DIE MATERIALS AND TREATMENTS

Tool steels are used to construct the die components subject to wear. They are used in a variety of pressworking operations. These steels are designed especially to develop high hardness levels and abrasion resistance when heat-treated.[1]

The plain carbon and low-alloy steels are readily machinable and weldable. These low cost steels are used for machine parts, keys, bolts, retainers, and for support tooling. Cast-steel dies are used for large drawing and forming dies where maximum impact toughness is required. At carbon levels of 0.35% and higher, cast-alloy-steel dies can be effectively flame-hardened at points of wear.

Cast irons are a plural term for cast iron because many different compositions having special properties are used for shoes, plates, dies, adapters and other large components. Die irons are often alloyed to permit flame hardening when used for the wear surfaces of large sheet metal drawing and forming dies. The ductile (nodular) irons retain the casting advantages of cast iron, while having toughness, stiffness and strength levels approaching those of steel.

In addition to ferrous die materials, varieties of die components are made of non-ferrous metals such as zinc and copper alloys. Elastomer products find widespread application as die pads, rubber springs and automation components. Even wood and wood fiber products are used for low-cost dies.

Characteristics of Tool and Die Steels

The steels listed in Table 1 are used in the great majority of the metal-stamping operations. The list contains 27 steels, which are available from many tool steel sources. Some of these steels have slight variations for improved performance under certain conditions. [2]

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[1] D. Jarvis, Metallurgy of Tool Steels, sponsored by the Society of Manufacturing Engineers Livonia, Michigan May 3-4 2000.

[2] D. Smith, ***Die Design Handbook***, Third Edition, Section 28, Ferrous Die Materials, the Society of Manufacturing Engineers, Dearborn, Michigan, © 1990. Rod Denton, Late President and Timothy Zemaitis, Metallurgical Engineer, Sun Steel Treating Inc., South Lyon, Michigan graciously assisted in editing the material in the Third Edition of the Die Design Handbook is work for technical content.

AISI	**Nominal Steel Composition Percent**							
Type	**C**	**Mn**	**Si**	**W**	**Cr**	**Mo**	**V**	**Other**
W1	**1.05**	**0.25**	**0.20**	——	**0.20**	——	**0.05**	——
W2	**1.00**	**0.25**	**0.20**	——	——	——	**0.20**	——
O1	**0.90**	**1.25**	**0.30**	**0.50**	**0.50**	——	——	——
O2	**0.90**	**1.60**	——	——	——	——	——	——
O6	**1.45**	**0.80**	**1.10**	——	——	**0.25**	——	——
A2	**1.00**	**0.60**	**0.30**	——	**5.25**	**1.10**	**0.25**	——
A8	**0.55**	——	**1.00**	**1.25**	**5.00**	**1.25**	——	——
A9	**0.50**	——	**1.00**	——	**5.20**	**1.40**	**1.00**	**1.40 Ni**
D2	**1.55**	**0.30**	**0.40**	——	**11.50**	**0.80**	**0.90**	——
D3	**2.10**	**0.40**	**0.90**	**0.80**	**11.70**	——	——	——
D4	**2.25**	**0.35**	**0.50**	——	**11.50**	**0.80**	**0.20**	——
D7	**2.30**	**0.40**	**0.40**	——	**12.50**	**1.10**	**4.00**	——
S1	**0.50**	——	**0.50**	**2.25**	**1.30**	——	**0.25**	——
S5	**0.60**	**0.85**	**1.90**	——	**0.20**	**0.50**	**0.20**	——
S7	**0.50**	**0.75**	**0.30**	——	**3.25**	**1.40**	——	——
T1	**0.75**	——	——	**18.00**	**4.00**	——	**1.10**	——
T15	**1.55**	——	——	**12.25**	**4.00**	——	**5.00**	**5.00 Co**
M1	**0.80**	——	——	**1.50**	**3.75**	**8.50**	**1.05**	——
M2	**0.85**	——	——	**6.25**	**4.15**	**5.00**	**1.90**	——
M4	**1.30**	——	——	**5.50**	**4.00**	**4.50**	**4.00**	——
M7	**1.00**	——	——	**1.70**	**3.75**	**8.75**	**2.00**	——
M42	**1.08**	——	——	**1.50**	**3.75**	**9.50**	**1.10**	**8.00 Co**
H12	**0.35**	——	**1.00**	**1.25**	**5.00**	**1.35**	**0.30**	——
H13	**0.38**	——	**1.00**	——	**5.20**	**1.25**	**1.00**	——
H21	**0.30**	**0.25**	**0.30**	**9.00**	**3.25**	——	**0.25**	——
H26	**0.53**	——	——	**18.00**	**4.00**	——	**1.00**	——
L6	**0.75**	**0.70**	——	——	**0.80**	**0.30**	——	**1.50 Ni**

W - Water Hardening
O - Oil Hardening
A - Air Hardening
H - Hot Working
D - High Carbon, High Chromium Die Steels
S - Shock Resisting
T - Tungsten Base, High Speed
M - Molybdenum-base High Speed
L - Special Purpose, Low-alloy

Table 1. Readily available tool and die steels. *Sun Steel Treating*

AISI-SAE letter and number designations identify the steels in this list. The letter represents the group of the steel involved. The number indicates a separation of one grade or type from another. The use of standard industry identification is encouraged rather than shop jargon and trade names to describe the steels.

Some highly alloyed steels made by the powdered metallurgy process rather than cast ingots produce a product of uniform composition and grain structure. This process permits the high volume production of tool steels that would be very difficult to make in any other way.

Choosing Tool Steels

The wise choice of tool steels is important when dies are designed in order to insure good wear performance. Specifying more costly tool steel than is justified by die wear requirements is wasteful.

Expensive die details should be designed for long wear. Likewise, die parts that wear rapidly requiring downtime for replacement and high repair costs should be designed for good wear resistance. The die repair activity should carefully track die repair costs as an aid to achieving the most cost effective tooling material and processing methods. This information should be used to update the die standards for each type of tooling. In this way, tooling dependability can be continuously improved and costs minimized.

W, Water-hardening Tool Steels

W1 and W2 are both readily available and low in cost. W2 contains vanadium, which provides a finer grain size attended by lower hardenability and higher toughness. Both are shallow hardening. In large sections, this results in a hard case and a softer internal core, having high toughness. Closely controlling the vanadium content helps assure a more closely level of hardenability, especially when compared to W1. They are quenched in water or brine and are subject to substantial size changes when heat-treated.

