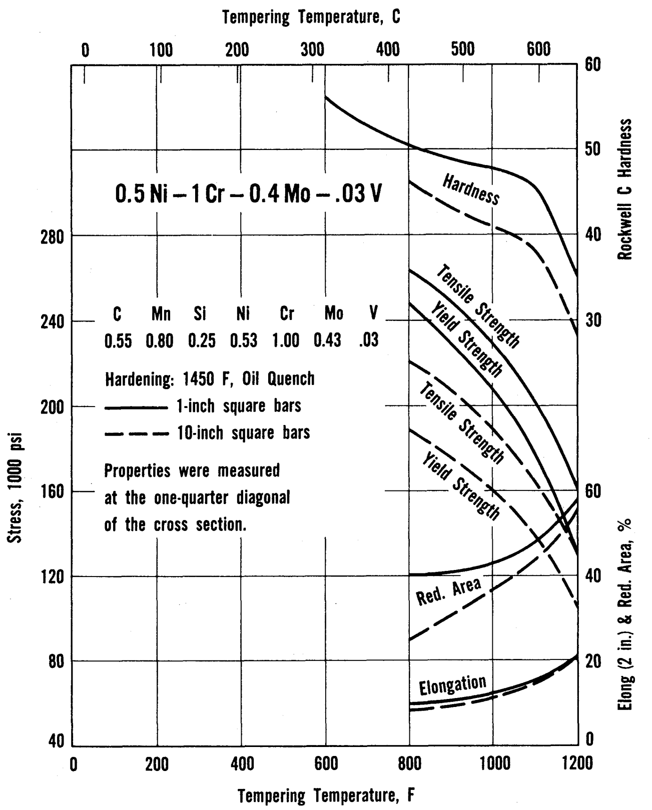

Fig. 1. Effect of tempering on the longitudinal tensile properties of 0.5 nickel-1 chromium-0.4 molybdenum-.03 vanadium hot work tool steel. Heppenstall Company.

In response to the need for even higher hardenability to produce dies stronger and/or tougher than those discussed in the two preceding paragraphs, the AISI A9 and the 4.3 nickel-1.4 chromium-0.8 molybdenum-0.15 vanadium steels of Table III were developed. These grades can be used at high hardnesses and strengths, particularly because they retain strength at high die temperatures. Their resistance to softening on tempering is shown in Table IV. Data on the effect of tempering on the hardness and tensile properties of the AISI A9 steel are presented in Figures 2 and 3. Table V provides short-time elevated temperature tensile properties and Table VI gives some impact data, both on the 4.3 nickel-1.4 chromium-0.8 molybdenum-0.15 vanadium steel.

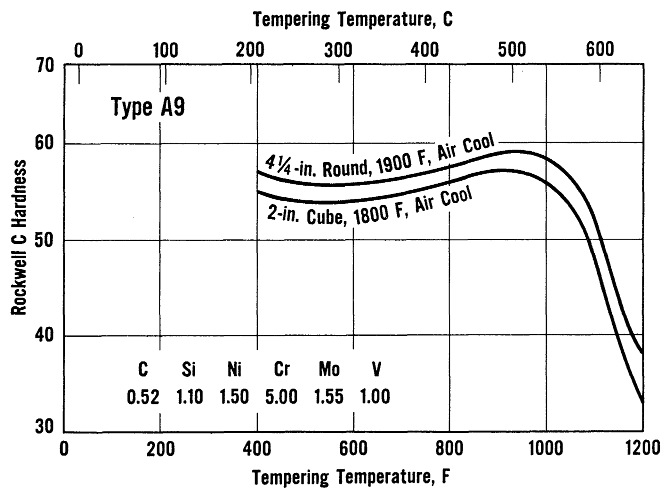

Fig. 2. Effect of tempering on the hardness of Type A9 hot work tool steel.

TABLE IV

Effect of Tempering on Hardness of Some Hot Work Tool Steels

Steel Type [a]	Hardening: Temperature, F	Hardening: Cooling Medium	Typical Values of Rockwell C Hardness[b] after Tempering at . . . 400 F	600 F	800 F	900 F	950 F	1000 F	1050 F	1100 F	1200 F
0.5 Ni-1 Cr-0.4 Mo-.03 V	1450	Oil	—	55-57	50-52	47-50	46-48	45-47	42-45	40-42	28-31
2 Ni-0.9 Cr-0.7 Mo	1630	Air[c]	—	52-58	49-52	47-51	46-50	45-49	43-47	42-45	33-36
		Oil	—	54-57	50-52	49-51	48-50	46-49	45-47	43-45	34-36
2.7 Ni-1.4 Cr-0.6 Mo-0.2 V	1550	Oil	—	—	—	—	—	—	42-46	36-39	—
AISI A9 (1.50 Mo)	1825	Air	55	55	56	57	58	56	53	47	34
AISI A9 (1.35 Mo)	1800	Air	—	—	—	56	55	54	49	—	—
	1850	Air	—	—	—	57	56	55	50	—	—
4.3 Ni-1.4 Cr-0.8 Mo-0.15 V	1670	Oil	—	50-52	—	49-51	—	48-50	47-49	46-48	42-44
1.8 Ni-2.8 Cr-10 W	2000	Air	45	45	45	47	—	49	50	48	36
	2300	Air	48	49	50	51	—	54	54	53	44

[a] Compositions are given in Table III.

[b] These hardness values may deviate somewhat because of variations in composition, size, conditions of heat treatment and testing procedure.

[c] Small, thin and intricately shaped sections should be cooled in air.

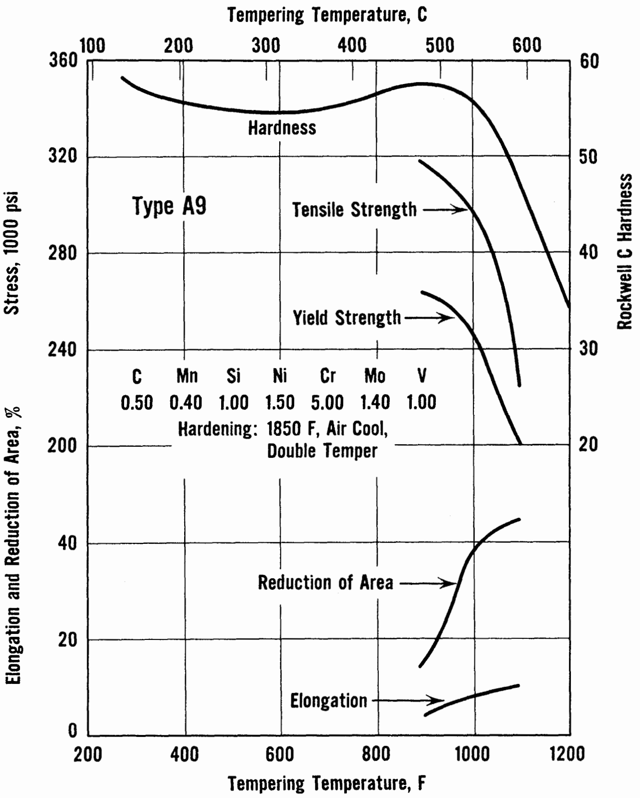

Fig. 3. Effect of tempering on the tensile properties of Type A9 hot work tool steel.

TABLE V

Short-Time Elevated Temperature Tensile Properties of Two Hot Work Tool Steels[a]

Rockwell C Hardness	Test Tempera-ture, F	Tensile Properties			
		Tensile Strength, psi	Yield Strength (0.2% Offset), psi	Elonga-tion, %	Reduction of Area, %
0.5 Ni-1.0 Cr-0.4 Mo-.03 V Steel					
36	70	158,000	138,000	16	49
—	800	130,000	104,000	20	66
—	900	116,000	98,000	20	72
—	1000	93,000	82,000	24	81
32	70	143,000	127,000	18	54
—	800	122,000	95,000	21	66
—	900	104,000	86,000	24	75
—	1000	90,000	75,000	25	79
27	70	136,000	123,000	21	56
—	800	114,000	87,000	22	67
—	900	99,000	79,000	24	74
—	1000	85,000	67,000	26	80
4.3 Ni-1.4 Cr-0.8 Mo-0.15 V Steel					
44-45	70	218,000	190,000	12	33
—	800	184,000	155,000	10	36
—	900	155,000	121,000	14	50
—	1000	144,000	133,000	10	39

a One-inch square bars oil quenched and tempered to hardness indicated. Heppenstall Company.

