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Review

A review of cryogenic cooling in high speed machining (HSM) of mold and die steels

Aznijar Ahmad-Yazid[1]*, Zahari Taha[1] and Indra Putra Almanar[2]

[1]Faculty of Engineering, Universiti Malaya, 50603 Kuala Lumpur, Malaysia.
[2]School of Mechanical Engineering, Universiti Sains Malaysia, 14300 Nibong Tebal, Pulau Pinang, Malaysia.

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Metal cutting generates heat which influences the quality of a finished product, the force needed in cutting as well as limiting the life of the cutting tool. There are various attempts by researchers all over the world to understand the mechanism and theory behind the temperature built-up during machining in order to achieve optimized machining procedure and best workpiece results. Theories are developed, experiments conducted as well as models and simulations proposed. The latest attempt in metal cutting cooling is through the use of chilled air, cryogenic cooling. A Ranque-Hilsch vortex tube (RHVT), a device with no moving parts, is used for this low-cost refrigeration purpose. Backgrounds of RHVT, various studies conducted on it, its performance and applications are discussed for the high speed metal cutting cooling application for mold and die steels. Option for future research is proposed.

Key words: High speed machining, end milling, cryogenic cooling, vortex tube, mold and die.

INTRODUCTION

Metal cutting, sometimes simply referred as machining, is an operation where a wedge-shaped tool removes from a larger body, a thin layer of metal (Trent and Wright, 2000). This discarded thin layer is called chip or swarf. Operations included in metal cutting are such as turning, boring, drilling, milling etc. Other being prominent in big industries of aluminium, steel, automotive and aerospace, metal cutting also plays a crucial role in a wide range of manufacturing industries such as in the manufacture of magnetic heads, quantum electronic and other similar small scale devices.

Everyone seems to agree on one thing, metal cutting is indeed an art that is also science (Armarego and Brown, 1969; Black, 1961; Komanduri, 2002). The use of lathe as a cutting machine is said to have started from very ancient times, but the most accepted modern lathe is attributed to Henry Maudslay of England in 1797. Early progress to the industry was made through trial and errors of machinist, at slow pace and very un-scientific. Even though systematic studies on the mechanics of cutting have been made early in 1798 by Komanduri (2002) and in 1851 by Cocquilhart, major analysis were credited to the later works of Hans Ernst, Martellotti, Kronenberg and Merchant in the 20th century (Armarego and Brown, 1969).

Being a significant contributor to the economy, many researches have been conducted by various people in different countries, so as to remain as the top metal cutting player. The evolution and progress of the metal cutting technology is performed through indirect observations on the phenomena concerning forces and stresses, temperatures, metal flows and interaction between the cutters and work-pieces since direct observation is largely difficult to be performed. Sharp (1960) even remarked the difficulties faced by machinist since there are many milling applications in which theory and practice do not go hand in hand. From basic theoretical and experimental observations of early year, researchers are now putting more effort using modelling and simulations for the studies of metal cutting. As early as in 1954, various discussions and researches have been attempted, focusing on (1) machine design, (2) tool problems, (3) cutting fluids, (4) machining variables, (5) specific materials machining techniques, and (6) work handling and holding (Hollingsworth et. al., 1954). In the

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*Corresponding author. E-mail: aznijar@um.edu.my. Tel: +603-79676838. Fax: +603-79675330.

early 1950s, Shaw (1958) has noted that other than the American and Russian (Zagorskii, 1960), the German are quite advanced in their metal cutting research.

High speed machining (HSM) is generally associated with rotational speeds of end mill of about 100 000 rev/min. Manufacturers employing HSM normally use expensive machining centres with typical spindle speed between 10 000 up to 20 000 rev/min and of feed rate up to 20 m/min. Expensive and high-strength cutting tool is also used (Urbanski et al., 2000). Even though the idea of HSM was initially rejected by Schmidt (1958) in favour of other cutting techniques such as spark machining (electro discharge machining, EDM), Schulz and Hock (1995), and Urbanski (2000) noted that works on HSM over the years has drastically increased due to swift need of production demands. Following this new development, Dewes and Aspinwall (1997) has conducted an extensive review of the various works being pursued at HSM. Woody and Smith (2006) noted significant advances have been made in the HSM technology for the past 10 to 20 years. Chatter phenomena limitation in HSM is addressed by numerous studies using the stability lobe diagram since HSM increases material removal rate equal and beyond the natural frequency of the cutting machines (Altintas and Budak, 1995).

HEAT IN CUTTING

One of the key areas being investigated in metal cutting is the heat built-up, its effects and the various techniques to counter it. Metal cutting generates heat which influences the quality of a finished product, the force needed in cutting and limits the life of the cutting tool. Yong and Zhao (1999) stressed that in machining, heat is generated due to the plastic deformation of layer being cut and as well as due to the frictional forces created between the tool/chip and tool/work interface.

