FRESH APPROACHES TO MOLD STEEL SELECTION

F.T. GERSON

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Presented at the 1991 annual
technical conference of the
Society of Plastics Engineers, Montreal

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Fresh approaches to mould steel selection

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Introduction

Mould making plays a key role in the continued growth of the plastics industry which is illustrated in *Figure 1*.

Mould making realizes the unique capability of polymer compounds to be net-shape-formed in one or two simple steps to generate a finished component. Resin manufacturers, product designers and even moulders and fabricators tend to forget that some of their finest achievements could not have reached the market place without the help of mould makers — without those skilled people who so often fail to get enough credit for the competence and technical savvy which they bring to their work; or for the heavy investments which they have made in CAD/CAM and CAE and in software to model the complex thermal and rheological changes which take place inside the mould and which govern the successful shaping of plastics.

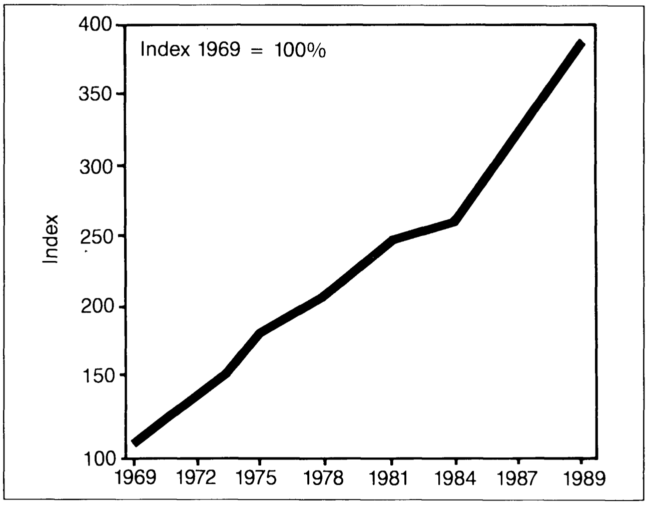

Figure 1 World consumption of plastics. (5 year moving average)

Why has mould steel selection been neglected?

Given the significant advances in mould making, it is surprising that alloy selection for plastics moulds has remained an underrated and underfunded aspect, too often neglected not only by the moulder, extruder or fabricator but even by some of the mould makers themselves. Please note the qualifying word "some". Clearly, there are other mould makers whose rigorous approach to design and technique includes an enlightened attitude to alloy selection. However, in general, and with few exceptions, alloy selection has not kept pace with advances in plastics materials or processing methods, or even with the fundamental improvements in other aspects of mould making.

Why did this happen ? Why have some excellent mould designers and builders not availed themselves of the superior materials and processes which are available ? How can we stimulate appropriate advances in mould steel selection? A quick overview of the types of steel currently available will help answer these questions.

Injection mould steels

Table I lists an arbitrary range of mould steels; *Table II* expresses characteristics of mould alloys in terms of common metallurgical data found in alloy specification sheets. The far right column of *Table II* indicates the alloy's relative cost.

Table I Typical compositions of plastic mould steels.

Steel Designation	C	Mn	P	S	Si	Cr	Ni	Mo	Other
AISI 4140	0.40	0.90	0.03	0.04	0.25	1.00		0.20	
AISI P20	0.35	0.80	0.03	0.03	0.50	1.70		0.40	
P20 + *	0.35	1.50	0.03	0.03	0.50	1.80	0.55	0.20	
P20 Super*	0.55	0.80	0.01	0.01	0.50	0.75	1.75	0.30	
AISI P21	0.20	0.30	0.03	0.03	0.30	0.25	4.25		$\frac{V}{0.2}$
AISI P6	0.10	0.50	0.03	0.03	0.20	1.50	3.50		
AISI H.13	0.40	0.40	0.03	0.03	1.00	5.20	0.30	1.65	$\frac{V}{1.00}$
UNS S42000 (420 Stainless)	0.30	1.00	0.04	0.03	1.00	13.50			
Alloy A*	0.15	1.50	0.04	0.10	0.30	0.30	3.00		$\frac{Cu}{1.00}$ $\frac{Al}{1.00}$
Alloy B*	0.02	0.75	0.04	0.03	1.00	15.00	4.75		$\frac{Cu}{3.50}$
Alloy C*	0.07	1.00	0.04	0.03	1.00	14.0-15.5	3.5-5.5		$\frac{Cu}{3.5}$ $\frac{NbTa}{QS}$
18(300) Maraging	0.03						18.00	5.00	$\frac{Co}{10.0}$ $\frac{Ti}{1.0}$

* proprietary alloy

Table II Average property and cost comparisons of certain mould alloys.