The two tungsten-rich steels, in the fouth group of Table III, show greater resistance to softening than the tungsten-free steels. This is suggested in Table IV by the data for the 10 per cent tungsten steel and the two tungsten-free steels, AISI A9 and the 4.3 nickel-1.4 chromium-0.8 molybdenum-0.15 vanadium steel. However, these two tungsten-free steels resist thermal shock to a greater degree than the tungsten-rich types. The steel containing nominally 10 per cent tungsten, shown in Figure 4, requires a very high austenitizing temperature to achieve full hardness. The tungsten-free types, such as AISI A9 in Figure 2, do not require such a high temperature.

The low-carbon ASM 6F4 steel, the last one in Table III, was developed especially for hot-press forging dies, hot-forging die blocks and similar applications.[5] It contains 3 per cent nickel and 3.3 per cent molybdenum in a low-carbon base and exhibits substantial secondary hardening characteristics. Hardness increases with tempering temperatures to 1050 F as

TABLE VI

Impact Properties of 4.3 Nickel-1.4 Chromium-0.8 Molybdenum-0.15 Vanadium Hot Work Tool Steel[a]

Rockwell C Hardness	Charpy Impact (V-Notch), ft-lb, at Test Temperature of . . .	
	80 F	300 F
42-43	15-17	22-24
44-45	10-12	18-20
46-47	10-12	18-20

a One-inch square bars oil quenched and tempered to hardness indicated. Heppenstall Company.

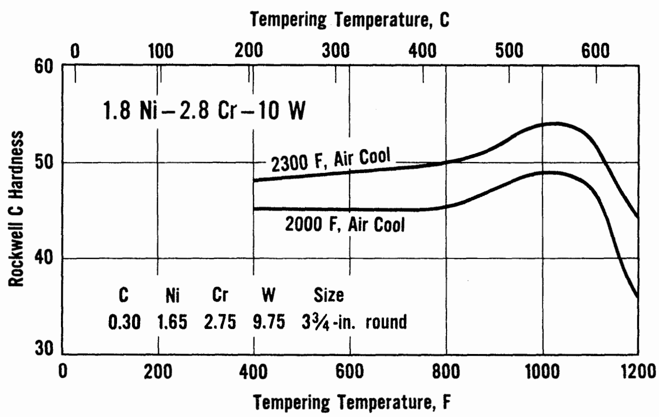

Fig. 4. Effect of tempering on the hardness of a 1.8 nickel-2.8 chromium-10 tungsten hot work tool steel.

indicated in Figure 5. This low-carbon tool steel has high toughness both at room temperature and at operating temperatures as also shown in Figure 5 and in Figure 6. It has the ability to withstand repeated thermal cycling during hot-press forging.

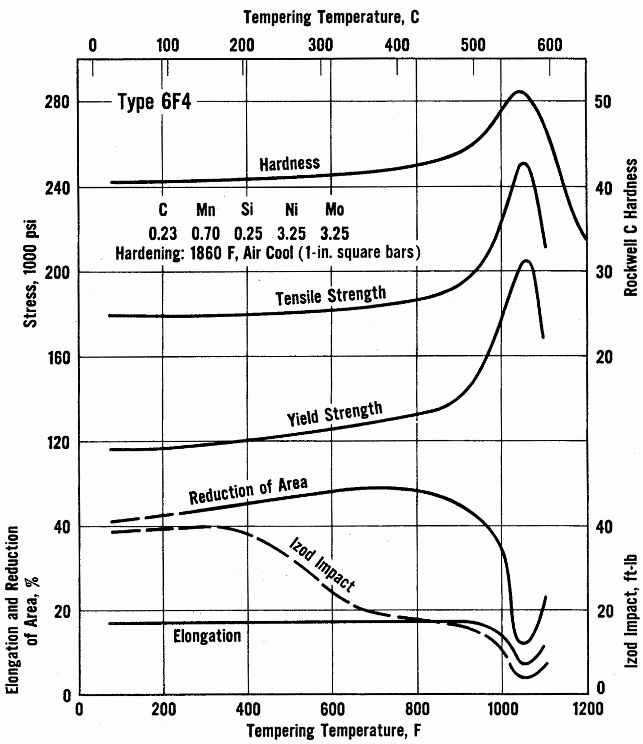

Fig. 5. Effect of tempering on the room-temperature mechanical properties of Type 6F4 age-hardening hot work tool steel. Succop.[5]

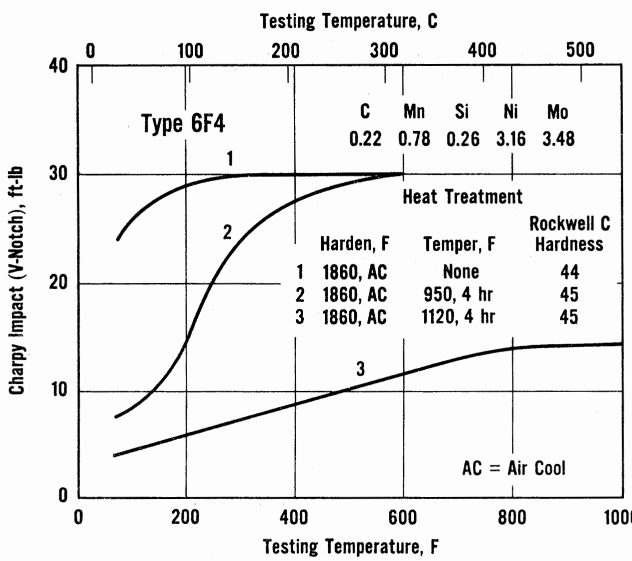

Fig. 6. Notch-impact toughness of Type 6F4 age-hardening hot work tool steel at elevated temperatures. Succop.[5]

PLASTIC MOLD STEELS

Carburizing Grades

Most of the nickel-containing steels used for carburized plastic molds fall within the AISI P2, P3 or P6 classifications, and are shown in Table VII. Type P3 is preferred for molds in which the cavity is formed by cold hubbing, because of its low annealed hardness and great ability to accept plastic deformation in the annealed condition. This steel develops good core strength and toughness, and maintains dimensional stability through carburizing and hardening. Type P2 also combines these characteristics to a useful degree.

When plastic mold cavities are to be machine-cut, and extreme softness in the annealed steel is therefore no longer necessary, Type P6 is recognized as one of the best mold steels available. It is a deep-hardening carburizing steel, providing very high core strength together with superior toughness. It is chosen frequently for large molds and for molds to be operated on long runs or in difficult service. Type P6 has been used successfully for molds which weigh several tons and incorporate the result of many months of intricate machine work.

The principles and practices for carburizing and heat treating the alloy constructional grades can be applied to mold steels of similar compositions with equal success. Details of carburizing practices can be found in another bulletin.*

Table VIII lists representative core and case properties of the P2, P3 and P6 steels in one-inch section size after carburizing, furnace cooling, oil hardening, and tempering at 300 F.

Table IX shows the effect of tempering at temperatures up to 1200 F on the core and case properties of a Type P6 steel heat treated in several section sizes.

The influences of different quenching and tempering practices on the properties of another Type P6 steel are indicated in Table X. The core properties do not vary materially, but direct quenching after carburizing may lower the case hardness somewhat if excessive

TABLE VII

Nominal Composition of Plastic-Mold Steels

Steel Type	Composition, %							
	C	Mn	Si	Ni	Cr	Mo	V	Al
Carburized Mold Steels								
AISI P2	0.10 max	0.50	0.15	0.50	1.25	0.25	—	—
AISI P3	0.10 max	0.50	0.20	1.25	0.60	—	—	—
AISI P6	0.12 max	0.40	0.20	3.50	1.50	—	—	—
Non-Carburized Mold Steels								
AISI P21	0.20	0.30	0.30	4.10	0.25	a	0.20	1.20
3.5 Ni-1.6 Cr-0.25 Mo	0.35	0.50	0.30	3.50	1.60	0.25	—	—

a Molybdenum is optional.

* Bulletin 2-B: "Carburized Nickel Alloy Steels."

austenite is retained.* The effect of section size on the core properties of this steel is shown in Table XI.

Prehardened Grades

Nickel alloy steels prehardened before machining are used for molds where service permits somewhat lower hardness and strength than is available from carburized molds. Mold blocks are prehardened by quenching and tempering to the maximum hardness compatible with machining, usually 302 to 331 Brinell. Table VII lists one typical non-carburizing, or through-hardening composition: a 3.5 nickel-chromium-molybdenum grade with 0.35 per cent carbon. Compositions corresponding to AISI grades also may be produced and sold for mold requirements. Alloy contents are selected generally with sufficient hardenability to develop the required hardness in the center sections of a mold after quenching and tempering.

