UNDERSTANDING AND PREVENTING CRACKS IN MOLD STEEL

F.T. GERSON

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Understanding and preventing cracks in mold steel

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In order to build precision and reliability into their product, mold makers require and expect that the cavity steel they purchase provides a combination of desirable characteristics which include soundness, cleanliness, uniformity of structure, hardenability, safe and predictable response to heat treatment, machinability, polishability, strength and – especially – toughness. In short: the alloy must not crack, because cracks can be the bane of a mold maker's life. Yet, before he or she attains full qualification in the industry, a mold maker will likely have to deal with several cracked steel molds.

This paper examines types and causes of cracks in alloy steel molds, the role of mold steel selection in preventing such cracks and a new, inexpensive and disarmingly simple technique which helps to guard against their occurrence.

First a quick overview of relevant alloy properties and crack characteristics:

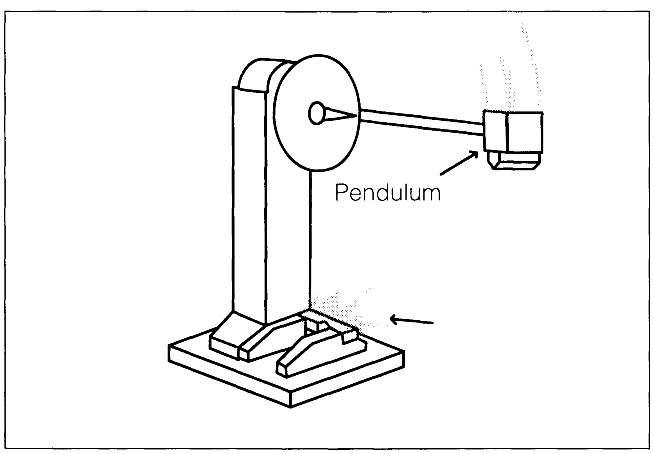

Figure 1 Typical impact testing machine

Toughness

Strictly defined, toughness represents the amount of work which a material can absorb before it breaks. Strictly measured, it is proportional to the area under a stress strain curve carried to fracture. But because we have become accustomed to measure toughness by swinging pendulum methods (eg the Charpy V-Notch or Izod tests, *Figure 1*) we have come to classify toughness of mold steels by their resistance to sharp and sudden impact loads. But in an extruder or injection press, the type of loading is gradual and sustained; hence its behaviour under impact is not the best available method of gauging the performance of a given cavity alloy. Instinctively, therefore, we have come to regard toughness as the opposite of brittleness but we have lacked a practical quantitative way to measure it reliably.

The Nature of Cracks

We distinguish between two principal classes of fracture, namely ductile and brittle. Ductile fracture is commonly the result of overload, there is more or less pronounced yielding before a break occurs, and the rate of crack growth or propagation is slow, usually less than 6 meters per second (20 ft/s). In contrast, brittle fracture can occur in the absence of any load or under very modest loading, well below the specified strength of an alloy. The rate of crack growth associated with brittle fracture is very fast, say several thousand meters (or feet) per second. The crystalline appearance of a crack can indicate whether fracture was brittle or ductile – indeed the earliest tests for alloy steel toughness consisted of breaking a sample piece and examining the irregular crack surface.

Since **ductile fracture** is almost always the result of abuse, error or deficient mechanical design, alloy selection is generally not an appropriate way to deal with it; the rest of this paper is therefore not concerned with cracks involving ductile fracture.

Brittle fracture is more complex; it occurs under normal service conditions. It is the kind which bedevils the mold maker by showing up in a new cavity after only a few hours in an injection molding press or, in extreme cases, even before a mold has been fully assembled and shipped to the customer.