In the past, these steels were more popular than at present because of low cost and were widely used for short to medium run tooling. They are still a good choice for a variety of applications where cost is a prime factor such as short run automotive applications. Automotive body panel dies seldom exceed one million pieces per model year.

O, Oil-hardening Tool Steels

Steels O1 and O2 were once the workhorses of the industry. These are known as manganese oil-hardening steels. They are readily available and low in cost. These steels, which are normally quenched in oil, have less size change than the water-hardening steels. Compared to the water hardening steels, they are easier to harden throughout the workpiece and are at least equally tough. Type O6, which contains free graphite, has excellent machinability.

AISI Steel Type	Preheat Temperature	Rate of Heating For Hardening	Hardening Temperature Degrees	Minimum Time at Temperature, Minutes	Quenching Medium
W1	**1200°/1250° F 649º/677º C**	**Slow**	**1425°/1500°F 774º/816ºC**	**15 min.**	**Brine or Water**
W2	**1200°/1250° 649º/677º C**	**Slow**	**1425°/1500°F 774º/816ºC**	**15 min.**	**Brine or Water**
O1	**1200°/1250° 649º/677º C**	**Slow**	**1450°/1500°F 788º/816ºC**	**15 min.**	**Warm Oil**
O2	**1200°/1250°F 649º/677º C**	**Slow**	**1400°/1475°F 760º/802ºC**	**15 min.**	**Warm Oil**
O6	**1200°/1250° 649º/677º C**	**Slow**	**1450°/1500°F 788º/816ºC**	**30 min.**	**Warm Oil**
A2	**1450°/1500°F 788º/816ºC**	**Slow**	**1725°/1800°F 982º/1,010ºC**	**30 min.**	**Air, Salt, Oil**
A8	**1450°/1500°F 788º/816ºC**	**Slow**	**1800°/1850°F 788º/816ºC**	**30 min.**	**Air, Salt, Oil**
A9	**1450°/1500°F 788º/816ºC**	**Slow**	**1800°/1850°F 982º/1,010ºC**	**30 to 60 min.**	**Salt, Air**
D2	**1450°/1500°F 788º/816ºC**	**Slow**	**1800°/1875°F 982º/1,024ºC**	**30 min.**	**Salt, Air**
D3	**1450°F 788ºC**	**Slow**	**1750°F**	**30 min.**	**Warm Oil**
D4	**1450°/1500°F 788º/816ºC**	**Slow**	**1800°/1850°F**	**30 min.**	**Air, Salt, Oil**
D7	**1450°F 788ºC**	**Slow**	**1875°/2000°F**	**45 min.**	**Air, Oil**
S1	**1400°F 760ºC**	**Slow**	**1700°/1750°F**	**15-20 min.**	**Salt, Warm Oil**
S5	**1250°F 677ºC**	**Slow**	**1550°/1650°F**	**15-20 min.**	**Salt, Oil, Water**
S7	**1200°/1300°F 649º/704ºC**	**Slow**	**1725°/1750°F**	**20 min.**	**Oil, Salt**
T1	**1500°/1600°F 816º/871ºC**	**Quickly from preheat**	**2100°/2350°F**	**3-7 min.**	**Salt, Warm Oil**
T15	**1450°/1550°F 788º/843ºC**	**Quickly from preheat**	**2175°/2275°F**	**3-5 min.**	**Salt, Warm Oil**
M1	**1500°/1550°F 816º/843ºC**	**Quickly from preheat**	**2150°/2225°F**	**2-5 min.**	**Salt, Warm Oil**
M2	**1500°/1550°F 816º/843ºC**	**Quickly from preheat**	**2175°/2275°F**	**3-7 min.**	**Salt, Warm Oil**
M4	**1500°/1550°F 816º/843ºC**	**Quickly from preheat**	**2150°/2250°F**	**3-7 min.**	**Salt, Warm Oil**
M7	**1500°/1550°F 816º/843ºC**	**Quickly from preheat**	**2175°/2225°F**	**3-7 min.**	**Salt, Warm Oil**
M42	**1500°/1550°F 816º/843ºC**	**Quickly from preheat**	**2150°/2200°F**	**3-7 min.**	**Salt, Warm Oil**
H12	**1400°/1500°F 760/816ºC**	**Slow**	**1825°/1875°F 996º/1024ºC**	**30-60 min.**	**Salt, Air**
H13	**1400°F 760ºC**	**Slow**	**1825°/1875° 996º/1024ºC**	**30-60 min.**	**Salt, Air**
H21	**1500°F 816ºC**	**Slow**	**2000°/2250°F**	**10-30 min.**	**Oil, Air**
H26	**1500°F 816ºC**	**Slow**	**2100°/2250°**	**10-30 min.**	**Oil, Air**
L6	**1200°/1250°F 649º/677º C**	**Slow**	**1450°/1550°**	**30 min.**	**Warm Oil**

Table 2. Hardening and tempering treatments for tool and die steels.

AISI Steel Type	Tempering Temperature Degrees	Depth of Hardening	Resistance to Decarburization	As Quenched Hardness RC	Maximum Tempered Hardness RC
W1	350°/550°F 177°/288°C	Shallow	Best	65-67	62-64
W2	350°/550°F 177°/288°C	Shallow	Best	65-67	62-64
O1	350°/600°F 177°/316°C	Medium	Good	63-65	62-64
O2	350°/600°F 177°/316°C	Medium	Good	63-65	62-64
O6	350°/600°F 177°/316°C	Medium	Good	63-65	61-63
A2	350°/950°F 177°/510°C	Deep	Fair/Good	63-64	62-63
A8	350°/950°F 177°/510°C	Deep	Fair	62	60-62
A9	350°/1000°F 177°/538°C	Deep	Poor/Fair	58	56-58
D2	350°/1000°F 177°/538°C	Deep	Fair	62-64	61-63
D3	350°/950°F 177°/510°C	Deep	Fair	63-65	61-63
D4	400°/1000°F 204°/427°C	Deep	Fair	63-65	61-63
D7	300°/1000°F 149°/538°C	Deep	Fair	65-67	65
S1	300°/800°F 149°/427°C	Medium	Fair	57-59	56-58
S5	300°/800°F 149°/427°C	Medium	Fair	60-62	59-61
S7	400°/1000°F 204°/538°C	Medium	Poor/Fair	58-60	57-59
T1	1000°/1100°F 538°/593°C	Deep	Good	64	64-65
T15	1000°/1100°F 538°/593°C	Deep	Fair/Good	64-66	66-68
M1	1000°/788°/8538° C/621°F	Deep	Fair	64-66	65-67
M2	1000°/1100°F 538°/593°C	Deep	Fair	65-66	64-65
M4	1000°/1100°F 538°/593°C	Deep	Fair	65-66	65-66
M7	1000°/1100°F 538°/593°C	Deep	Fair/Good	66-67	65-67
M42	975°/1075°F 524°/579°C	Deep	Fair/Good	64-66	67-69
H12	1000°/1100°F 538°/593°C	Deep	Fair	51-53	51-53
H13	1000°/1150°F 538°/621°C	Deep	Fair	54-56	53-56
H21	950°/1250°F 510°/677°C	Med./Deep	Fair	53-55	54-55.5
H26	1000°/1200°F 538°/647°C	Deep	Fair/Good	57-59	56-58
L6	350°/600°F 177°/316°C	Medium	Good	62-63	62