* Bulletin 2-B: "Carburized Nickel Alloy Steels."

TABLE VIII

Representative Properties of Carburized Mold Steels[a]

Steel Type	Nominal Composition, %				Core Properties			Case
	C	Ni	Cr	Mo	Tensile Strength, psi	Yield Strength, psi	Brinell Hardness	Rockwell C Hardness
AISI P2	.07	0.50	2.00	0.20	100,000	70,000	200	63
AISI P3	0.10	1.25	0.60	—	100,000	70,000	200	62
AISI P6	0.10	3.50	1.50	—	180,000	145,000	375	61

a One-inch sections carburized, box cooled, reaustenitized, oil quenched, tempered 300 F. Carpenter Steel Company.

TABLE IX

Effect of Heat Treatment and Section Size on Mechanical Properties of a Type P6 Mold Steel[a]

Heat Treatment			Core Properties						Case
Hardening Temperature, F	Tempering Temperature, F	Section Size, in.	Tensile Strength, psi	Yield Strength (0.2% Offset), psi	Elongation (2 in.), %	Reduction of Area, %	Izod Impact, ft-lb	Brinell Hardness	Rockwell C Hardness
Carburize 1650-1700, cool; reheat 1425-1475, oil quench	300	1	172,000	132,000	20	60	60	341	62
		4	153,000	108,000	22	64	68	311	60
		8	149,000	100,000	18	63	68	293	58
Austenitize 1525, oil quench	400	1	173,000	140,000	16	56	70	352	—
		8	148,000	109,000	16	61	80	302	—
	600	1	169,000	144,000	16	57	72	347	—
		8	137,000	117,000	17	64	66	278	—
	800	1	150,000	130,000	18	60	74	306	—
		8	124,000	108,000	19	65	52	253	—
	1000	1	126,000	109,000	22	64	85	260	—
		8	110,000	94,000	20	64	62	226	—
	1200	1	114,000	86,000	28	74	106	235	—
		8	94,000	75,000	25	72	110	195	—

a Composition, %: 0.12 C, 0.50 Mn, 0.20 Si, 3.25 Ni, 1.50 Cr. Atlas Steels Limited.

TABLE X

Effect of Different Heat Treatments after Carburizing on the Properties of a Type P6 Mold Steel[a]

Type of Heat Treatment	Tempering Temperature, F	Core Properties					Case
		Tensile Strength, psi	Yield Point, psi	Elongation, %	Reduction of Area, %	Brinell Hardness	Rockwell C Hardness
Direct Quench[b]	300	181,000	149,000	15	57	375	59
	450	181,000	153,000	15	58	375	55
Single Quench[c]	300	180,000	146,000	14	57	363	61
	450	180,000	150,000	14	58	363	58
Double Quench[d]	300	177,000	144,000	15	58	352	61
	450	176,000	146,000	15	59	341	58

a Composition, %: 0.10 C, 0.40 Mn, 3.25 Ni, 1.50 Cr. Bar size: ½-inch diameter. Bethlehem Steel Corporation.

b Carburized 1700 F, 8 hr, quenched in agitated oil.

c Carburized 1700 F, 8 hr, cooled to room temperature, reheated to 1500 F, quenched in agitated oil.

d Carburized 1700 F, 8 hr, cooled to room temperature, reheated to 1500 F, quenched in agitated oil, reheated to 1450 F, quenched in agitated oil.

TABLE XI

Effect of Section Size on the Core Properties of a Type P6 Mold Steel[a]

Bar Diameter, in.	Tempering Temperature,[b] F	Brinell Hardness	Tensile Properties: Tensile Strength, psi	Yield Point, psi	Elongation, %	Reduction of Area, %
½	300	341	172,000	142,000	15	64
1	300	293	146,000	112,000	17	61
2	300	285	140,000	103,000	18	66
4	300	269	130,000	94,000	20	65
½	450	321	165,000	131,000	16	64
1	450	285	145,000	110,000	18	65
2	450	277	136,000	100,000	18	68
4	450	262	130,000	89,000	20	64

[a] Composition, %: 0.10 C, 0.40 Mn, 3.25 Ni, 1.50 Cr. Properties are for bar centers. Bethlehem Steel Corporation.
[b] Heated to 1700 F, 8 hr; reheated to 1500 F, oil quenched, tempered as indicated.

Age-Hardening Grades

Age-hardening compositions, such as Type P21 in Table VII, can be machined in the solution-treated condition, at a relatively low hardness, and then raised to substantially higher final hardness simply by aging at 1000 F. Thus the danger of scaling and the distortion inherent in a heat treatment involving quenching are eliminated. The properties of P21 steel in the solution-annealed condition and after subsequent aging are given in Table XII.

TABLE XII

Properties of Type P21 Age-Hardenable Mold Steel[a]

HEAT TREATMENT	Solution Annealed 1350 F, Oil Quenched	Solution Annealed 1350 F, Oil Quenched, Aged 1000 F
MECHANICAL PROPERTIES		
Brinell Hardness	248	363
Tensile Strength, psi	128,000	179,000
Yield Strength (0.2% Offset), psi	84,000	164,000
Elongation (2 in.), %	24	16
Reduction of Area, %	50	40
PHYSICAL PROPERTIES		
Coefficient of Expansion (72 to 900 F), per °F	7.1×10^{-6}	7.1×10^{-6}
Thermal Conductivity Btu in. per hr sq ft °F	249	249

[a] Composition, %: 0.20 C, 0.30 Mn, 4.10 Ni, 0.25 Cr, 0.20 V, 1.20 Al. Latrobe Steel Company.

TABLE XIII

Nominal Compositions of Saw and Knife Steels

Steel Type	Composition, %: C	Mn	Si	Ni	Cr	Mo
2.5 Ni	0.75	0.35	0.25	2.6	—	—
0.7 Ni-0.5 Cr	0.75	0.35	0.25	0.7	0.50	0.15[a]
1.4 Ni-0.3 Cr	0.90	0.35	0.25	1.4	0.30	—
1.4 Ni-0.7 Cr	1.00	0.40	0.25	1.4	0.65	—

[a] Molybdenum is optional.

SAW AND KNIFE STEELS

Several nickel alloy steels ranging from 0.75 to 1.0 per cent carbon are used for saws and industrial knives, Table XIII. They are preferred over plain carbon tool steels because they can be oil or air hardened rather than water quenched, thus reducing the tendency to distort. The nickel alloy steel compositions also are somewhat tougher at equal hardness.

The favored type for large and heavy-duty saws contains nominally 2.5 per cent nickel with or without small additions of molybdenum and/or chromium. The carbon level is usually about 0.75 per cent but is sometimes as high as 0.90 per cent. These steels are long wearing, resistant to embrittlement at low atmospheric temperatures and can be welded to join the ends of band saws. Similar compositions also are used extensively for metal-cutting circular saws employing inserted, high-speed steel teeth.

The effect of tempering on hardness and smooth-bar, non-standard Charpy impact properties of a 2.5 nickel steel (containing 0.15 per cent chromium) are given in Figure 7. The operating hardness is usually in the neighborhood of Rockwell C 48. Tensile properties are given in Table XIV. The effect of different tempering temperatures upon the hardness of typical circular saw compositions is shown in Table XV.

A lower alloy type with 0.7 nickel-0.5 chromium (with 0.15 per cent molybdenum optional) is used frequently for the cutting teeth in chain-saw chains and industrial knife applications where its relatively

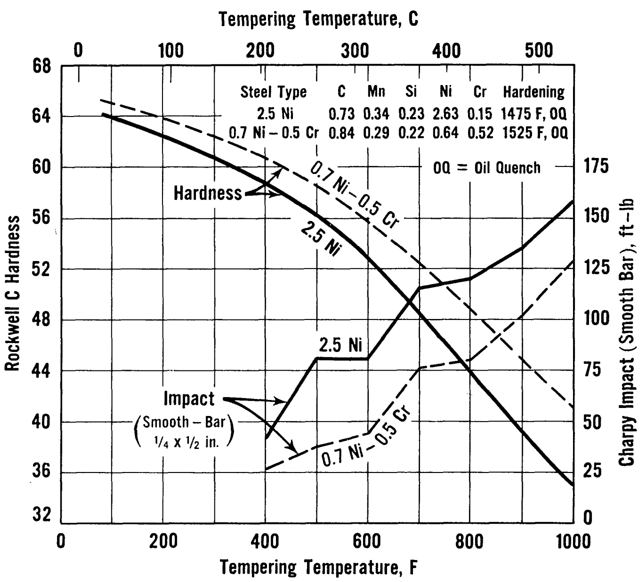

Fig. 7. Effect of tempering on the hardness and smooth-bar Charpy impact properties of a 2.5 nickel and a 0.7 nickel-0.5 chromium saw steel. The tensile properties of these steels are given in Table XIV.

low cost, good toughness and abrasion resistance are attractive. Tables XIV and XV and Figure 7 show properties vs tempering temperature of a typical steel of this type.