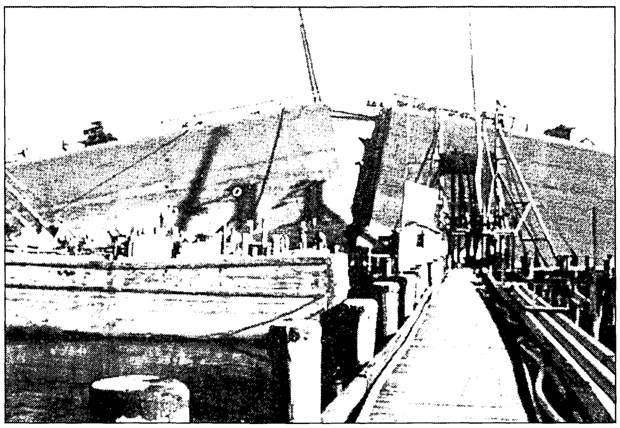

Figure 1a Brittle fracture of 178m (584 ft) long barge

Brittle fracture gained front page attention during World War II when dozens of freighters in North Atlantic convoy duty – the famous Liberty Ships – broke in half, some of them while still brand new and moored empty at dockside. Studies in fracture mechanics led to the understanding that any piece of steel contains discontinuities or micro-cracks which can initiate failure under stress. The term fracture toughness was created to express a material's resistance to the growth and propagation of cracks. Note the difference between this definition and the earlier one given for toughness. Not only is fracture toughness a more realistic measure of a material's performance in plastics molding or extrusion service but it is also possible to determine it quantitatively for a given mold block before that block is machined or otherwise fabricated.

Causes of Cracks

Aggressive heat treatment is generally recognized as a cause of brittleness in steel because fast quenching not only sets up complex thermal stresses in a mold block but also generates several different micro structures within the block, thereby causing dislocation and additional internal stress. Stress level is the most obvious of the three contributors to brittle fracture discussed below.

1. Stresses (external, residual or both) are necessary for brittle fracture to occur. External stresses can be determined by conventional stress analysis techniques for any particular mold. The mold maker intuitively tends to analyze mold breakage on the basis of externally applied forces. If a mold cracks in service – particularly if it cracks twice in succession in the same place – the designer is apt to conclude that he needs additional section thickness, and he will try to change his design to beef up that part of the mold.

2. Crack size is a less well-known contributor. Brittle fracture almost always originates at a discontinuity of some kind: a notch, a sharp corner, internal micro cracks or very small fissures. These are especially prone to occur in or near welds or cold worked areas. The mold maker learns many procedures and tricks to avoid stress raisers in design, fabrication and welding practice. But he can do little, if anything, to prevent internal discontinuities and cracks which are always present. As long as they are small enough, they are a normal feature of steel and do not create a problem. However, they can grow in service under sustained stress, fatigue or corrosion to reach a critical size.

3. **Fracture toughness (K_{IC}).** The third property which affects the likelihood of cracks in a steel mold is the fracture toughness of the material. It indicates the inherent and specific resistance of an alloy to the growth and propagation of cracks. It can be defined as the ability to sustain a load or deform plastically in the presence of a notch, a micro crack, or other kind of discontinuity or stress raiser under plane strain conditions. Although calculations can be made to translate into fracture toughness values obtained by impact methods, such as Izod or Charpy V-notch, it was shown that these are inappropriate – possibly misleading – when applied to materials in plastics extrusion or injection molding service where gradually applied and sustained loads are more common than sudden shock loads.

Therefore, fracture toughness is determined by different methods and expressed by a different term: K_{IC} is defined as the critical stress intensity factor which is a shape- and material-specific value expressed as stress per square root of unit length (MPa$\sqrt{m}$ or ksi$\sqrt{in}$). It provides a reliable quantitative indication under load patterns of the kind normally associated with plastic molding and extrusion. Although K_{IC} is a more realistic measure than those obtained from impact tests, both types are useful, and testing of mold steel by impact methods is preferable to no toughness testing at all.