Table 2. (Continued)

A, Air-hardening Die Steels

The most popular air-hardening die steel is A2. This steel has low size change when hardened, and has higher toughness than the oil hardening die steels. Compared to oil-hardening steels, the wear resistance is equal or superior. The availability of the popular A2 steel is excellent. Type A8 is the toughest steel in this group, but its low carbon content makes it less wear-resistant than A2.

D, High-carbon High-chromium Die Steels

The principal steels of wide application for long-run dies are steels in this group. Grade D2 containing 1.50% carbon is of moderate toughness and intermediate wear resistance. Grades D3, D4 and D7, contains additional carbon, which increases wear resistance, however, the toughness is somewhat lower. Selection between the grades is based on the length of run desired, machining and grinding problems. D2 and D4, containing molybdenum, are quenched in air and have low size change when hardened. Type D2 tends to be overspecified compared to the S and M series.

S, Shock-resisting Tool Steels

These steels contain less carbon and higher toughness than the high carbon types that are more wear resistant. Shock resistant steels are used where heavy cutting or forming operations is required and chipping or breakage of high-carbon wear-resistant steels is a problem. Choice among the grades is usually determined by finding which type provides the best results in service. All steels are readily available, with S5 and S7 being widely used. Grade S5 is an oil-hardening type of silicomanganese steel and is more economical than steel S1. S5 has equivalent toughness properties with greater wear resistance compared to S1.

S7 can be quenched in air up to sections of three inches (76 mm) or more. For thicker sections interrupted oil or complete oil, quenching may be used. The S series tool steels are superior to most other steels for severe work where chipping is a problem. As a class, the S series tool steels should be specified more often, especially where extreme toughness and a reduction of chipping problems are required.

T and M, Tungsten and Molybdenum High-speed Steels

High-speed steels T1 and M2 are approximately equal in performance and have excellent properties for cold work dies. They have higher toughness than most other tool steels, combined with excellent wear resistance.

High-speed steels are often less costly and give better performance than the popular D2 tool steel. They are also readily available. T15 and M4 are hardened in a neutral atmosphere rather than carburizing because they already have a very high carbon combined with high vanadium content.

AISI Steel Type	Non Deforming Properties	Safety In Hardening	Tough-ness	Resistance to Softening Effect of Heat	Wear Resist-ance	Decarburi-zation Risk During Heat Treatment	Brittle-ness	Machin-ability
W1	L	F	G	L	G	L	L/M	B
W2	L	F	G	L	G	L	L/M	B
O1	G	G	G	L	F	L	L	G
O2	G	G	G	L	F	L	L	G
O6	G	G	G	L	F	L	L	B
A2	B	B	F / G	F	G	L	L	F/G
A8	G / B	B	B	G	G	M	L	F/G
A9	B	B	B	B	G	M	L	F/G
D2	B	B	L / F	F	G	L	L	L
D3	G	B	L	F	G/B	L	L	L
D4	B	B	L	F	G/B	L	L	L
D7	B	B	L / F	F	B	L	L	L
S1	F	F / G	B	F	F/G	M	L	G
S5	F	G	B	F	G	L	L	G
S7	F	G	B	F	G	M	L	G
T1	G	G	G	B	G/B	L	L	F
T15	G	G	L	B	B	L	M	L/F
M1	G	G	G	B	G/B	L	L	F
M2	G	G	G	B	G/B	L	L	F
M4	G	G	G	B	G/B	L	L	F
M7	G	G	G	G/B	B	L	L	F
M42	G	G	G	G/B	G/B	L	L	F
H12	G	G / B	G / B	G/B	F/G	L/M	L	F/G
H13	G	G / B	G / B	G/B	F/G	L/M	L	F/G
H21	G	G	G	G/B	F/G	L/M	L	F/G
H26	G	F	F	B	B	L/M	L	F/G
L6	F/G	G	G	L	F	L/M	L	G

L - Low **F - Fair** **M - Medium** **G - Good** **B - Best**

Table 3. Comparison of basic characteristics of tool and die steels.

Application	AISI Steel Type, Group	Hardness Rc
Blanking Dies and Punches (Short Run)	**O, A, W**	**58-60**
Blanking Dies and Punches (Long Run)	**A, D** **M**	**60-62** **61-63**
Bending Dies	**O, A, D**	**58-60**
Coining Dies	**S** **W** **D**	**52-54** **57-59** **58-60**
Drawing Dies	**H** **W, O** **D**	**52-54** **58-60** **50-62**
Dies — Cold Extrusion	**W** **D** **M**	**59-61** **60-62** **62-64**
Dies — Embossing	**W, L, O, A, D**	**58-62**
Dies — Lamination	**D, A, M** **M, D**	**60-62** **58-60**
Dies — Sizing and Ironing	**W**	**59-61**
Punches — Embossing	**S**	**58-60**
Punches — Trimming	**W, D, O. A**	**58-60**
Punches — Notching	**M**	**60-62**

Table 4. Some examples of applications of tool steels including typical hardness. These are representative examples of a few applications of steels for cold work operations.

Type M1 may occasionally be used in place of T1 and M2, but it is more susceptible to decarburization. Steel T15 is the most wear-resistant of all steels in the list. Steel M4 is slightly greater in wear resistance than tool steels such as D4. These steels are more difficult to machine and grind than the other high-speed steels, but the improved performance obtainable often justifies the extra machining expense.