TABLE XIV

Tensile Properties of Two Low-Alloy Saw Steels[a]

Steel Type	Composition, %			Tempering Temperature,[b] F	Tensile Strength, psi	Yield Strength, psi	Elongation (2 in.), %	Reduction of Area, %
	C	Ni	Cr					
2.5 Ni	0.73	2.63	0.15	700	238,000	207,000	10.5	30
				800	206,000	189,000	11.5	33
				900	182,000	166,000	13.5	35
0.7 Ni-0.5 Cr	0.84	0.64	0.52	700	271,000	242,000	5.5	11
				800	242,000	218,000	8	21
				900	217,000	198,000	11	28
				1000	190,000	177,000	12	32

[a] For complete chemical compositions, hardnesses, and impact properties see Figure 7. Simonds Saw and Steel Company.

[b] Before tempering, the 2.5 Ni steel was oil quenched from 1475 F and the 0.7 Ni-0.5 Cr from 1525 F.

TABLE XV

Effect of Tempering on Hardness of Some Saw Steels[a]

Steel Type	Composition, %					Heat Treatment		Rockwell C Hardness
	C	Mn	Ni	Cr	Mo	Oil Hardening Temperature, F	Tempering Temperature, F	
2.5 Ni	0.70-0.80	0.35	2.60	—	—	1475-1500	As Quenched	62-63
							400	58
							600	53-54
							850	43-44
							1000	37-38
0.7 Ni-0.5 Cr[b]	0.70	0.50	0.70	0.50	0.15	1475-1500	As Quenched	60-62
							400	58
							600	54-55
							850	45-46
							1000	38-39
1.4 Ni-0.3 Cr	0.70	0.25	1.35	0.35	—	1475-1500	As Quenched	61-62
							400	59
							600	53-54
							850	43
							1000	37
1.4 Ni-0.7 Cr	1.00	0.40	1.40	0.65	—	1475-1500	As Quenched	61-63
							400	58-59
							600	55
							850	43-44
							1000	38

[a] Jessop Steel Company.

[b] Molybdenum (0.15 per cent) is optional.

TABLE XVI

Nominal Compositions of Graphitic Tool Steels

Steel Type	Composition, %					
	C	Mn	Si	Ni	Cr	Mo
AISI A10	Total 1.35 Graphite 0.35	1.85	1.20	1.85	—	1.50
1 Si-1.8 Ni-0.5 Cr-0.5 Mo	Total 1.50 Graphite 0.30	1.25	1.00	1.75	0.50	0.50

GRAPHITIC TOOL STEELS

The graphitic tool steels, Table XVI, are characterized by the presence of particles of free carbon (graphite) that have the effect of improving machinability. These compositions have been established to provide the capability of developing high hardness and wear resistance. The controlled graphitization is achieved by balancing the composition, chiefly carbon and silicon, to produce about 0.30 per cent carbon as graphite. The graphite particles form discontinuities which cause chips to break into short lengths during machining.

The nickel-containing graphitic steels are air-hardening. Type A10 hardens successfully to Rockwell C 58 in sections 8 inches in diameter when air cooled from 1500 F.[6] It is therefore quite suitable for complex dies with large variations in section size, and in applications where a high degree of dimensional stability on hardening is desired. Figure 8 shows the effect of tempering upon the hardness and impact toughness of A10 steel, and hot hardness data appear in Figure 9.

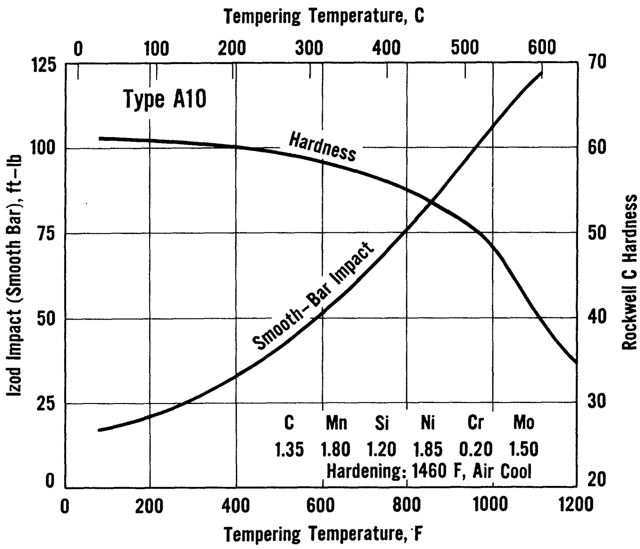

Fig. 8. Effect of tempering on the hardness and smooth-bar impact toughness of Type A10 steel, a graphitic tool steel.

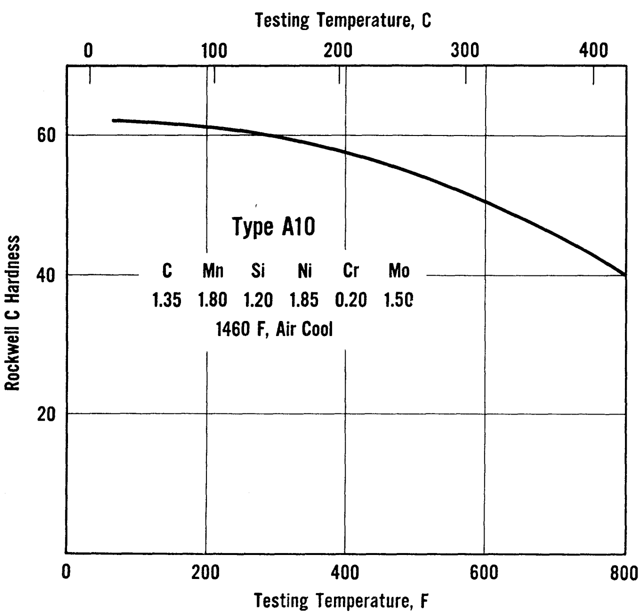

Fig. 9. Hot hardness of Type A10, a graphitic tool steel.

Applications include blanking dies and punches, trimming shear blades, spindle arbors, forming rolls, and cold forming dies.

COLD WORK DIE STEELS

A nickel-containing grade of the 12 per cent chromium type of cold work die steel has the greatest toughness of all the high-carbon, high-chromium die steels. It also has excellent wear resistance and very good non-deforming characteristics. A typical composition is shown in Table XVII and Figure 10 presents a tempering curve for this grade.

TABLE XVII
Nominal Composition of Nickel-Containing 12 Chromium Cold Work Die Steel

Steel Type	Composition, %						
	C	Mn	Si	Ni	Cr	Mo	V
1 Ni-12 Cr-0.5 Mo-0.25 V	0.75	0.30	0.25	1.00	12.0	0.50	0.25

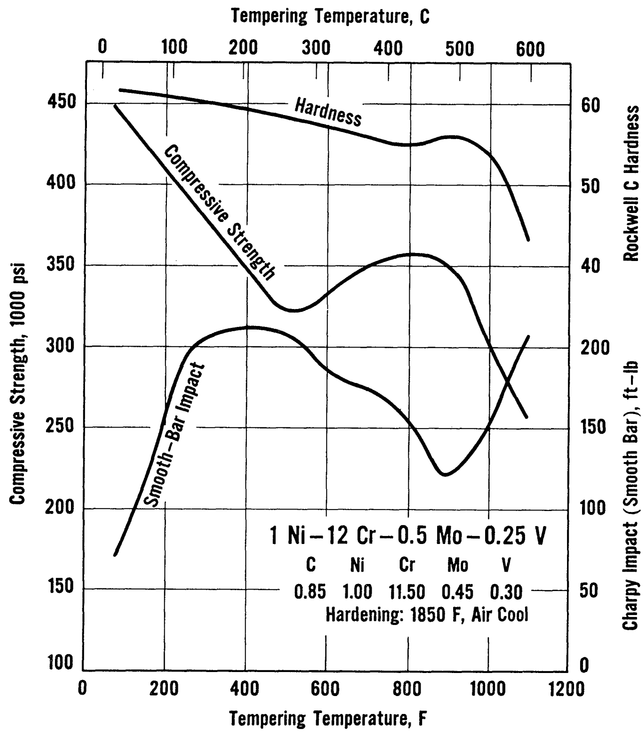

Fig. 10. Effect of tempering on the compressive strength and toughness of a 12 per cent chromium tool steel also containing nickel, molybdenum and vanadium.