Mold Steel Selection

It is significant to note that K_{IC} values enable us to show that plastics mold steels differ widely in the fracture toughness they provide to the designer. In other words,

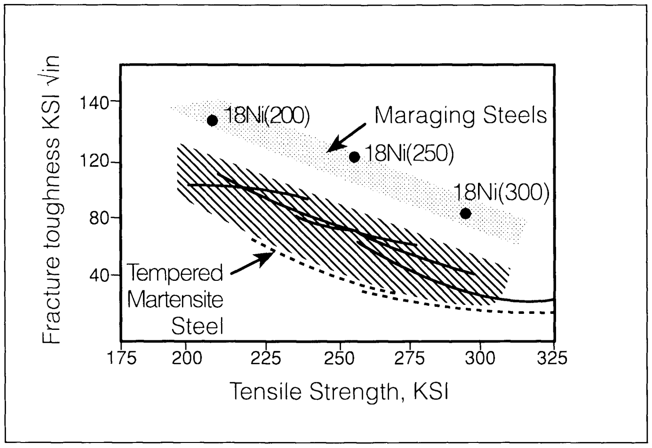

Figure 2 Fracture toughness as a function of tensile strength

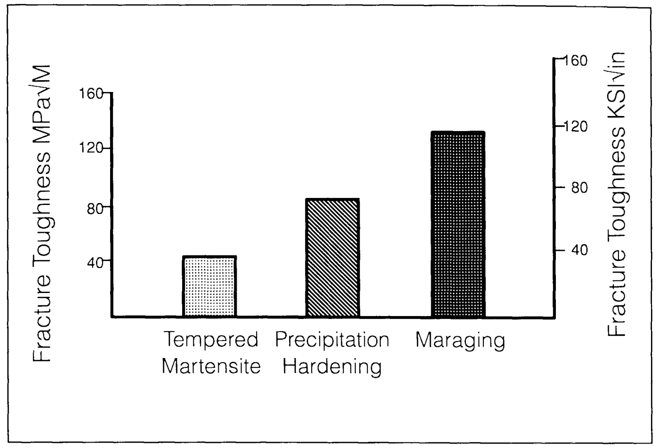

Figure 3 Fracture toughness of three alloy steels at 250 ksi (175MPa)

specifying increased section thickness is not the only – nor necessarily the best – strategy available for the prevention of cracks in a mold. Another and often more effective means is to change steel to an alloy with a higher K_{IC}, ie. higher fracture toughness and greater resistance to the growth and propagation of cracks.

Figure 2 gives an indication of the considerable differences in K_{IC} between various alloys. The dotted curve at the bottom shows the average value for steels hardened by quenching and tempering (eg such steels as AISI type 4140, P20, H13, or 420 stainless). The next-higher group of curves displays twice the fracture toughness of those represented by the dotted line. These are precipitation hardening alloys which, as their name implies, are hardened not by the usual quenching and tempering sequence but by gentle heating which releases microscopic particles to lock up the slip planes. Still greater fracture toughness is available from the so-called maraging steels which are identified in the area nearest the top of the diagram and which appear to score three times as high in fracture toughness as the conventional alloys represented by the dotted curve. Maraging steels are well described in the standard literature. Because they contain enough nickel (typically 18 per cent), they do not depend on their carbon content to harden. That means they do not need to be quenched but are age hardened by gentle heating.

Maraging steels achieve full hardness – up to 70 HRC – by being heated for three to four hours at 480°C (900°F). Because hardening does not depend on rapid cooling rates, full hardness can be developed uniformly in massive sections with almost no distortion. Decarburization is of no concern in these alloys, partly because they contain very little carbon and partly because their aging temperature is so low. However, caution is advised with molds for some engineering resins or composites where the recommended molding temperature may exceed the aging temperature (480°C; 900°F) of the mold alloy. Prolonged exposure at or above that level would lead to a significant drop in hardness.

As was the case with AISI H13, the 18 per cent nickel grade maraging steel was used in aluminum die casting molds and cores before it was found to solve some tough problems in plastics injection molding and extrusion. While easy to machine in the solution treated condition, the high hardness and abrasion resistance of the alloy after age hardening proved especially attractive for compounds containing abrasive fillers or reinforcement.

Figure 3 reproduces the values shown in the above graph (*Figure 2*) for steels stressed at 1,725 MPa (250 ksi). It indicates that a mold can be made three times more resistant to cracking by replacing heat treated AISI P20 by maraging steel.