L, Low-alloy Tool Steels

Of the many low-alloy steels effective as die materials, steel L6 is chromium-nickel steel. In large sizes, it is water-quenched and has a hard case and a soft core, with a high overall toughness. In small sizes, it may be oil-quenched.

H, Hot Working Steels

Die casting dies, extrusion dies, hot forming dies and hot drawing mandrels are typical hot-work applications for these tool steels. Type H13 is widely used for plastic molding dies. Modern cavity sinking is nearly all done with high speed CNC machining or die sinking EDM. These processes permit rapid material removal and good surface finishes. To take advantage of the high metal removal rates of modern CNC profile milling machines, coated ceramic and tungsten carbide cutters capable of high metal removal rates are used. Mold steels such as H13 are available as prehardened material.

Other Steels used in Tooling

Many alloy steels used in machine and aircraft construction find application as tool steels. Of these, AISI-SAE 4140 is very popular. It is readily available in a wide variety of sizes including material prehardened for toughness. Alloy 4140 weldable and can be coated for wear resistance. It is a good choice for drawing and forming tooling that must be built quickly in an emergency. While it is not recommended for long run tooling, dies built of 4140 to meet emergency production requirements have held up for long production runs over several years without the need to built higher quality tooling.

Heat Treatment of Die Steels

Iron has two distinct and different atomic arrangements—one existing at room temperature (and again near the melting point) and one above the transformation temperature. Without this phenomenon, it would be impossible to harden iron-based alloys by heat treatment.

Simplified Theory of Hardening Steel

Briefly, Figure 1 represents what happens in the heat treatment of die steels graphically. Starting in the annealed machinable condition **A**, the steel is soft, consisting internally of an aggregate of ferrite and carbide. Upon heating above the iron-carbon euctectoid transformation temperature of 1333° to 1700° F (723° to 927° C), the crystal structure of ferrite changes. The ferrite becomes austenite **B**, and dissolves a large portion of the carbide.

This new structure, known as austenite, is always a prerequisite for hardening. By quenching, cooling tool steel rapidly to room temperature, the carbon is retained in solution, and the structure known as martensite **C** results. This is the hard-matrix structure in steels.

Simplified Theory of Hardening Tool Steel

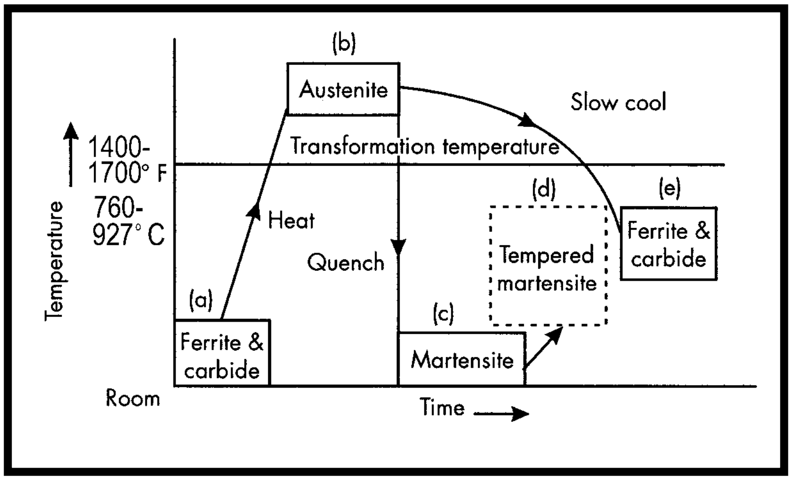

Figure 1. A simplified chart illustrating the sequential process for hardening steel.

Quenching and Tempering Tool Steels [3]

The rapid cooling results in high internal stresses. The transformation from austenite to martensite involves some volumetric expansion. This adds further stresses particularly in parts of varying cross section. These stresses together with the hard, brittle nature of martensite can be sufficient to cause cracking. To avoid this, the steel is reheated to an intermediate temperature **D** to soften the part to the desired hardness level. This operation known as tempering or drawing also serves to relieve those residual stresses which otherwise would cause brittleness in the steel.

If quenching is not rapid enough, the austenite reverts to ferrite and carbide **E**, and high hardness is not obtained. The rate of quenching required to produce martensite depends primarily on the alloy content. Low alloy steels require rapid cooling in water or oil, while highly alloyed steel usually can be air-quenched at a much slower rate.

Throughout all these heat-treating reactions, most die steels retain excess, or undissolved carbides, which take no direct part in the hardening. The high carbon high-chromium steels, for example, have large quantities of excess iron-chromium carbide, which give them in large measure the high degree of abrasion resistance possessed by this class of steel.

Influence of Heat Treatment on Die Life

Each type of die steel must be handled slightly differently from any other for optimum results. Different temperatures, different heating and cooling rates and variable tempering procedures must be used as recommended.

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[3] S. G. Fletcher, ***The Selection and Treatment of Die Steels***, The Tool Engineer, April 1952. The diagram provides an easy to understand explanation of the heat-treating process. It is reproduced in the third and previous editions of reference 2.

In general, it may be said that the harder a given die, the longer it will wear, while the softer a die is, the tougher it becomes. Assuming the proper die steel is being used, dies which are wearing out too quickly should be made harder for improved life and dies which are breaking or cracking should be made softer.

Within limits, heat treatment can be used to adjust these variables to best advantage. Oil-hardening steel may work best on one application at Rockwell C62 and on another involving higher stresses and shock at Rockwell C58. Adjustments of the drawing temperature easily produce the hardness desired.

Double drawing and in some instances triple drawing is desirable for tools in severe applications. This is because steels retain austenite when quenched. The first temper affects the martensite formed during quenching and conditions the austenite so that it transforms upon air-cooling from the draw. Double drawing is necessary to affect the martensite, which forms after the first draw. Triple drawing eliminates nearly all retained austenite, further increasing toughness.

Cold and Cryogenic Treatment

Cooling to very low temperatures, as part of the drawing process will maintain hardness while actually improving the toughness and fatigue strength of hardened tool steel. This improvement occurs due to the continued transformation of retained austenite into the more desirable martensite, at temperatures from -120° to -300° F (-84° to -184° C).

In some tool steels, the martensite finish temperature, which is the temperature at which the austenite to martensite transformation is completed, is below room temperature. Here cold treatment at -120° F (-84° C) extends the range of heat-treating temperatures and enhances the transformation of austenite. Cold treatment is often done between the last two draws.