Alloy Designation	Tensile Strength 0.2% Yield	Working Hardness	Coeff. of Thermal Expansion	Thermal Conductivity	Cost Index
	MPa	Rockwell C	µm/m/°C	W/m/°C	(AISI 4140=1)
AISI 4140	860	27-30	12.7	36.3	1.0
AISI P 20	1030	28-35	12.9	34.6	1.3
AISI H 13	1550	40-45	12.9	29.4	3.5
UNS S42000	1720	28-30*	11.7	26.0	2.5
PH 15.5	1510	38-40	11.2	20.8	4.5
MAR 18(300)	2500	48-56	10.1	29.4	7.5

*pre-hardened

While *Table I* is far from exhaustive, it shows that mould makers can choose from a reasonable variety of mould steels to arrive at the correct balance of properties. In practice such intelligent choice does not occur nearly as often as it should. The prevailing tendency is not only to pick the material with which the mould maker is most familiar but, above all, the alloy with the lowest possible first cost. In many cases, that is an expensive mistake. A little history helps us understand why so many of us persist in making it.

Evolution of plastics mould steels

Early moulds were made from boiler plate. They worked quite well with soft resins and products which permitted generous tolerances. In the those days, AISI type 1020 (Unified Numbering System, UNS G10200) — mild steel — was considered a high quality mould alloy; heat treatable AISI 4140, UNS G41400 seemed pretty advanced but gradually became popular and remains so today. Demand for higher indentation resistance, greater toughness and better control of heat treatment subsequently established AISI P20, UNS T51620, as the leading contender in good quality plastics moulds. Preferred by both fabricators and toolmakers, P20 received a good deal of attention by mould steel producers. They improved its cleanliness and homogeneity; they began to produce proprietary variations of AISI P20 which were fortified with additional elements — notably nickel — although the specification does not call for it. *Figure 2* shows the beneficial effect of such alloying on through-hardness. Gradually, P20 became the material of choice for steel moulds. Competition among steel producers caused its quality to rise and its price to fall. Mould makers became so accustomed to P20 that they tried to extend its use into applications which really called for higher performance or different alloys. Many convinced both themselves and their customers that alloys better than it were too expensive. Some do it to this day. Some have become so preoccupied with raising the hardness of mould surfaces that they mistakenly equate hardness with

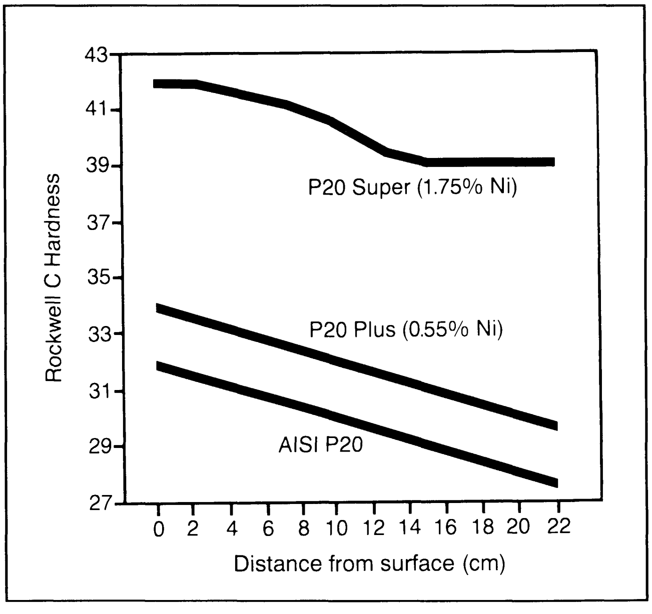

Figure 2 Through-hardness versus composition (44cm–thick mould block).

strength, durability and resistance to wear, indentation and fracture. They accept as inevitable the brittleness of quenched mould steels which have undergone phase- and dimensional-changes and thermal stresses severe enough to have cracked many a mould before it ever left the tool shop. Whether or not relieved by tempering, quench stresses are sensitive to both shape and thickness, and can therefore severely limit the options available to the designer.