The more advanced steels cost more than P20 but they can resolve some tricky situations for the mold maker, especially in cases where space limitations make it impossible to beef up section thickness. Conversely, the higher strength and crack resistance of precipitation hardening alloys allows the mold maker to reduce the wall thickness dividing the cavity from a cooling channel, thus permitting faster cooling rates and shorter molding cycles.

As noted earlier, fracture toughness of a given mold block is not only a function of its chemical composition and metallurgical structure but also of its heat history and the state of strain within the block. In other words, the mold maker would be helped by knowing the K_{IC} or fracture toughness of a particular block of steel before he began to work on it, ie before he invested what might aggregate to many thousands of dollars in labour and overheads to produce a cavity or core.

Determining Fracture Toughness

Until quite recently, it would have been very expensive and time consuming to determine K_{IC}. *Figure 4* illustrates a typical test piece into which holes and an artificial crack had to be machined to close tolerances. In a universal testing rig, tension was then applied across the crack while a strain gauge determined the rate of growth of the synthetic crack. A slightly simpler test piece (*Figure 5*) could be loaded in bending but it was still necessary to fit strain gauges and electrically measure the rate of crack tip opening *(Figure 5a)*.

Without going into detail, it was found that even routine in-house determinations of K_{IC} would cost in excess of $100.00 per specimen as opposed to a cost of only $5.00 per specimen for a Charpy V-notch (CVN) or Izod impact test. High cost ruled out K_{IC} measurements from virtually all routine or custom quality control testing.

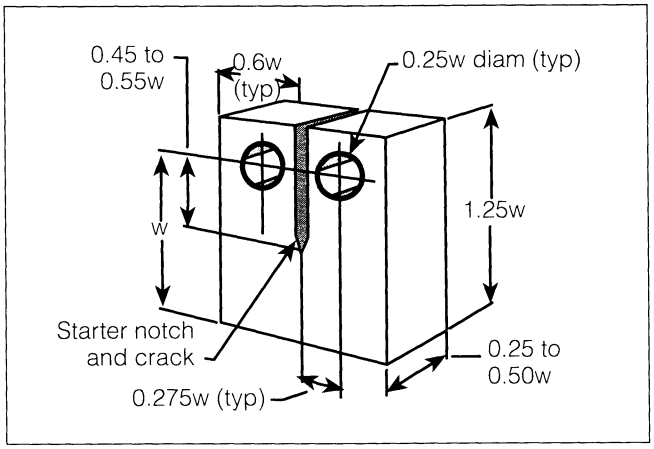

Figure 4 Standard test specimen (ASTM E399-72)

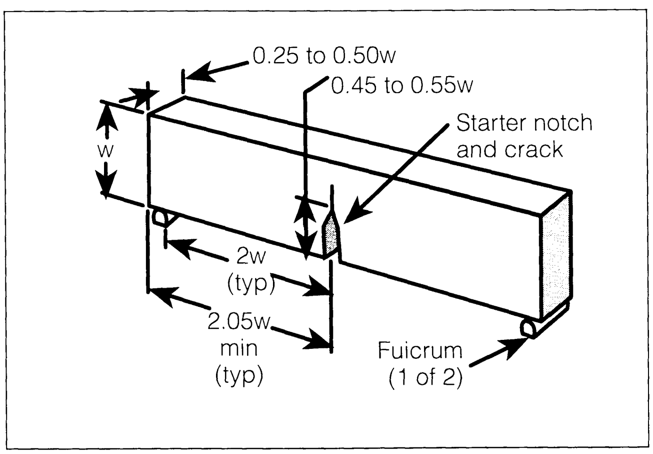

Figure 5 Standard test specimen (ASTM E399-72)