Cryogenic treatment occurs at the temperature of liquid nitrogen, which is approximately -300° F (-184° C). Size change is negligible but can occur if the material is not properly heat-treated. Cryogenic treatment should not be used to attempt to correct poor heat treatment practices. Multiple draws or tempers should not be eliminated knowing that the cold process will convert austenite to martensite. The value of cryogenic treatment is not fully agreed upon within the tooling industry.

Control of Surface Chemistry

Furnaces for heat-treating tool-steels are often equipped with gas generators that provide an atmosphere containing a controllable amount of carbon. Without a protective atmosphere, surface decarburization to a considerable depth can occur because of the oxidizing effects of free oxygen, water vapor or carbon monoxide. Typical decarburization rates are 0.010 in. to 0.030 in. (0.25 to 0.76 mm) per hour. The loss of surface carbon can produce poor wear resistance. It is customary to make tools sufficiently oversize so that they can be ground to remove the surface affected by chemical change during heat treatment.

If the atmosphere used to heat dies for hardening is strongly reducing, it is possible to carburize the surface although the carbon content is already quite high. A carburized case may be beneficial to tool life if not carried to excess.

Shops doing only a small amount of heat-treating often wrap the die details to be heat-treated in a stainless steel or titanium foil especially produced for the purpose. This procedure effectively avoids decarburization without the expense of maintaining an atmosphere furnace. The most popular tool steel heat treated in this way is A2.

Molten salt baths provide decarburization protection for die steels. Careful maintenance involving desludging and rectification is necessary to maintain a neutral condition. Various molten salts are used for both heating steels to quenching temperature and as a quenching medium. In some cases, the recommended quenching procedure might involve a high temperature initial quench in molten salt followed by cooling to room temperature in oil or air.

Control of Dimensional Change

Dimensional changes occur during the hardening operation on dies because the hardened steel occupies a greater volume than the annealed steel from which it came. Unfortunately, the dimensional changes, which result from the volume of change, are usually not the same in all three directions, making it impossible to predict the changes accurately. The size and shape of the individual workpiece are the most important factors influencing this variable.

The dimensional changes resulting from hardening may vary from nil up to approximately three parts per thousand. Dimensional changes of this amount are of no concern, provided enough grind stock is allowed for complete removal of scale and decarburization.

If the furnace atmosphere or salt bath is carefully controlled, there may be little or no scale or decarburization. If grind stock is not required, the avoidance of dimensional changes is of great importance.

Air-hardening tool steels usually produce dimensional changes, which are less than one part per thousand and therefore are widely used where minimal size change in heat treatment is needed. It is also possible to control the size changes in tools made of type D2 high-carbon high-chromium steel to so-called “zero size change” by an austenite-martensite balance control obtained by multiple tempering.

Keeping data on the size changes that actually occur when identical die details are heat-treated is a good practice. From this information, dimensional allowances for expected size changes could be made.

Die Design for Successful Heat Treatment

Tool steels cannot be selected based on dimension alone. The designer must consider the type of steel used, with particular regard as to whether the steel is quenched in water, oil or air. Generally, liquid-hardened tools must be conservatively designed, while air-hardened tools can incorporate features, which would cause cracking during liquid quenching. The design of a tool must also take into account the equipment available for heat treatment.

Tool Steel Production Methods

Tool steels are produced by a variety of methods. At one time, essentially all tool steels were made by the cast ingot process. These products are known as cast and wrought tool steel alloys. This is still a high volume method of producing tool steels. Great care is required to produce uniform tool steel by any process. The size of the ingot is limited by problems with segregation of the elements that make up the tool steel.

The alloying element segregation problem tends to limit the ingot size of highly alloyed tool steels made by this process. Vacuum degassing may follow the melting process. In addition, producing tool steels in a vacuum is superior to melting in the presence of atmospheric gases.

There is still a considerable volume of tool steel including A, D and H series produced by this process. The cast ingots are rolled or press forged into the desired finished product. Finally, the material is annealed and finished as required.

This process is used for the production of most of the tool steel grades. For higher carbon, higher alloy or for applications requiring steels having exceptionally good shock resistance or exceptional wear resistance, alternative production methods are used.

Using careful procedures to insure clean homogeneous steel, this process remains popular for the majority of commercial tool steels. The main limiting factors are the extent to which the steel is alloyed, the alloying elements used and the size of the ingot required.

Electro Slag Remelted Tool Steels

Electro slag remelting is a process used to produce a variety of quality steel alloys including tool steels. A highly useful application early in the development of this process is the production of critical parts alloyed steel such as turbine shafts. Very clean homogeneous tool steels are produced by use of the electro slag remelting process.

The tool steel alloy is first cast into a conventional ingot using melt and cast technology. Next, the ingot is then refined in a vertical furnace by means of electro slag remelting.

The conventionally cast ingot to be purified is suspended at the top of the furnace opening. A special molten slag separates that ingot from a metallic starter plate that forms the bottom of the vertical cylindrical furnace.

The current melts both the slag and the end of the old ingot being fed into the furnace. Electrical current passes through the ingot being remelted and purified as it seeps through the slag and forms a new ingot on the bottom of the cylindrical furnace, which is water-cooled. Since the slag serves to both purify the steel alloy and protect the new ingot from atmospheric gasses, the purified ingot is quite pure and very homogenous.

Vacuum Arc Remelting

Vacuum arc remelting (VAR) of tool steel is used for secondary or premium melting of tool steels. The results are much the same as the ESR process. The VAR process produces steels having excellent microcleanliness.

Powder Metallurgy Tool Steels

Tool-steel produced by the powdered metallurgy process is first atomized in a non-reactive gas atmosphere into very fine particles having uniform properties. This material is placed in large steel canisters, which are evacuated and sealed shut. Placing the canisters in a hot isostatic compacting furnace and heating under pressure to fuse the canister’s contents into a solid inclusion free ingot produce solid powder metallurgy steel. A combination of heat and high-pressure gas fuses the steel powder into a homogeneous mass.

The chief advantages of this process are uniformity and freedom from the imperfections due to segregation of constituents associated with the cast ingot process. Tool steels such as AISI grades D2, M2 and M4 produced by the powder metallurgy process have better uniformity than the corresponding wrought product.

Higher alloy constituencies than can be obtained conventional melt and cast technology are possible. For example, powdered metallurgy tool steels produced by the Crucible Materials Corporation containing 10% to 15% vanadium have a substantial amount of vanadium carbide in the heat-treated tool steel matrix exhibit extreme resistance to abrasion.