You will have noticed that our discussion focuses on alloy composition rather than on melting and refining of mould steels.

The hard-to-predict effect of conventional heat treatment can be sidestepped by pre-hardening, generally in the range between Rockwell C 28 and 32. However, for use with tough resins and composites, that range does not provide adequate resistance to abrasion or indentation. Yet some steelmakers have been known to deliver pre-hardened blocks at RC 26 or even softer. This saves the mould maker time because the alloy is relatively easy to machine. It does not help the mould user who is apt to experience premature parting line wear or collapse.

Possible solutions

The foregoing problem can be overcome by specifying one of the precipitation hardening steels of which Alloys A, B, C and 18(300) in *Table I* are typical examples. These harden by a fundamentally different mechanism, that is, by precipitation of micro constituents which lock the crystal slip planes. These alloys gain hardness by gentle heating to a relatively low level, for example, 480°C (900°F) and by being held at that temperature. The longer they are so held, up to about four hours, the harder they become. The rate of heating can be as slow as you like — an important advantage in massive moulds. Dimensional changes resulting from this type of hardening are highly predictable and of the order of one in 50,000. Some can be safely hardened to RC 58/60. They provide true fracture toughness, as measured by K_{1C}, a material- and structure-specific property which makes them superior to AISI P20 or H13, UNS T20813, in resisting brittle fracture. That type of fracture can cause an alloy to fail well below its specified strength. Please refer to *Figure 3*.

Because of their different metallurgy, precipitation hardening alloys are easier to weld and may even be supplied in the form of castings or weldments. This can realize important cost savings in mould repair and by eliminating rough machining of mould cavities for large and deep parts such as panels or structural components for automotive use or major appliances.

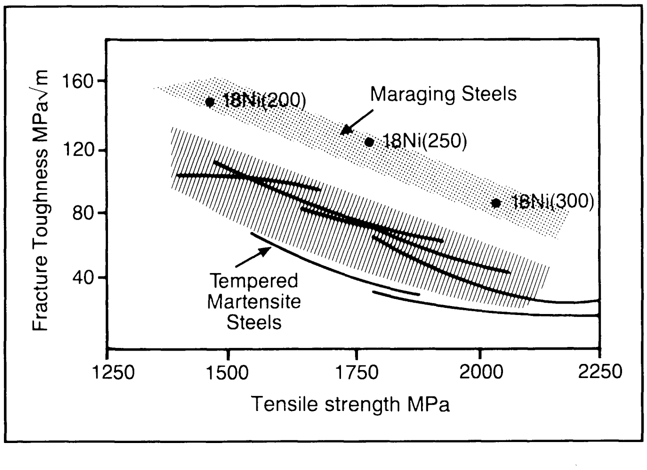

Figure 3 Fracture toughness as a function of tensile strength.

Economics of effective alloy selection

Mould material selection has become much more critical, not only because we now mould everyday items which require an accuracy of plus or minus 0.001mm (0.00004 in.), not only because the mould must handle hard and abrasive compounds but also because more and more moulds have become key elements of a manufacturing cell or an integrated manufacturing system.

Mould failures, or even unplanned mould repair or maintenance, create a much more costly and damaging disruption compared to the need of shutting down a stand-alone press. *Figure 4* illustrates the unexpectedly rapid growth of integrated systems versus stand-alone machines.

As a result, mould makers as well as mould users are challenged to evaluate how much they spend on mould maintenance — planned and unplanned — or on the aftermath of just one breakdown which wastes much more money than a good mould alloy would have cost in the first place.