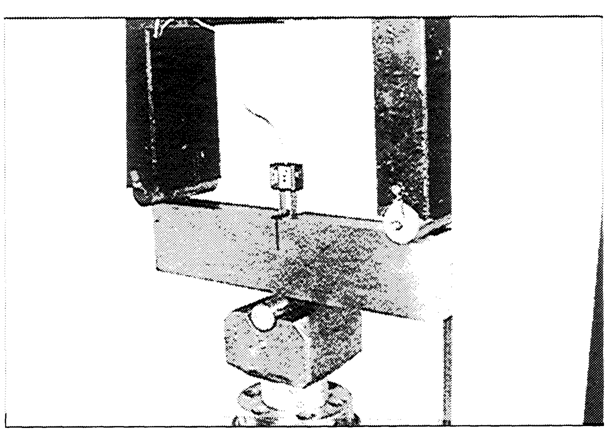

Figure 5a Three point blend test set-up for K_{IC}

A New and Simple Way to Determine Fracture Toughness

A novel test technique has been developed by Quesnel and Stromswold, researchers in the Materials Science Program at the University of Rochester, New York; theirs is a fast and simple method of measuring K_{IC}. It employs a notched four point bend specimen. It is an inexpensive manual test method requiring no more than an ordinary shop vise and a torque wrench tool, all of which can be put together for a few hundred dollars or purchased from the developers in Rochester. As a result, the cost per K_{IC} determination is no higher than, if as high as, that for a CVN or Izod impact test.

Details of the more complicated methods mentioned above are published in ASTM E-1304, which is a recognized standard. ASTM E-399 defines and prescribes measurement of plane strain fracture toughness. The much simpler and much cheaper technique developed in Rochester is currently being evaluated by the American Society for Testing and Materials (ASTM) and may shortly gain recognition as a standard because, in parallel tests with tool steels, the new method has consistently yielded results comparable to those obtained by the more elaborate procedures referred to above.

The Toughness Tool

Figure 6 shows the simple toughness tool in use. *Figure 7* is a line drawing of the torque wrench. *Figure 8* is a schematic sketch of the test specimen with its lower end held in a vise and the upper end held in the sample holder of the toughness tool. The test specimen consists of a notched bar approximately 13mm (0.5 in.) square by 50mm (2 in.) long. To perform the test, the operator exerts a steadily increasing force to the upper

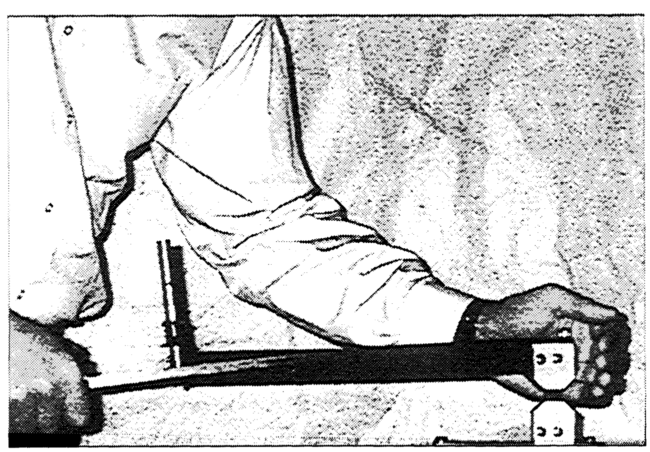

Figure 6 Determining K_{IC} by the torque wrench method

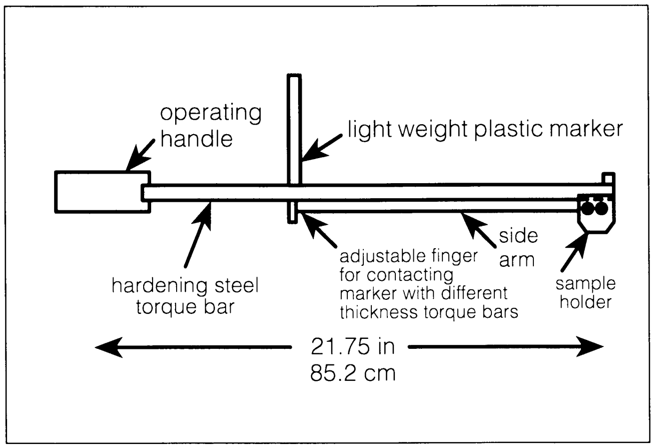

Figure 7 Schematic of toughness tool.