A Crucible Powder Metallurgy grade 3V™ has toughness approaching grade AISI grade S7 and substantially higher wear resistance. Grades V3, V10 and V15 are trademarks of the Crucible Materials Corporation. Depending on the application, they may outperform most of the tool steels listed in Tables 1 through 4.

Repairing Dies by Welding

Three welding methods are used for die repair. These are the shielded metal arc welding (SMAW) or stick electrode-welding process, which is the most popular because of its versatility and wide range of filler metals available.

Another popular process is the gas metal arc welding (GMAW), also known as MIG or wire welding. The filler metals are available as either solid or tubular wire. The latter offers the widest range of alloy selection.

Optimum operator control is offered by the gas tungsten arc welding (GTAW) also called TIG or heliarc welding. The selection of filler rods is somewhat limited.

Die Welding Applications

In die welding, wear resistant alloys are applied to the surface of dies to increase service life, avoid down time, or to rebuild or repair dies that have been damaged. Welding is useful to correct machining errors and to increase the wear resistance of die surfaces. Varying degrees of hardness, toughness and wear resistance is available in welding alloys depending upon the application.

Die Welding Materials

Tool steel welding materials are normally heat treatable alloys. Alloys for SMAW (stick) welding have a wire core covered with a flux coating, which may also contain alloy constituents, including rare earth elements. During the welding process alloying elements in the flux coating melt with the wire core. This molten filler metal passes across the arc. It forms a homogeneous weld deposit on the workpiece.

The tool steel groups most commonly repaired by welding are water, oil and air hardening steel. The degree of welding difficulty depends on the alloy content of the base metal. Usually steels with higher carbon contents require higher preheats before welding, more care during welding, and greater care in tempering after welding.

Base Metal

Tool steel welding requires taking precautions similar to those necessary with any other type of welding process to prevent cracking of the base metal during heating and cooling. All base metals with carbon content higher than 0.35% should be pre-heated and post-heated to decrease brittleness in the base metal near the heat-affected zone.

High-carbon alloy steels such, as air-hardening tool steels are more difficult to weld because of the likelihood of cracking, thus requiring greater care and procedural control. Hot extrusion tools are a notable example of successful use of this type of repair.

In welding, tensile stresses occur upon cooling. These stresses are often mechanically relieved as cooling takes place. Careful peening with a pneumatic hand tool between each pass upsets the weld metal. The finished weld must be as stress free as possible, although slight compressive stresses are not harmful.

Repairing Cast Iron

Welding cast iron requires a different method of application of the weld from that for steel because cast iron melts at a lower temperature. Nickel materials with lower melting temperatures are excellent for underlayment on cast irons. Generally, after careful preparation involving grinding out the area to be repaired and preheating, a deposition of nickel alloy weld is made, followed by the desired welding material required to obtain the needed surface properties. In all welding operations on cast iron careful pre-heating and post-heating is a necessity.

Welded trim edges can be built up on iron castings. Generally, two types of weld are deposited. A layer of unique nickel alloy weld is deposited first to act as a buffer for the hard weld material that forms the cutting edge. Materials commonly used include AISI-S7, H12 and H19.

The buffer layer serves to prevent excessive carbon and other elements from the gray iron mixing with the air hard weld and changing its properties. The nickel alloy layer also provides a good bond with the casting. The final cutting edge is built up with air-hard weld. After cooling to room temperature, the casting is carefully tempered.

Brazed Repairs of Broken Iron Castings

Brazing can repair large broken iron die-castings and press parts. Preparation by machining, chipping or grinding is required to provide a large area for adhesion of the braze material. Studding the surfaces with unalloyed low carbon threaded studs will improve adhesion. Again, careful procedural control including peening, pre and post heating are necessary for success.

Die Surface Coatings and Treatments

The uses of die surface coatings, treatments and plating is increasingly important to increase tool life and reduce the lubricant requirements. The use of coatings or other surface modifications is often an effective means to eliminate the need for extreme pressure additives. Lubricants considered to contain hazardous materials often require disposal as hazardous waste.

Chromium Plating

A thin layer of chromium may be applied to forming and drawing dies in order to increase wear resistance and reduce galling. This chromium-plated surface has a very low coefficient of friction with excellent non-galling characteristics.

The usual practice is to apply a layer of chromium 0.0005 to 0.001 in. (0.013 to 0.025 mm) thick to a very finely ground or polished surface. The time taken to polish the surface is well spent. Any defects or irregularities present on the surface prior to plating will show through and actually be more objectionable after the plating process.

Chromium plating is also used to repair worn dies. It is possible to build up a layer of as much as 0.010 in. (0.25 mm), or more of chromium on a worn surface and thus, increase the total production life of the die.

Gas Nitriding

The use of gas nitriding to produce a hard, wear-resisting case on steels has been commercially practiced for many years. This procedure can be used also on some tool steels to improve wear resistance.

Gas nitriding can be used on tool steels which do not temper back excessively at the nitriding temperature, typically 975° F (524° C). This limits gas nitriding largely to the hot-work steels and the high-carbon high-chromium grades. High-speed steels form an exceptionally brittle nitrided case; therefore, gas nitriding should not be used on these steels.

Gas nitriding of tool steels requires from 10 to 72 hours. Typical case depths range from 0.002 to 0.018-inch (0.05 to 0.46 mm).

Ion Nitriding

Uses range from improving the wear resistance of small tool steel die sections to large iron alloy sheet metal drawing punches weighing 10 or more tons. Unlike the older gas nitriding process, a *glow discharge* or *ion processing* takes place when a DC voltage is applied between the furnace as the anode and the workpiece as the cathode. The furnace atmosphere consists of nitrogen gas under much less than atmospheric pressure.

The nitrogen gas in the furnace becomes ionized and emits electrons with a negative charge, and ions of nitrogen, which are positively charged. These are attracted toward the cathode, which is the workpiece. The ions are accelerated to a high velocity by the sharp electrical potential drop just in front of the cathode surface. Here, the ions energetically bombard the workpiece. [4]

Ion nitriding furnaces large enough to process the largest dies commonly used in the automotive, appliance and aerospace industry are available. The ion nitriding process is more costly than chromium plating in large die applications but provides longer wear live and is easier to repair without destroying the hard case.

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[4] R. Denton, Late president of Sun Steel Treating, ***Application of Ion Nitriding***, Society of Manufacturing Engineers, Selecting Tooling Materials and Tooling Treatments for Increased Tool Performance Clinic, November 1989.