Increasingly, mould makers and users therefore take an informed interest in alloy selection; some now insist that evidence on fracture toughness and through-hardenability be provided as part of the routine Quality Control documentation accompanying each shipment of mould steel.

Relationship between alloy cost and finished mould cost

In a typical injection mould, material represents some five per cent of the final assembled cost which consists mainly of heavy investments in design, machining and finishing.

IBM Corporation, an extensive user of steel moulds, conducted a systematic survey of the principal determinants of mould costs, as reported in the June 1989 issue of *Plastics Engineering*. They analyzed 85 different moulds from a variety of geographical locations, all purchased within the

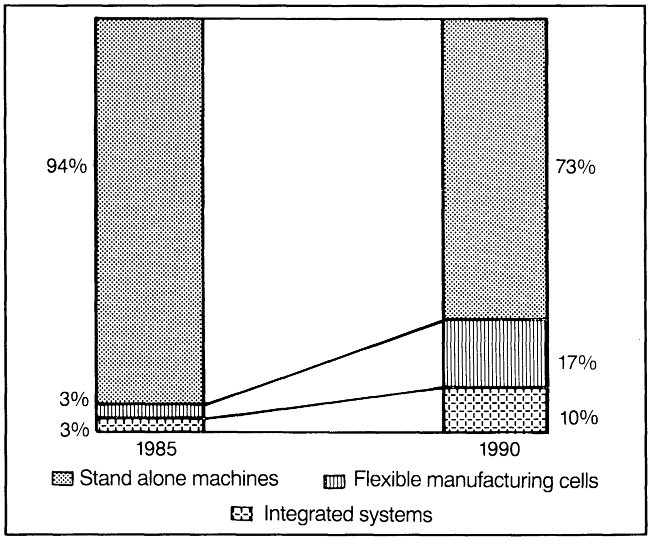

Figure 4 Growth of integrated manufacturing capacity in the plastics industry.

past two years. Their report concluded that only six parameters exerted significant influence on the cost of a mould for estimating purposes:

1. Number of dimensions on the print.
2. Number of different surface finishes required.
3. Length of part.
4. Depth of part.
5. Tightest tolerance.
6. Number of cavities.

Mould material was not among the significant cost factors. The IBM system indicates an average 85 to 90 per cent accuracy and is now in place at 22 IBM locations worldwide. It tends to give the lie to the frequently heard claim that "we can't afford to upgrade the quality of steel for our moulds."

Surface enhancement of mould steels

Early moulds were frequently pack-carburized to increase surface integrity. Today, varieties of chemical and physical vapor deposition techniques vie with corona treatments, plasma and other radiation techniques and even ion implantation as means to create strong, smooth and resistant mould surfaces. Good as they are, these treatments can create havoc. Such as the engineering change which arrives by frantic phone call just as the finished mould is ready to ship. Or the undercut cavity which was shielded during processing and remained bare.

Hardened and toughened mould surfaces can tend to mask the weakness of the substrate alloy. In these circumstances, moulds for parts with large, flat surfaces are particularly prone to collapse at the centre. Here is another argument in favor of through-hardness and gentle heat treatment. This may explain the trend in Europe and Japan to specify precipitation hardening compositions or alloys similar to AISI type P21, UNS T51621 (see *Table I*).

Some unconventional approaches

Nickel vapor deposition is gaining ground as a means of producing freeform shells for use as mould cavities. In this process, gaseous nickel carbonyl touches a heated master shape in a closed chamber kept under a soft vacuum. Upon contact, the vapor decomposes, building up, atom by atom, a hard coat of metallic nickel which faithfully reproduces surface detail. The typical deposition rate of 0.25mm (0.010 in.) per hour exceeds that of conventional plating or electroforming by a wide margin. Acceptance of this technique has been held back by the extreme toxicity of nickel carbonyl, one of the most acute respiratory carcinogens known. Safe hardware and cost effective backings for these mould shells have been developed, so that this technique is now ready for rapid advance.