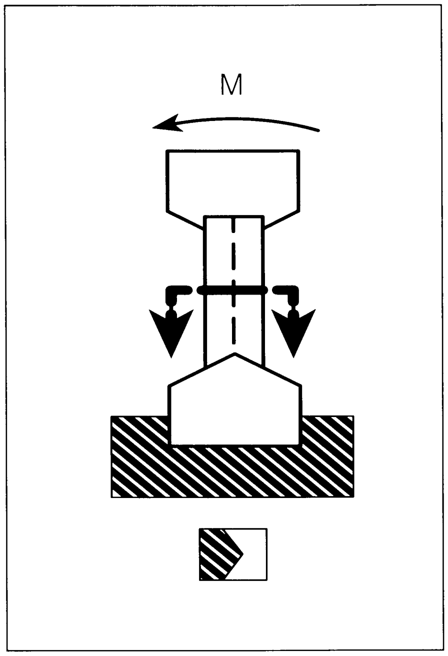

Figure 8 Chevron notched bar set-up for k_{IC} determination.

head by pushing down on the operating handle of the toughness tool. A plastic marker indicates the amount of force that was needed to break the specimen. For virtually all the alloy grades used in a steel mold, that value is a good indicator of fracture toughness. By exerting a force of about 270N (60 lb.) on the operating handle, the notched specimen held in the fixture will be broken. Both the theory and practice underlying the simplified test is detailed in a paper by Quesnel and Stromswold which appeared in *Engineering Fracture Mechanics*, Volume 41, No. 3, 1992, which also contains 23 useful references showing the evolution of fracture toughness determination.

In summary, the Charpy or Izod impact methods are easy to apply but the results do not readily correlate with fracture toughness values. The ASTM methods define and measure plane strain fracture toughness but are expensive and time consuming to execute. They do not work with minimum size test pieces. They are not suitable for routine testing. ASTM test specimens are difficult to make and somewhat limited in application. A universal testing machine or similar servo mechanism is required to perform the ASTM test.

The torque wrench method is so simple, fast and inexpensive that it can be used for materials characterization, for acceptance testing and as a routine quality assurance procedure. It enables the mold maker to verify the fracture toughness of a mold block on his own workbench before investing expensive fabricating effort in it. Given recognition by ASTM, the simplified method could enable K_{IC} values to become part of the routine quality control reports rendered by producers of mold steel.

Conclusion

One of the many benefits flowing from widespread reporting of fracture toughness values will be an even keener appreciation by mold designers, mold makers and mold users of the improvements in steel mold performance and reliability which can be achieved as a result of more discriminating mold steel selection. That trend has been apparent for some time and leads logically to the specification and adoption of more advanced alloys.

The drive for improved quality through development, recognition and adoption of innovative techniques and materials has long been a guiding principle for progress in the design and production of steel molds for the plastics industry. It is hoped that routine testing for fracture toughness will help to reinforce material quality control. Simple methods are at hand to realise that objective at nominal cost. The mold maker who uses them will demonstrate the significance of fracture toughness and will thereby lead the industry-wide trend to alloys which impart superior performance to the steel molds on which our customers depend.

Bibliography

(1) "Maraging Steels" in *METALS HANDBOOK*, ASM International, 10th Edition Volume 1, 1990, p.793 - 800.

(2) "Fracture and Fatigue Control in Structures", J.M. Barsom and S.T. Rolfe, Prentice Hall Inc., 1987, p.64 -108.

(3) "An Engineering Tool for Fracture Toughness Testing", E.I. Stromswold and D.J. Quesnel, *ENGINEERING FRACTURE MECHANICS* (Pergamon Press) Vol.41, No.3, 1992, p.309 - 320.

(4) *TOOL STEELS*, G.A.Roberts and R.A.Cary, ASM International, 4th Edition 1980, p.64 - 66.