Applications for the steel include blanking dies, deep drawing dies, plug gages, punches, trimming dies, mandrels and shear blades.

SHOCK-RESISTANT STEEL

Table XVIII lists an oil-hardening composition developed for shock-resisting applications by modifying tungsten chisel steel with nickel and chromium. The normal hardening temperature range is 1650 to 1750 F, but by lowering the hardening temperature below 1600 F the steel can be water quenched with a minimum risk of cracking. This steel is employed for both hot and cold work applications. For hot working applications it is tempered usually to a hardness range of Rockwell C 44 to 52, and for cold work to a range of Rockwell C 54 to 57. Typical applications include hand and pneumatic chisels, hot and cold shear blades, hot heading and forming dies, concrete drills, bolt clippers, rock drills, and striking dies.

TABLE XVIII

Nominal Composition of Nickel-Tungsten Shock-Resistant Tool Steel

Steel Type	Composition, %					
	C	Mn	Si	Ni	Cr	W
1.5 Ni-0.7 Cr-2 W	0.65	0.80	0.25	1.50	0.70	2.00

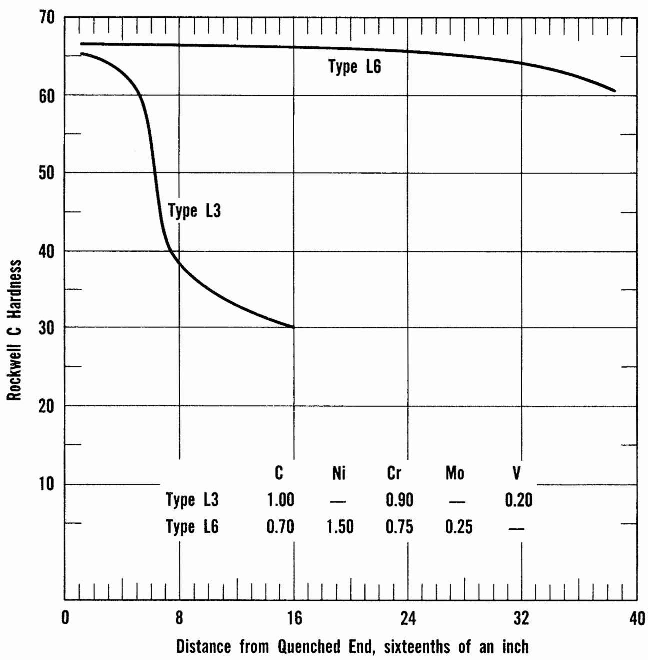

Fig. 11. End-quench hardenability of AISI Types L3 and L6 tool steels. American Society for Metals.[2]

LOW-ALLOY SPECIAL PURPOSE TOOL STEELS

Low-alloy nickel-containing tool and die steels fall into two classes as discussed below and as shown in Table XIX.

TABLE XIX

Nominal Compositions of Low-Alloy Tool and Die Steels

Steel Type	Composition, %						
	C	Mn	Si	Ni	Cr	Mo	V
Carbon over 0.65%							
AISI L6 (Reference 1)	0.70	0.55	0.25	1.50	0.75	0.25[a]	—
AISI L6 (Reference 9)	0.75	0.55	0.25	1.75	1.00	0.30[a]	0.15[a]
AISI L6	0.70	0.55	0.25	1.75	1.00	0.25[a]	—
Carbon under 0.65%							
1.3 Ni-0.6 Cr-0.15 Mo	0.40	0.75	0.25	1.25	0.60	0.15	—
ASM 6F2	0.55	0.50	0.25	1.40	0.90	0.30	—
ASM 6F3	0.55	0.55	0.80	1.60	1.00	0.75	0.15[a]
ASM 6F5	0.55	0.90	1.00	2.70	0.40	0.45	0.15[a]
3.3 Ni-1.1 Cr-0.25 Mo	0.60	0.50	0.25	3.25	1.10	0.25	—
ASM 6F7	0.40	0.30	0.25	4.50	1.60	0.85	—

[a] Optional element.

Grades with Carbon Over 0.65 Per Cent

The high-carbon low-alloy tool steels, represented by AISI L6, are designed to provide oil-hardening capabilities and higher toughness and resistance to tempering than available from plain carbon tool steels. Carbon levels are above 0.65 per cent to achieve the required hardness and wear resistance. Hardenability is obtained by using at least 1.5 per cent nickel and 0.75 per cent chromium, sometimes supplemented by molybdenum and vanadium. These steels are used for shear blades, blanking dies and punches, and press-brake dies.

The deep-hardening characteristics of the Type L6 steels are indicated by the end-quench hardenability curve for one of them in Figure 11. Shown for comparison are hardenability data for a Type L3 low-alloy chromium-vanadium steel. Some L6 steels can be hardened to Rockwell C 65 at the center of 3-inch rounds by oil quenching, whereas a 1-inch round of L3 steel is about the largest bar that can be hardened similarly.

The effect of tempering on the hardness of a number of compositions of the L6 type is shown in Table XX and presented graphically in Figure 12.

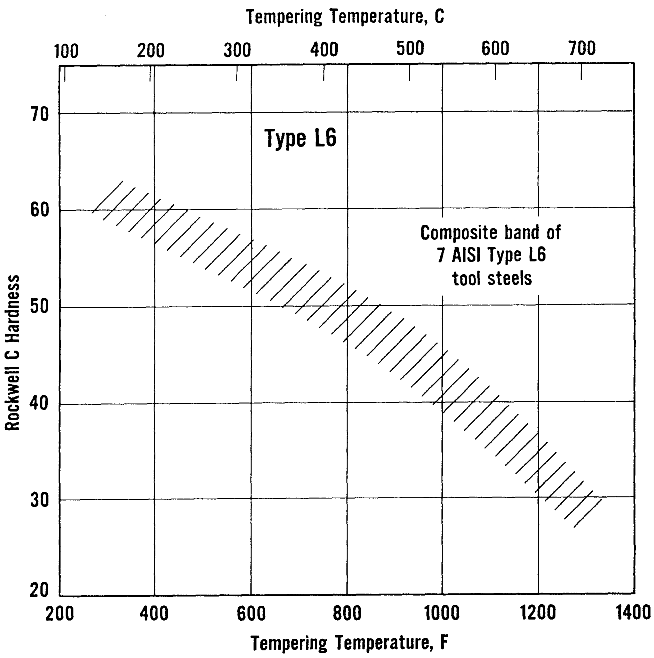

Fig. 12. Effect of tempering on the hardness of the Type L6 tool steels of Table XX.

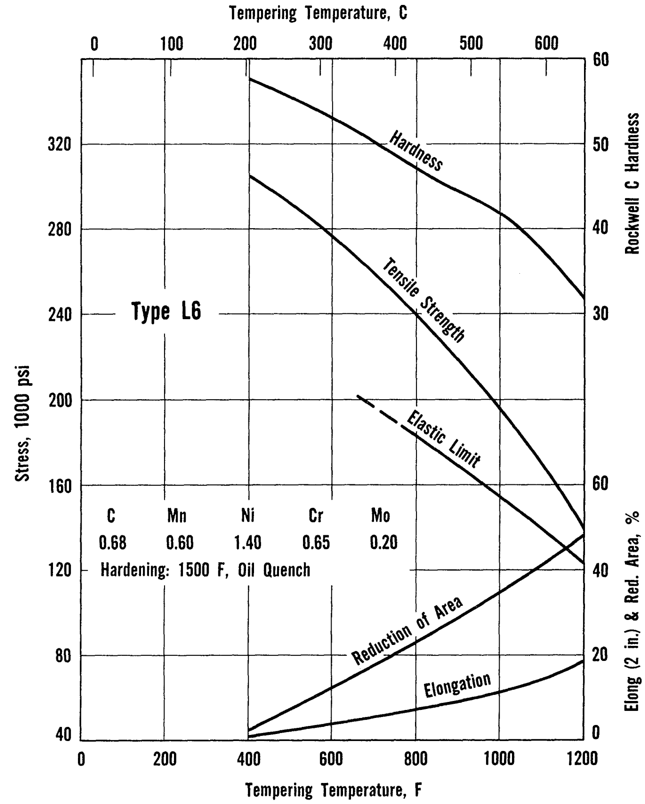

Fig. 13. Effect of tempering on the tensile properties of a Type L6 tool steel. Allegheny Ludlum Steel Corporation.

TABLE XX

Effect of Tempering on the Hardness of Seven AISI Type L6 Tool Steels[a]

STEEL NUMBER	1	2	3	4	5	6	7
COMPOSITION							
Carbon, %	0.70	0.75	0.68	0.70	0.70	0.75	0.70
Manganese, %	0.65	0.70	0.60	0.55	0.40	0.75	0.35
Nickel, %	1.25	1.35	1.40	1.40	1.60	1.75	1.75
Chromium, %	0.65	0.80	0.65	0.85	1.00	0.90	1.00
Molybdenum, %	0.45	0.30	0.20	0.25	—	0.35	—
Vanadium, %	—	0.15	—	—	—	—	—
HARDENING							
Temperature, F	1550	1500	1500	1450	1500	1550	1525
Quenching Medium	Oil	Oil	Oil	Oil	Oil	Oil	Oil
ROCKWELL C HARDNESS after Tempering at . . .							
300 F	—	63	63	62	60	62	60
400 F	—	61	60	60	58	60	56
600 F	56	56	55	55	56	55	52
700 F	52	53	52	53	52	53	48
800 F	52	—	49	50	49	50	46
900 F	48	—	47	49	45	46	—
1000 F	46	—	42	45	41	43	—
1100 F	38	—	39	41	36	38	—
1200 F	—	—	—	33	29	32	—

a Data are from various sources.

The tensile properties of a typical L6 steel are given in Table XXI and Figure 13. Data on the effect of tempering on hardness and smooth-specimen (or smooth-bar) impact values are presented in Figure 14.*

TABLE XXI

Hardness and Tensile Properties of a Type L6 Tool Steel[a]

Tempering Temperature,[b] F	Brinell Hardness	Tensile Properties: Tensile Strength, psi	Elastic Limit, psi	Elongation (2 in.), %	Reduction of Area, %
Annealed[c]	192	94,000	55,000	29	58
400	600	298,000	—	1.3	2.0
600	532	291,000	—	4.3	9.3
800	444	231,000	180,000	8.5	25
1000	387	195,000	155,000	12	34
1200	302	140,000	122,000	19	47

a Composition, %: 0.68 C, 0.60 Mn, 1.40 Ni, 0.65 Cr, 0.20 Mo. Allegheny Ludlum Steel Corporation.

b Oil quenched from 1500 F before tempering.

c Furnace cooled from 1425 F.

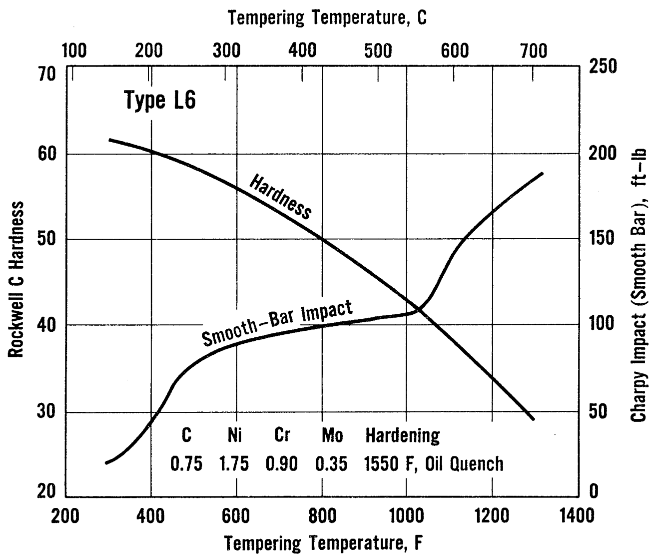

Fig. 14. Effect of tempering on hardness and smooth-bar impact of a Type L6 tool steel. Bethlehem Steel Corporation.

Comparisons of hardness and impact data for two L6 tool steels and a carbon tool steel, are given in Figure 15. The alloy steels, based on smooth-bar impact specimens 3/8 inch in diameter, can be used at substantially higher hardness while maintaining equivalent toughness, or provide higher toughness at equivalent hardness. The greater resistance to softening on tempering Type L6, in contrast to an unalloyed steel of equal carbon content, is illustrated in Figure 16.

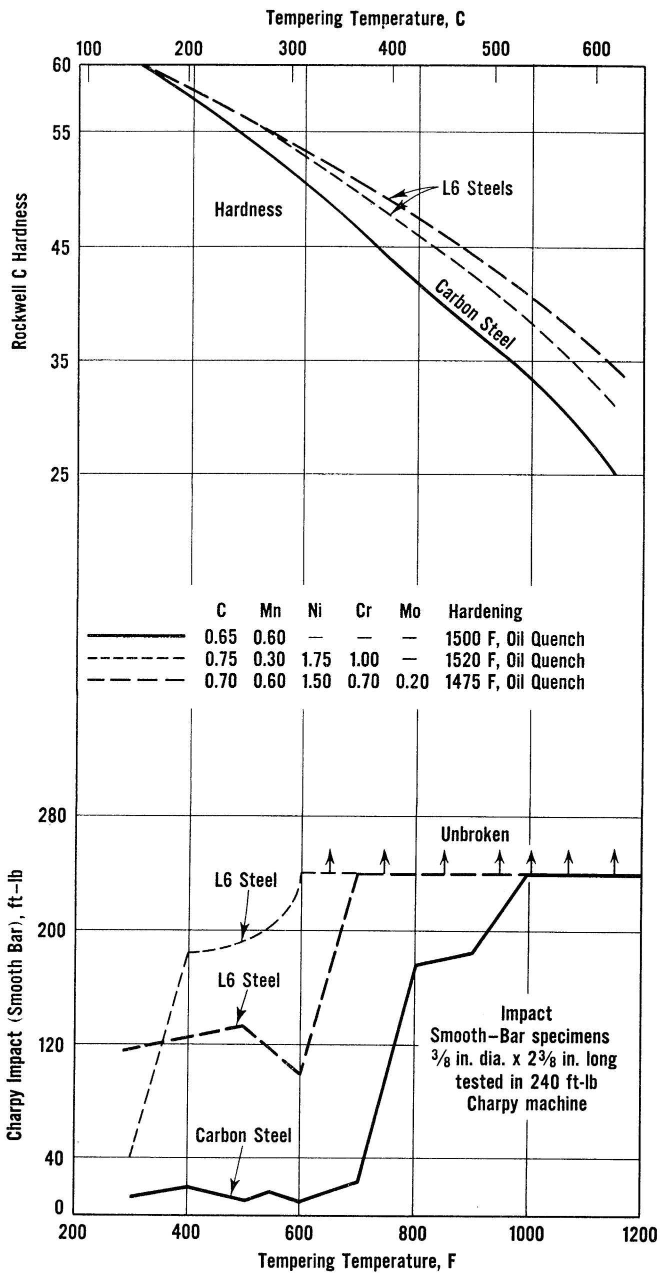

Fig. 15. Effect of tempering on hardness and smooth-bar impact of two Type L6 tool steels and a carbon tool steel. Bredenbeck.[7]

* No standard tests have been developed to evaluate the toughness of steels at high hardness. Therefore this bulletin contains values determined with a number of test methods including:

1. Impact loading in Charpy and Izod machines of standard and non-standard bars with or without notches.
2. Torsional loading at low and high (impact) strain rates. Quantitative correlations cannot be made between toughness indications determined by these different tests.

The torsional properties for a similar composition in the as-quenched and the quenched and lightly tempered conditions are shown in Figure 17. Additional data on the effect of tempering temperature upon smooth-bar Izod and Charpy impact values of two L6 steels are shown in Figure 18. Figure 19 presents data on the effect of tempering on torsional impact for another L6 steel.