Titanium Nitride (TiN) and Titanium Carbide (TiC)

Both of these coatings improve the life of tools by acting as a chemical and thermal barrier to diffusion and fusion. The coatings are very thin, typically 0.0001 to 0.0003 in. (0.0025 to 0.0076 mm) in thickness, and quite hard. Although the thin coatings are very brittle, they tend to assume the ductility and deformation characteristics of the substrate material. The coatings are also quite lubristic, serving to lower the coefficient of friction between the tool and the workpiece. By depositing TiN or TiC onto a steel or carbide tool, the improvement in lubricity causes the tool to resist galling.

Physical Vapor Deposition of Titanium Nitride

This coating process is carried out in a high vacuum at temperatures between 400° to 900° F (204° to 482° C). This range of temperatures does not exceed those used to draw hardened high-speed tool steel. Because there is very little distortion or size change on the workpiece, this coating process is frequently used to coat finished punches and buttons whenever rapid wear or galling is found a problem.

The plasma source coats the workpiece in a straight line of sight process. Special rotating fixtures with water-cooling may be required to insure that all surfaces are evenly coated, and that small sections are not overheated. A TiN coating deposited by the PVD process is easily recognized by its gold color.

Chemical Vapor Deposition of Titanium Carbide and Nitride

This coating process is done at much higher temperatures, 1740° to 1920° F (949° to 1049° C) than the PVD process. For this reason, it is a normal practice to follow the coating procedure with a conventional heat treatment of the tool steel substrate.

TiC is limited to tool steel and solid carbide die materials because the substrate surface must act as a catalyst. It is superior to PVD coatings when extreme abrasive wear is a problem. The coating is deposited from a vapor; so uniform coating including blind slots and blind holes is possible.

A CVD coating is dull gray in color. When a CVD-coated tool is polished, the resultant tool is silver, indistinguishable from the base metal.

Thermal Diffusion (TD)

The TD process is performed by immersing parts in a fused salt bath at temperatures of 1600° to 1900° F (871° to 1039° C) for one to eight hours. Carbide constituents dispersed in the salt bath combine with carbon atoms contained in the tooling substrate, which must contain at least 0.3% carbon or greater. The carbide layer most commonly produced is vanadium carbide; although, depending on the composition of the salt bath, other carbides can be deposited. These include niobium carbide, chromium carbide, and in some newer processes, a niobium vanadium combination. There is a die part size limitation due to limitations on salt bath size, which is a limiting factor on the application of this process.

Choice of Methods

The CVD coating method can deposit both TiN and TiC. Coatings can be applied to all tool steels as well as solid carbide tooling. When very high wearability qualities are required, and the distortion caused by the post coating heat treatment that is usually needed is not a problem, CVD may be the best choice.

PVD is a low temperature process that can be applied to all tool steels, but is generally used to increase the wearability of finished high-speed steel parts, solid carbide and brazed carbide tooling.

CVD coating requires a post heat treatment to restore the hardness to the steel substrate. In the TD process, popular tool steels such as D2 and A2 are usually quenched upon removal from the fused salt bath. The diffused layer, typically of vanadium carbide, is quite thin, but is exceedingly hard, having higher hardness than tungsten carbide. In situations requiring high volume production runs, tungsten carbide is also treatable.

Wrought Low Carbon Steels and Cast Irons

Wrought-steel plate, rounds and shapes are often used in the fabrication of brackets, frames, feeding, ejecting and transfer mechanisms, and other die auxiliary devices where structural strength and weldability rather than wear resistance are the primary requirements. Short-run steel dies are sometimes made with carburized hot-rolled-steel wear surfaces. Where the properties of AISI-SAE 1018 or similar steel (boilerplate) suffice, they have the advantage of being readily available and economical.

Cast Carbon and Low-Alloy Steels

Cast-steel shoes and other die components are often used for large drawing, forming or trimming dies where a combination of high toughness and strength is required. These steel castings are usually annealed or normalized to provide a homogeneous structure, free from casting stresses. Heat-treating or flame hardening is often employed to obtain the desired strength, wear resistance and toughness.

Cast and Ductile Die Irons

The high compressive strengths, manufacturing economy, and ease of casting gray cast iron make this material useful, especially in large forming and drawing dies. Soft, unalloyed gray irons are widely used for plates, jigs, spacers and other die parts.

Fully pearlitic irons with random uniform flake-graphite structures are excellent for wear resistance. Resistance to wear is significantly improved by flame hardening draw radii or other wear areas. Alloy additions of chromium, molybdenum and nickel are commonly used to produce uniform pearlite structures and to improve the iron's response to flame hardening.

The ductile (nodular) irons retain the casting advantages of cast iron, but because of the free graphite present in spheroidal shape rather than in flake form, this material develops toughness and strength levels approaching those of steel.

This combination of properties is especially useful in large forming and drawing dies where heavy impact loads or high transverse stresses are encountered. It should be specified for dies where breakage has occurred with gray iron castings.

Nonferrous and Nonmetallic Die Materials

Dies made of nonferrous materials are used for a variety of reasons. They are economical for limited production runs including experimental models. Often they have superior functioning, such as preservation of part finish, relative lightweight and portability for extremely large tools. Other advantages may include corrosion resistance, ease of fabrication, and low lead-time requirements. Often, they permit fast, easy corrections when design changes are necessary. Nonferrous die materials include aluminum alloys, zinc-based alloys, lead-based alloys, bismuth alloys, cast-beryllium alloys, copper-based alloys, plastics, elastomers and tungsten carbides.

Dies made with tungsten carbide elements are most economical for large production quantities and for stampings having critical tolerances. Tungsten carbide is an expensive die material. Die parts made of tungsten carbide are also expensive because of their hardness (which makes them difficult to machine) and the close tolerances to which they are normally held.

Nonferrous Cast Die Materials

Cast aluminum bronzes are used for forming and drawing stainless steel and other difficult to work materials. They resist metal pickup, which often causes scratching, or galling. Proprietary bronzes (e.g., Ampco ® metal) cast to the die shape are used for such applications. These alloys are also used for die wear plates and die guide pin bushings where resistance to wear under conditions of high load capacity is required.