One of the above backing materials is macro-defect-free concrete or MDF. In the 1990s, this may well attract the interest of both moulders and mould makers. By eliminating the large voids present in ordinary concrete (*Figure 5a*) and by replacing water with a dilute polymer solution, you can generate a paste which sets by ordinary hydrating reactions to form a solid which has mechanical properties approaching those of mild steel (*Figure 5b*). It is anticipated that, eventually, MDF will be injection moulded or otherwise net-shape-formed. That could mean big changes in building construction: extruded concrete beams, formed right at the job site; moulded joints; no more falsework!

What is the relevance of MDF to mould steel selection? Simply that the moulds to shape such concrete will have to resist abrasion by a corrosive mix of sand, grit and limestone, much more aggressive than even engineering resins filled with glass or ceramic fibres.

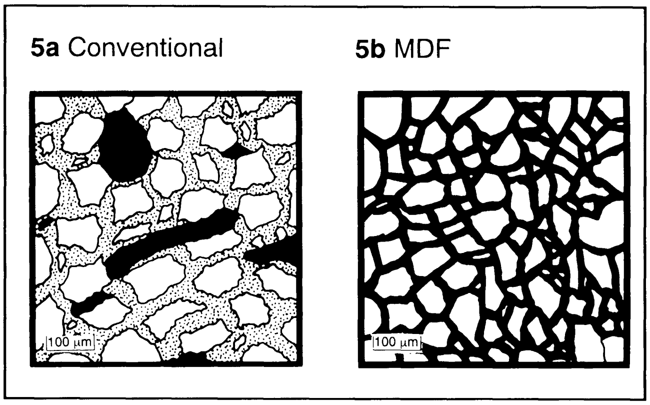

Figure 5 Microstructure of concrete.

Another example speaks directly to problems encountered with long or large area mouldings such as auto parts. In these applications, critical differences in the coefficient of thermal expansion, CTE, are common between the resin to be formed and the material from which the mould is constructed. As *Table II* shows, the CTE of mould steel tends to vary in a range between 10 and 12x10^{-6}/°K. The corresponding value of a typical carbon fibre filled epoxy would be 1.5x10^{-6}/°K. Over the range of applicable moulding temperatures, the linear interference could be large enough to snap off surface ribs or distort ridges. To solve this problem, the designer may choose a low expansion alloy which permits accurate control of CTE over an extended range of values starting well below 1x10^{-6}/°K, as shown in *Figure 6*.

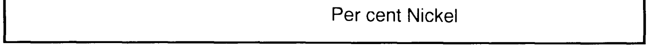

Figure 6 Coefficient of linear expansion as a function of nickel content (in an alloy containing 0.4% Mn, 0.1% C, bal. Fe).

How to lower the barriers to progress

What can be done to speed the use of better mould alloys? Progressive mould makers have not been slow to broaden the range of mould steels they select. But why do so many others shun the newer and more advanced alloys and persuade their customers against specifying them?

There is no simple answer. Lack of information and experience with unaccustomed alloys plays an important part. So does the mistaken notion that one cannot afford the higher cost of better steel. Perhaps his bill for steel looms unduly large to the mould maker because it represents one of the biggest single cash outlays he makes for a current cost item that is not related to labor. Perhaps he is unaware of the IBM study referred to earlier.

More importantly, perhaps he does not know about the strongly held views of German and Japanese mould makers who found out long ago that better alloys added value to their products for which their customers were more than ready to pay.

There are still more barriers to progress:

> Those mould makers who rely on outside services for heat treatment, polishing or other surface improvement, may unnecessarily worry that their contractors could lack the knowledge and experience to deal with new alloys.
>
> Last but not least, there are the horror stories which seem to attach themselves to new mould steels as they do to many other innovations.

Again, as it did in the case of AISI 4140 and P20, it takes time for the newer alloys to become established in the distribution chain and, until they do, they are priced as "specials".

Time, competition and new data will help to dispel these misconceptions and to speed the introduction of higher performance materials. So will the keener interest which mould users have taken in specifying better material properties for their moulds.

Conclusion

As mentioned at the outset, mould makers have mightily contributed to the success of our industry. None of these remarks are meant to detract from their acknowledged competence and excellence; their know-how is the envy of competitors around the world. The foregoing are merely suggestions to them and to their customers of a few alternative approaches to the increasingly important aspect of mould steel selection.