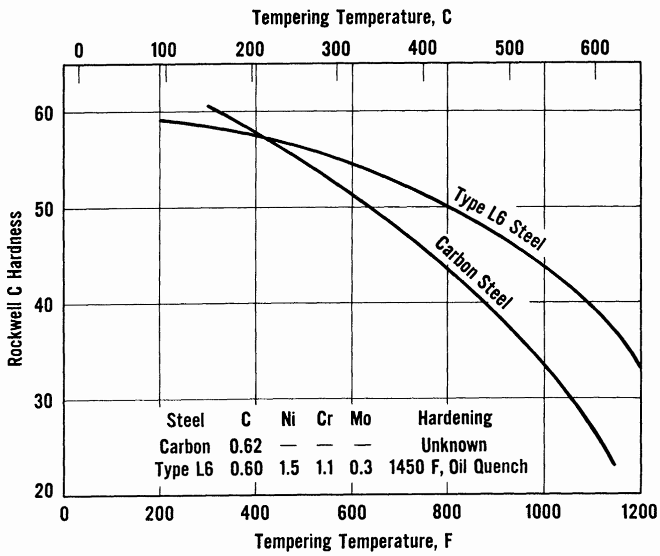

Fig. 16. Effect of tempering on the hardness of a Type L6 tool steel and a carbon tool steel. Gill.[8]

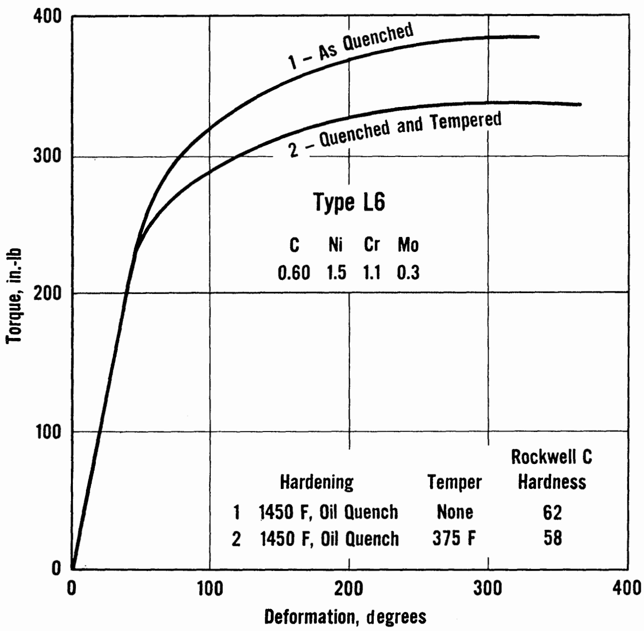

Fig. 17. Slow strain-rate torsion properties of a Type L6 tool steel. Gill.[8]

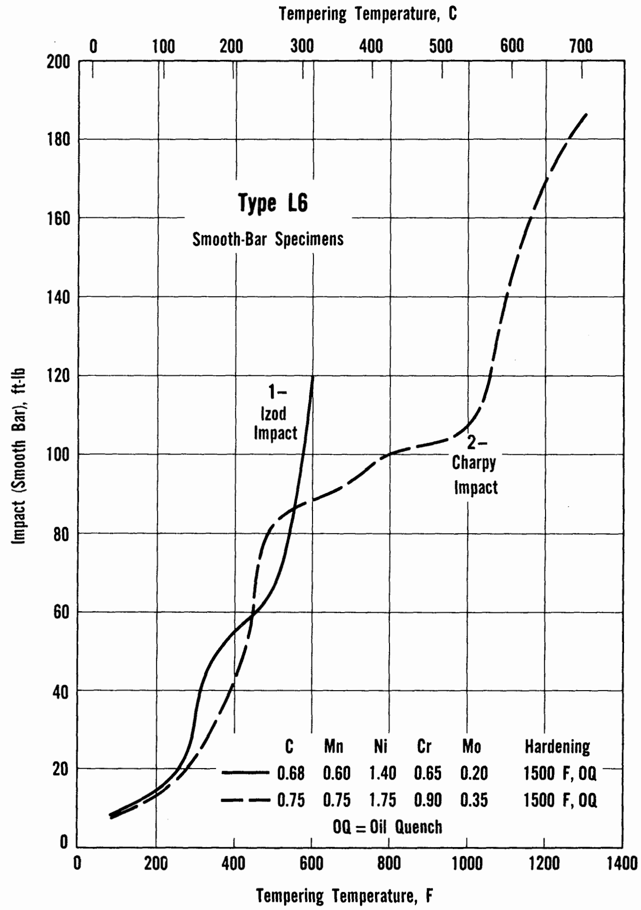

Fig. 18. Effect of tempering on impact values of smooth-bar specimens of Type L6 tool steel. Curve 1, Allegheny Ludlum Steel Corporation. Curve 2, Bethlehem Steel Corporation. Roberts, Hamaker and Johnson,[9] p. 360.

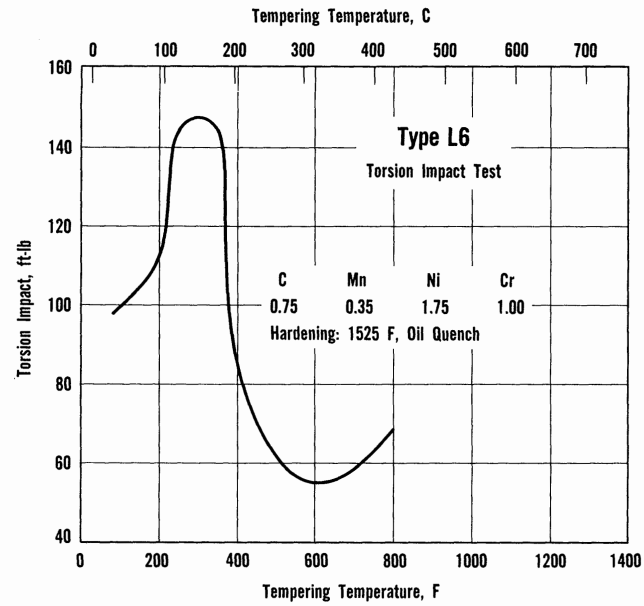

Fig. 19. Effect of tempering on torsion impact values of Type L6 tool steel. Roberts, Hamaker and Johnson,[9] p. 360, and Palmer and Luerssen.[10]

Grades with Carbon Under 0.65 Per Cent

Another class of low-alloy tool and die steels is represented by the ASM 6F series.[2] These steels range from 0.40 to 0.60 per cent carbon and from 1.25 to 4.5 per cent nickel along with chromium and molybdenum, as shown in Table XIX. They are oil hardening in heavy sections, as shown in Figure 20, and some grades have enough hardenability for air hardening in small sections. Steels of the 6F type are used in both cold and hot shock-resisting applications. The compositions containing the greater amounts of chromium and molybdenum are more resistant to tempering and thus are better adapted to hot-working tools. Typical applications include drop-forging dies, upsetter dies, hot trimmers and punches, shear blades, chisels, swaging dies, and die-casting dies for low-melting alloys.

The tensile properties of a Type 6F5 steel tempered to different hardnesses are given in Table XXII. The effect of tempering on hardness and standard Charpy V-notch impact values is shown in Figure 21.

A tempering curve for a vanadium-modified Type 6F7 steel is shown in Figure 22. Data on the effect of tempering on the tensile properties of a lower carbon, higher nickel modification of Type 6F2 is presented in Figure 23. The retention of hardness at elevated temperatures in three modified Type 6F compositions, designed primarily for hot forging-die service, is shown by Figure 24.

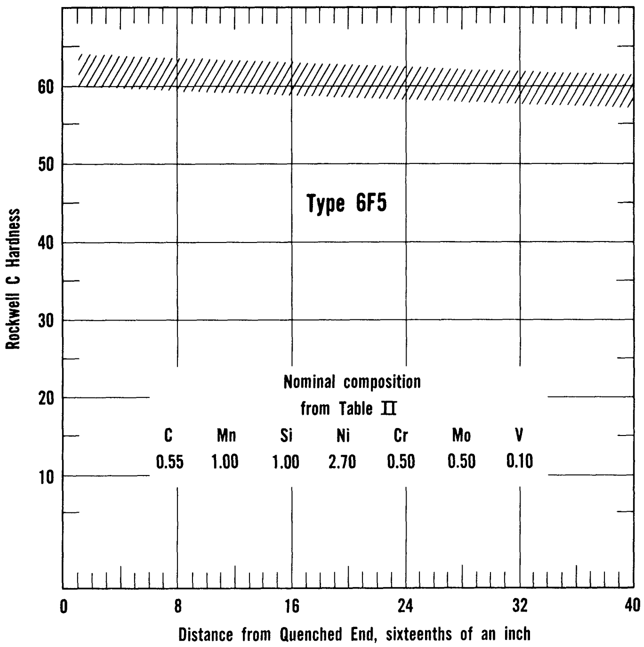

Fig. 20. End-quench hardenability of Type 6F5 tool steel. American Society for Metals.[2]

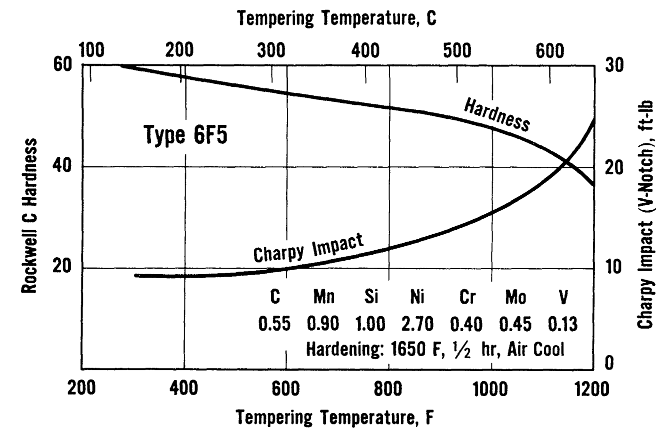

Fig. 21. Effect of tempering on the hardness and impact strength of a Type 6F5 tool steel. (Table XXII gives tensile data for this steel.)

TABLE XXII

Hardness and Tensile Properties of a Type 6F5 Tool Steel[a]

Tempering Temperature,[b] F	Brinell Hardness	Tensile Properties			
		Tensile Strength, psi	Yield Strength, psi	Elongation (2 in.), %	Reduction of Area, %
400	578	285,000	242,000	5	20
600	534	270,000	235,000	11	25
800	461	245,000	220,000	12	27
1000	420	220,000	195,000	13	28
1200	335	190,000	165,000	15	35

[a] Composition, %:
0.55 C, 0.90 Mn, 1.00 Si, 2.70 Ni, 0.40 Cr, 0.45 Mo, 0.13 V. Latrobe Steel Company.

[b] Oil quenched from 1600 F before tempering.

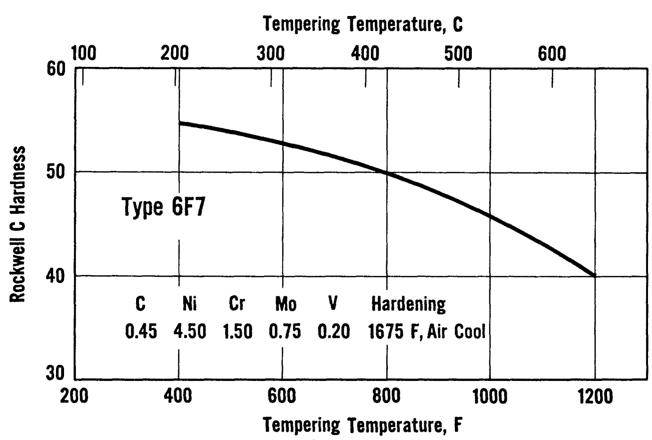

Fig. 22. Effect of tempering on the hardness of a Type 6F7 tool steel.

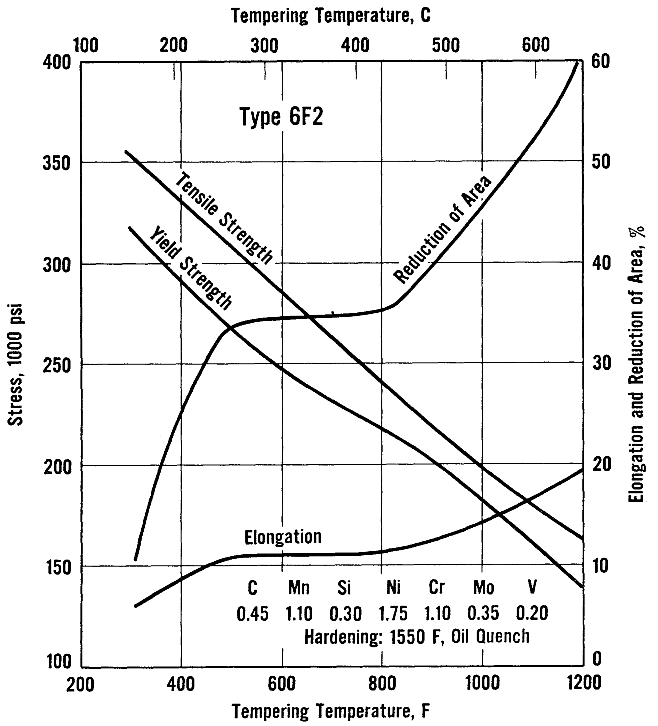

Fig. 23. Effect of tempering on the tensile properties of a modified Type 6F2 tool steel.

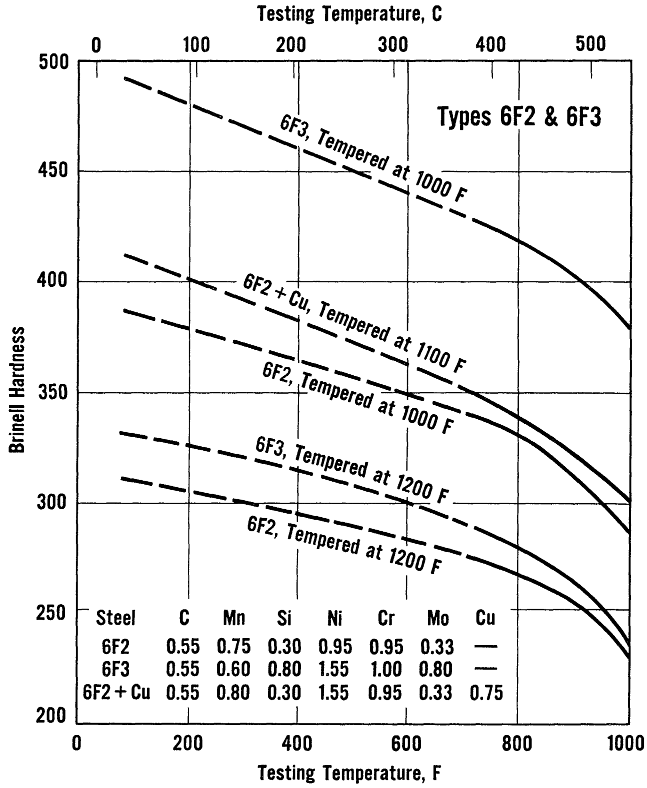

Fig. 24. Hot hardness of three hot work tool steels after 100 hours at temperature.

NON-MAGNETIC TOOL STEELS

The non-magnetic tool steels are high-manganese steels containing relatively large amounts of nickel and are modifications of the 13 per cent austenitic manganese (Hadfield) steel. These compositions are suited particularly for wear-resisting applications because of their great ability to work harden. Properties of several of these steels are given in Table XXIII.

TABLE XXIII

Composition and Mechanical and Physical Properties of Three Non-Magnetic Tool Steels[a]

Steel Type	11.5 Mn-7.5 Ni*	12 Mn-3.3 Ni-4 Cr-0.5 Mo*	12.5 Mn-3 Ni†
COMPOSITION			
Carbon, %	0.35	0.35	0.60- 0.90
Manganese, %	11.50	12.40	11.0 -13.5
Nickel, %	7.50	3.25	2.5 - 3.5
Chromium, %	0.50 max	4.15	—
Molybdenum, %	—	0.50	—
MECHANICAL PROPERTIES			
Tensile Strength, psi	80,000-95,000	115,000-150,000	140,000-150,000
Yield Strength (0.2% Offset), psi	30,000-60,000	55,000-100,000	55,000- 60,000[b]
Elongation (2 in.), %	25-50	35-45	72
Reduction of Area, %	30-60	40-50	54
Charpy Impact, ft-lb	50-70	60-80	—
Brinell Hardness	—	—	180[c], 550[d]
PHYSICAL PROPERTIES			
Density, lb/cu in.	0.285	0.286	—
Coefficient of Expansion (68 to 1832 F), per °F	11×10^{-6}	12.3×10^{-6}	—
Electrical Resistivity, microhm-cm	70	68	—
Magnetic Permeability (H = 200)	1.25 max	1.10 max	—

[a] Data from Jessop Steel Company* and Stulz-Sickles Steel Company.† [b] Elastic limit. [c] As rolled. [d] After work hardening.

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