Zinc Based Alloys

Zinc alloy die materials have a higher tensile strength and impact resistance than pure zinc. The alloys can be cast into dies for blanking and drawing a variety of aluminum and steel parts, especially complicated shapes and deeper draws than are possible with plastic or wooden dies. The working surface is dense and smooth, and requires only surface machining and polishing. Dies made of this material are frequently mounted in die sets, and used for blanking light gages of aluminum.

Frequently one member of the die set is composed of a zinc alloy, and the other member is made of a softer material such as lead. Drop-hammer operations are an example. Harder punches are required for forming steel sheets where sharp definition is necessary. Worn and obsolete dies made of zinc alloy and lead is remelted to achieve nearly 100% material reuse. Lead punches, composed of 6 to 7% antimony, 0.04% impurities and the remainder lead, have been used with zinc alloy dies. Health concerns over the hazards of lead toxicity must be considered when using this material.

Various proprietary zinc alloys, such as those called Kirksite ® alloys, are available. A typical composition consists of 3.5 to 4.5% aluminum, 2.5% to 3.5% copper and 0.02% to 0.10% magnesium. The remainder is 99.99% pure zinc. In order to minimize health hazards from grinding dusts generated when working these materials, the impurity levels of lead and cadmium must be very low.

Cast Beryllium Copper and Bismuth Alloys

Cast alloys composed of beryllium, cobalt and copper have characteristics comparable to the Ampco ® alloys. Beryllium is a very toxic substance, and proper precautions regarding ventilation and industrial hygiene must be taken when working with these alloys.

Some alloys of bismuth are used as a cast in place material to secure punch and die parts in die assembly. These low melting point alloys are as cast punches and dies for short run forming and drawing operations. These alloys are classified as low melting point alloys. The melting temperature of some of these alloys occurs below the boiling point of water.

Carbide Die Materials

Cemented carbides consist of finely divided hard particles of the carbide of a refractory metal. The carbide sintered with one or more metals such as iron, nickel or cobalt as a binder, forming a body of high hardness and compressive strength. Cemented tungsten carbide is the most common form of tooling carbides. However, carbides of titanium and tantalum are also used.

Years ago, Dow Chemical Company developed a pure tungsten carbide made by hot isostatic pressing. Since it contains no binder, it is a ceramic material. Because the material has lower tensile strength than cemented carbides, it has not found applications in pressworking tooling. However, in highly abrasive applications such as water jet cutting nozzles, it will outwear cemented tungsten carbide by a factor of approximately twenty to one.

Thermal expansion is an important physical characteristic of carbide. For most carbide grades, it ranges from one-third to one-half that of steel. This must be considered when carbide is attached to a steel support or body.

Application of Cemented Tungsten Carbide

Cemented tungsten carbide is widely used for dies intended for high volume production of difficult to stamp materials. For example, motor and transformer lamination cutting dies used for high volume production are often made of cemented tungsten carbide. Such dies have produced millions of parts before resharpening.

Other widespread applications include cutting, drawing, forming and ironing dies used in high volume production of parts ranging from razor blades and stainless steel drawn shells to beverage containers.

Restrictions exist on the use of lubricants on some carbide die materials, particularly those containing sulfur. While tungsten carbide is essentially an inert material, some lubricants attack the cobalt binder material. Electrolytic corrosion can also result from stray currents from electrical part sensing.

Machinable Carbides

These are machinable ferrous alloys sold under the trade name of Ferro-Tic®, and are made in ten standard grades. These range from 25-45% (by volume) titanium carbide, tungsten carbide, titanium-tungsten double carbides or other refractory carbides as the hard phase. These are contained in a heat-treatable matrix or binder that is mainly iron.

The ten standard grades are suitable for most applications requiring machinable carbide. The standard grades can and have been modified by Ferro-Tic® to meet specific operating requirements. The heat treatment required to harden the matrix is much the same as for conventional tool steels. The manufacture's recommendations should be closely followed for proper product application, machining and heat treatment.

Nonmetallic Die Materials

Wood and Hardboard Laminates

Hardwood can be used for form blocks, but laminated impregnated wood, hardboard and plastics have largely replaced it. Hard maple and beech are good woods for die applications if they are carefully selected for close grain structure.

High-density panels composed of compressed wood fiber and lignin are used for jigs, dies, fixtures, templates, patterns and molds. Masonite ™ is a cellulose semiplastic material available in various thicknesses finds application as both a jig and tooling material. It can be readily laminated with cold-setting adhesives. Such wood-based materials are suitable for short run dies for prototype work. Such dies are also widely used in the aircraft industry.

Rubber

Molded rubber female dies and rubber-covered punches are used in difficult forming operations, such as the production of deeply fluted lighting reflectors. Many types of rubbers and rubber compounds are used. Natural rubber, neoprene and polyurethane all find application in pressworking.

Specifications for rubbers used in the conventional Guerin, Marform and Hydroform processes are determined by the performance needed for the process. Some rubber compounds, especially polyurethane can be cast in place and cured to form the needed shape. This permits the economical production of forming die components, part strippers, pressure pads and non-marring automation fingers in the toolroom.

Cork

Soft, medium and hard cork layers, compressed into sheet form are sometimes used with, or in place of, rubber pads. Cork deforms only slightly in any direction other than that of the applied load, while rubber flows in all directions.

Plastics

Like wood, the pressures involved in the process limit the use of plastic materials for dies. Selection of plastics is based on economy relative to die life expectancy. Draw radii are a primary source of concern because maximum loads and abrasion occur in these areas.

Draw dies having a metal core of either ferrous or zinc-alloy materials, capped with a working face of epoxy, are used in the aircraft, appliance and automotive industries. Rubber forming dies are made of combinations of cast and laminated epoxy applied to a heavy steel base.

Polyester resins are used for low volume tooling. The chief advantage this material has over the stronger and more stable epoxy resins is cost.

Polyurethanes

Polyurethanes combine many of the good properties of both elastomers and plastics. They have demonstrated a unique combination of abrasion resistance, tensile strength and high load bearing capacity not available in conventional elastomers plus impact resistance and resilience not available in plastics.

Because of their liquid, uncured form and their excellent cured properties, these polymers are useful in draw dies, drop-hammer dies, forming and stamping pads, press-brake forming dies, mandrels, expanding punches and other tool design applications.

A major use of this material is for die automation components such as kickers, lifter heads and rollers where the excellent wear-resistance of the material, together with its non-marking characteristics are very useful. Polyurethane is available as a two-part liquid formulation that can be mixed and cast in place to form custom made die pads and transfer automation jaws.

NOTES: