
2. **Heinemeyer, D.,1976.** Investigations About the Durability of Closed-Die Forming Dies (in German), Thesis, University of Hannover, (1976). Stated that the dies are made of high strength, hardened material for example H-12 or H-13 steel. As such they must be prone to fatigue fracture particularly when subjected to heat treatment. Die material and heat treatment should produce minimum initial cracks and provide greatest fracture toughness to resist die breakage under fatigue crack growth.

3. **Kendall, A.L., and A.K. Sheikh, 1979.** Guidelines for the Application of Probabilistic Models in the Replacement Policies, *ASME Transactions*, (1979), pp.124-132. Concluded During use, dies may also undergo heat checking from thermal cycling. To reduce heat checking, (which has the appearance of parched land) and eventual dies breakage in hot working operations, dies are usually preheated to temperatures of about 1500C to 2500C (3000F to 5000F). Cracked or worn dies may be repaired by welding and metal deposition techniques, including lasers. Dies may be designed and constructed with inserts that can be replaced when worn or cracked. The proper design and placement of these inserts is important, because otherwise they can crack. Due to high speeds, at which tools operate in closed die forging, the tool failure due to fatigue is quite common. In closed die forging, about 25% of all tools failed by mechanical crack initiation, 3% by thermal crack initiation and about 5% by plastic deformation, the most prominent cause of failure however is wear.

time which could be viewed as a degradation of its embedded quality. The quality is related to the loss to the society caused by a product during its life cycle.

5. **Weiergräber, M., 1981.** Tool Wear in Bulk Metal Forming (in German), *Berichte aus dem Institut für Umformtechnik der Universität Stuttgart*, Nr. 73, Berlin, Springer (1981). The die life data will be used to determine empirical probability distribution, which will be plotted either on the Weibull probability paper, or after suitable transformation on a linear paper, and the validity of the Weibull distribution as a suitable model will be established. On a Weibull probability paper a straight line fit will validate the model, whereas when transformed data is plotted on a linear paper the validity can also be checked by regression.

6. **C.H. Tillhagen, Järnet och människorna, Gummessons Tryckeri AB, Falköping.** 9. P. Panjan, *et al., 1981* Improvement of hot forging tools with duplex treatment, Surf. Coat. Tech., 151-152, 2002, p. 505-509. In the late Copper age (around 4000 B.C.) it was discovered that hammering of metal brought a desirable increase in strength, and a type of hammer forging by hand became a popular way to form the metals. Most of the metal forming was done by hand until the 13th century, when the tilt hammer driven by waterpower was developed. During the Industrial Revolution at the end of the 18th century an, almost exponential, increase of hot forming industry occurred. The demands of larger hot formed quantities increased, which resulted in the invention of the high speed steam hammer, with a hydraulic press. Even tough several of new types of forming operations were developed the fundamental technique still remains.

7. **Sheikh, A.K., 1982.** Reliability of Cutting Tools, Towards Improved Performance of Tool Materials, *The Metal Society*, London, (1982), pp.195-204. have demonstrated that Weibull reliability model is an appropriate model to be used in the reliable life prediction of cutting tools, because of a number of reasons, some of which are mentioned below and they are quite applicable for forging and extrusion dies as well. Monotonically increasing failure rate of the tools or dies is best characterised by the power law type Weibull failure rate model.
8. S. Kalpakjian, 1982. In: Tool die failures, American Society for Metals, Materials Park, Ohio, 1982. Forming techniques such as hot forging and die casting are two popular ways of forming net and near net shaped components, since they are economical and high-speed methods. Also, modern statistical and computer based process design and simulations are becoming more important than ever in the struggle of reducing the production costs. Simply, because computer based process simulations can optimise the production, without using expensive tooling and testing. There are many ways in which a hot forming die can be damaged; for example wear, plastic deformation, gross cracking, thermal fatigue and mechanical fatigue.

9. Kup, B., and E. Walter, 1984. Process Monitoring and Control for Cold Bulk Forming (in German), Werkstatt u. Betr. 117 (1984), pp.601-664. Wear also constitutes a major cause of die failure. It is observed that the wear is more pronounced at locations of high stress concentration, resulting in wearing the die cavity unevenly. Die material should have a wear resistant surface, hence a proper surface treatment is essential to create such a surface, and tool material should be adaptable to this treatment without a greater sacrifice of toughness. Several mechanisms have been suggested for the wear of drop forging dies but the main one is micro-machining of the die surface by scale particles embedded in the forging stock.

10. Nehl, E., 1986. Measurement of Tool Wear in Cold and Semi-Hot Forming With Radionuclides (in German), Berichte aus dem Institut für Umformtechnik der Universität Stuttgart, Nr. 82, Berlin, Springer (1986). The knowledge of the die life is useful not only in predicting the number of dies required to suffice a production order but also to compare the different dies on the basis of their quality, shape and complexity, nature of heat treatment, and reconditioning or manufacturing.


Common for the two techniques, hot forging and die casting, is that they both have a die or a tool, which gives the product its final shape. These tools are usually very complex and expensive and in order to lower the production costs, they need to last for a long time. The materials used in the dies for hot forming are today completely made of a special type of steel, called tool steels.

13. L.J.D. Sully, In: 1988. Metals handbook, 9th ed., vol. 15, ASM International, Metals Park, Ohio, 1988, p. 286. The steels used for hot forming is a special type of tool steel, made to withstand a combination of heat, pressure and abrasion and has been classified hot-work tool steel, AISI type H. All hot-work tool steels are used in a quenched and tempered condition. The most essential properties for these types of steels are high levels of hot strength, ductility, toughness, thermal conductivity, creep strength, temper resistance and also low thermal expansion.

14. J.L. Chaboche, 1989. Constitutive equations for cyclic plasticity and cyclic viscoplasticity, International Journal of Plasticity. Vol. 5, 1989, p. 247-302. The isotropic part describes the change in size of the yield surface, and corresponds to the materials strength due the number of blocked dislocations, which in general, depends on dislocation structure and density and/or carbide morphology. The kinematic part illustrate the movement of the yield surface and describe the directional stress fields due to dislocation pile-ups at obstacles e.g. precipitates and grain boundaries.

15. R.W. Neu, H. Sehitoglu, 1989. Thermomechanical Fatigue, Oxidation, and Creep, Part1, Damage mechanisms, Metalurgical Transactions A, vol. 20A, 1989. The fourth step is to use the material related data in numerical simulation. Mainly, because hot forming involves several of different temperature and load conditions and with numerical simulation it may be possible to simulate the life and performance of certain technique without using expensive and time consuming tooling and testing. In this work, a non-linear kinematic and isotropic hardening model was used to simulate a hot-work tool material behaviour during specific hot forging and die casting conditions. There are two papers on material modelling one, which has focused on a specific hot forging operation and where the material behaviour is simulated. The other paper focuses more on the model itself, where the material related parameters are investigated in regard to the microstructure.
16. R.W. Neu, H. Sehitoglu, 1989. *Thermomechanical Fatigue, Oxidation, and Creep, Part 2*, Life Prediction, Metallurgical Transactions A, vol. 20A, 1989. Hot metal forming consists of a forming process either by plastic deformation or solidification where the metal is shaped by tools or dies. The hot deformation process occurs above the metals recrystallisation temperature, which usually is between 0.4 and 0.5 of the materials absolute melting point. At that temperature the metal is easy to shape, since it behaves in a perfectly plastic manner. The metals become neither internally stressed nor work hardened, and an unlimited amount of hot-working can be performed without component fracture.

17. Mitra, A., 1993. *Fundamentals of Quality Control and Improvement*. Macmillan Publishing Company, New York, (1993). Various aspects of the operating conditions of these dies suggest a potential for failure resulting from the growth of cracks on the bearing surface(s). First, during normal operations, the dies are subjected to large, cyclic stresses. Second, the cavities in both dies create regions of high stress concentration especially at raceways and at intricate barrages, where cracks can initiate and grow resulting in catastrophic failure.

18. J.R. Davis (Ed.), 1995. *ASM Speciality Handbook, Tool Materials*, ASM International, Materials Park, Ohio, 1995, p. 251. Steels that need to maintain its properties at high temperatures, e.g. hot-work tool steels, require having an increased temper resistance so that an appropriate strength can be achieved after tempering at 550 /650 °C. The most convenient method is to use a secondary hardening reaction involving the precipitation of alloy carbides.

19. Lewis, E.E.1996. *Introduction to Reliability Engineering*, John Wiley & Sons, (1996). For greater abrasion resistance the die surface should be as hard as possible. In addition to hardness, there is an opposing demand on the die material that it should minimise the susceptibility to cracking by providing a relative tough surface without initial cracks. This high fracture toughness is simultaneously desirable with the demand of high hardness.
20. N. Tsuji, G. Abe, 1996. High temperature low cycle fatigue behaviour of a 4.2Cr-2.5Mo- V-Nb hot work tool steel, Journal of Mat. Sci. let. Vol.15, 1996, p.1251-1254. tool steel behaviour at temperatures around tempering and that more work needs to be done in this area. For example, a greater effort to separate the kinematic and isotropic contributions must be done, which is difficult since the material behaviour is time depended at temperatures around tempering.


22 G. Bernhart, G. Mouliner, O. Brucelle, D. Delagnes,1998. High temperature low cycle fatigue behaviour of a martensitic forging tool steel, Int. Journal of fatigue vol.21 pp.179-186, 1998. Thin foils were prepared from the same specimen, from the waste where deformation had occurred and from the butt where no deformation had occurred. These two locations were observed and compared with each other. In general, it was found that the hardened and tempered martensite contained a high dislocation density and the substructure was formed from the martensite lath.

23. H. Sehitoglu, T.J. Smith, H.J. Maier, 2000. Stress-strain response experiments and modelling. Thermo-mechanical fatigue behaviour of materials, 3:rd vol., 2000, p.55-67. The strength of a material is associated with resistance to slip and dislocation motion and in a martensite material this is attributed to the deformed crystal structure. There are also other important contributing factors to the strength such as carbide precipitates and dislocation density and structure.

24. S. Bari, and T. Hassan, 2001. Kinematic hardening rules in uncoupled modelling for multiaxial ratcheting simulation, Int. Journal of Plasticity, 17, 885-905 (2001). The most stable carbide in this type of steel is the VC-carbide, and because of its stability it plays an important role in the heat treatment. The VC-carbide is responsible for pinning the grain boundary in order to obstruct the grains from growing. Thus, a higher austenitizing temperature can be used without a significant grain growth. A
typical example of this can be seen if the average grain size versus austenitizing temperature.

25. **K.D. Fuchs, 2002.** Hot-work tool steels with improved properties for die casting application, Proceedings of the 6th International Conference on Tooling, Karlstad, 2002, p.15-22. heat treatment conditions where a higher austenitizing temperature is used more of the primary carbides are dissolved into the austenite, which not only makes the martensite more saturated with alloying elements, but also in the following tempering the amount of small stable secondary carbides will increase. If the carbides between the different materials are compared it can first of all be seen that the majority of carbides in the material are chromium rich carbides such as M7C3 and M23C6, Fig. 4(b), which easily coalesce and coarsen.

26. **Z. Zhang, D. Delagnes and G. Bernhart, 2002.** Anisothermal cyclic plasticity modelling of martensitic steels, International Journal of Fatigue. Vol. 24. p. 635-648, 2002. it was found that initially there was a difference in micro strain between different heat treatment conditions, and a distinction between the various heat treatment initial softening rate parameters could be found. Also, it should be noted, that the present model used the initial strain-hardening behaviour to determine the material parameters during the entire simulation. However, it is recognised that it may change during a test, giving additional effects on the secondary softening.

27. **Ajayan, P.M.; Schadler, L.S.; Braun, P.V. 2003.** Nanocomposite Science and Technology; Wiley: New York, NY, USA, 2003; p. 112. Nanocomposites are as multiphase materials, where one of the phases has nanoscale additives. They are expected to display unusual properties emerging from the combination of each component. According to their matrix materials, nanocomposites can be classified as ceramic matrix nanocomposites (CMNC), metal matrix nanocomposites (MMNC), and polymer matrix nanocomposites (PMNC). In this review, the recent progress in PMNC is reported.


**G. Roberts, G. Kraus and R. Kennedy, Tool Steels 5th ed.** (ASM International), Metals Park Ohio, 1998. However, die casting is a fairly new technique and is
characterised by a source of hydraulic energy that pass on high velocity metal into a cold die chamber where the metal is solidified in to desired shape. This is a rapid event, with a filling time in the order of seconds.


Forged components are shaped either by a hammer or press. Forging on the hammer is carried out in a succession of die impressions using repeated blows. The quality of the forging, and the economy and productivity of the hammer process depend upon the tooling and the skill of the operator. In press forging, the stock is usually hit only once in each die impression and the design of each impression becomes more important while operator skill is less critical. The continuous development of forging technology requires a sound and fundamental understanding of equipment capabilities and characteristics. The equipment i.e. presses and hammers used in forging, influences the forging process, since it affects the deformation rate and temperature conditions, and it determines the rate of production. The requirements of a given forging process must be compatible with the load, energy, time, and accuracy characteristics of a given forging machine

30. Sanchez, C.; Julián, B.; Belleville, P.; Popall, 2005. M. Applications of hybrid organic-inorganic nanocomposites. J. Mater. Chem. 2005, 15, 3559-3592. The inorganic particles not only provide mechanical and thermal stability, but also new functionalities that depend on the chemical nature, the structure, the size, and crystallinity of the inorganic nanoparticles (silica, transition metal oxides, metallic phosphates, nanoclays, nanometals and metal chalcogenides). Indeed, the inorganic particles can implement or improve mechanical, thermal, electronic, magnetic and redox properties, density, refractive index.

Therefore, the composites have been widely used in the various fields such as military equipments, safety, protective garments, automotive, aerospace, electronics and optical devices. However, these application areas continuously demand additional properties and functions such as high mechanical properties, flame retardation, chemical resistance, UV resistance, electrical conductivity, environmental stability, water repellency, magnetic field resistance, radar absorption, etc. Moreover, the effective properties of the composites are dependent upon the properties of constituents, the volume fraction of components, shape and arrangement of inclusions and interfacial interaction between matrix and inclusion. With the recent development in the nanoscience and nanotechnology fields, the correlation of material properties with filler size has become a focal point of significant interest.

32. Osman, M.A.; Rupp, J.E.P.; Suter, U.W 2005. Effect of non-ionic surfactants on the exfoliation and properties of polyethylene-layered silicate nanocomposites. Polymer 2005, 46, 8202-8209. The properties of the nanocomposites are contributed to the properties of the components, shape and volume fraction of the filler, the morphology of the system and the nature of the interphase that sometimes develop at the interface of the two components.

33. C.J. Van Tyne and J. Walters-2007. “Understanding geometrical forging defects”- April 1, 2007 Selection of forging machine depends upon force and energy requirements, Material to be forged (soft material- use press, hard material- use hammers), Size-shape and complexity of forging, Strength of the work piece material, Sensitivity of material to rate of deformation, Production rate, Dimensional accuracy, Maintenance, Operating skill level required, Noise level, Cost. Usually involves discrete parts, May be done on hot or cold materials, Often requires additional finishing processes such as heat treating, machining, or cleaning, May be done at fast or slow deformation rates, May be used for very small or very large parts, Improves the physical properties of a part by controlling and refining the flow or grain of the material.

34. H. James Henning-2007. “Defects in Hot Forging”- May/June 2007 This crack penetrates into the interior after flash is trimmed off. Cause- Very thin flash Remedy-
Increasing flash thickness, relocating the flash to a less critical region of the forging, hot trimming and stress relieving.

35. Arkey 2007. Course Material by Technical Training and Research Institute, Pune, Maharashtra, India- “Defect analysis and Productivity improvement in forging industries”- October 2007 Forging is carried out at a temperature above the recrystallization temperature of the metal. The recrystallization temperature is defined as the temperature at which the new grains are formed in the metal. This kind of extreme heat is necessary in avoiding strain hardening of the metal during deformation.