Black (1961), Armarego and Brown (1969) and Abukhshim et al. (2006) further divides the heat source in cutting into 3 different stages, namely; (1) Primary deformation zone, where heat is generated through elasto-plastic deformation at the shear zone, (2) Secondary deformation zone, where heat is due to plastic deformation and the sticking-sliding friction of the tool rake face and the workpiece, and (3) Tertiary deformation zone, where further heat is generated through elastic deformation and rubbing friction of tool flank (clearance) face with the workpiece (Figure 1).

There are various attempts by researchers all over the world to understand the mechanism and theory behind the temperature built-up during machining in order to achieve optimized machining procedure and best workpiece results. Theories are developed, experiments conducted (Silva and Wallbank, 1999; O'Sullivan and Cotterell, 2001) as well as models and simulations proposed (Chen et al., 2000; Teramoto et al., 2006).

FINDINGS FROM EXPERIMENTS

Chou and Evans (1997) found that highly refined microstructure materials are a better cutting tool for having a reduced wear rate and producing competitive surface finish. Failure due to crater wear was noted on rake face (Casto et al., 1997; Chou and Evans, 1997). Following this, Ay and Yang (1998) used thermocouples and infrared thermovision and found that the rake face of tool has the highest temperature when studying the temperature distribution on cutting tools, but it is far away from the cutting edge. This was supported by the works of Gu et al. (1999) and Liu et al. (2002). Silva and Wallbank (1999) concluded that at higher material removal rates, a lower proportion of heat is passed to the chip with more heat being retained at the workpiece, and the reverse proportion occurs at lower rates. However, O'Sullivan and Cotterell (2001) differed and attributed the decrease of machined surface temperature when they increase the cutting speed during experiments to the higher material removal rate. It was the faster removal of the chip that drained away the high temperature as well as less heat being conducted into the workpiece.

MODELLING AND SIMULATIONS PERFORMED

Mackerle (1999, 2003) has reported extensively on the finite-element methods (FEMs) applied to the analysis and simulation of machining, performed from 1976 until 2002. Various aspects and areas explored by researchers were compiled and indexed at Mackerle's own database, MAKEBASE and reported at his website (Mackerle, 1996). Based on the analytical modelling of the orthogonal cutting process in conjunction with orthogonal cutting experiments, Tounsi et al. (2002) has proposed a methodology which identified the material coefficients of constitutive equation within the practical range of stress, strain, strain rate and temperature encountered in metal cutting. Accurate material constants are essential in the modelling exercises for metal cutting. Applying the methodology on different materials, the material constants estimated by the new methodology was shown comparatively effective against those obtained using the compressive split Hopkinson bar (CSHB) technique.

Chen et al. (2000) and Ng et al. (1999) used finite element analysis (FEA) to predict the temperature distribution during machining. Upon validation with pyrometer measurement, they have found that the tool-chip interface exhibited the highest temperature generation compared to the other regions. Majumdar et al. (2005) also concurred with this work. Komanduri and Hou (2001) has successfully shown that differences in the thermal properties of cutting tools, workpieces and cutting conditions bring about a different machining temperature distribution.

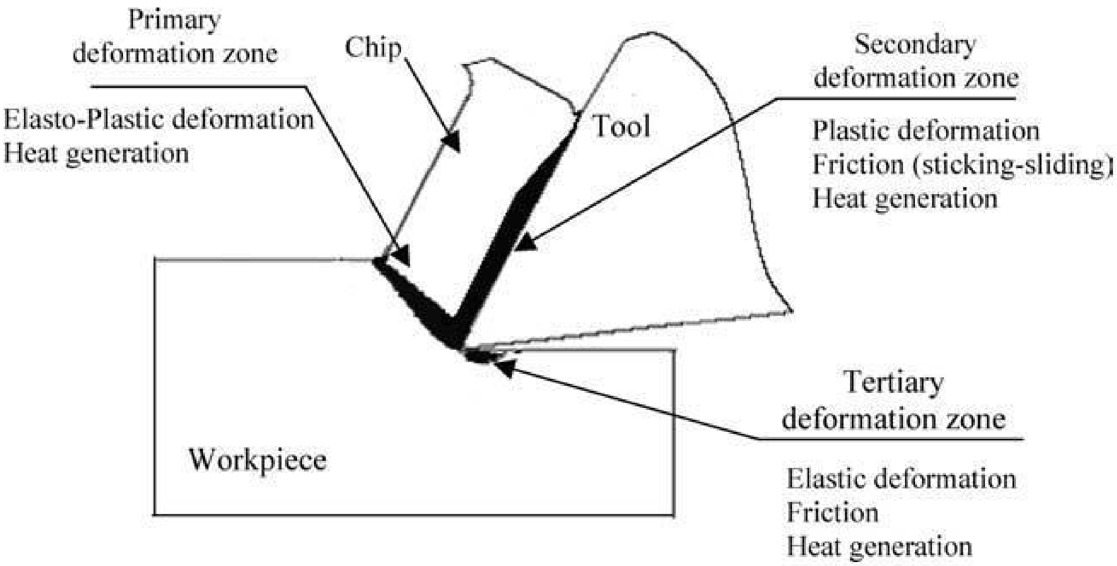

Figure 1. Heat source zone in metal cutting (Abukhshim et al., 2006).

Using FEA, Wang and Petrescu (2004) proved that lowering the temperature at the flank face using cryogenic cooling helped to avoid early tool failure. Teramoto et. al. (2006) used a combination of simulation and visualization technique to aid monitoring of machining process.

Chien and Chou (2001), in noting the previous works of researchers, continued working with artificial neural network (ANN) and genetic algorithm (GA) to achieve the optimum cutting condition for a 304 stainless steel. By adopting GA with ANN, experimental data needed to achieve the objective of optimized cutting condition were limited to only the cutting speed, feed and depth of cut.

HEAT DISSIPATION

Heat generated during machining is dissipated away through four systems within the machining system that is through the cutting tool, the workpiece, the chip and the use of cooling agents (Silva and Wallbank, 1999). The most popular approach towards reducing the heat generated during cutting is by far, by employing cooling mechanism. This is in spite of the findings by Abukhshim et al. (2006) that cutting fluid and tool geometry are the least affected by the heat generated during cutting as opposed to the combination of physical and chemical properties of workpiece and cutter material, their cutting conditions and parameters.

COOLING APPROACHES USED BY METAL CUTTING RESEARCHERS

As indicated by Silva and Wallbank (1999) that through cooling the cutting tool, freezing the workpiece, cooling the interface of tool/chip and tool/work, or with the chip draining the heat away, unwanted heat can be eliminated. However, since materials respond differently to different temperature and machining approaches; cooling needs to be strategized (Yong and Zhao, 1999). Matsuoka et al. (2005) also observed the same different results for different cutting tool materials subjected to similar cooling treatment.

The cutting conditions in metal cutting can be improved by the use of cutting fluids, acting both as a coolant and a lubricant (Boothroyd, 1965; Armarego and Brown, 1969; El Baradie, 1996a). Cutting fluids serves to lubricate at relatively low cutting speeds and acts as a cooling agent at relatively high cutting speeds (Shaw, 2005). However, Shaw (1970), El Baradie (1996b) and Sales et al. (2001) indicated that whilst cutting fluid also helps to dispose chip; has the disadvantages of being a corrosion agent, incurring additional cost and bringing about concerns towards health, safety and aesthetic during operation.

Shaw (1956) reported on various methods of applying cutting fluids, explaining many tests that were performed with cutting fluids in the form of a flood of liquid and a mist. Those studies observed the cutting tool life and the workpiece surface finish when subjected to various fluid conditions. Following the initial work using water and soda water flood cooling by Taylor in 1906, Shaw (1956) have indicated different directions of the cutting fluid being focused at either the tools and workpieces or both, by other researchers.

It is not a very attractive proposition for air to be considered as a coolant since all gases have relatively poor cooling capacity compared with liquids. Better performance in cooling by refrigerating the gases as shown by researchers indicated air, carbon dioxide and nitrogen in ascending order of performance (Shaw, 1956).

Yong and Zhao (1999) experimented in using super cold liquid nitrogen. Nitrogen being an environmentally-friendly gas can be released away, evaporating back to the atmosphere. This approach is good where the cooling agent, nitrogen is naturally recycled and not harmful to environment. However, since different results were achieved using different combination of tool/work, they concluded that different approaches are needed for different tools and workpiece materials. Having the gases at high pressure was found to be of an additional help. Experimentally, Dhar et al. (2006b) proved that high-pressure coolant jet reduces grinding zone temperature significantly due to effective cooling and lubrication at the grinding zone area. The surface roughness when compared to dry grinding is lower.

Faust, Brosheer, Thuma and Chamberland were credited by Shaw (1956) for mist lubrication approach. Many different schemes varying the concentration of liquid and particle size has been conducted by different researchers, with different results being achieved (Matsuoka et al., 2006). While minimal quantity lubricant (MQL) is slowly being accepted as an alternative to flood cooling and provides up to 80% longer tool life, further studies were needed to find the best design of external nozzles and getting the right amount of fluid to the cutting point (Tolinski, 2007).

Some other conclusions from the observation of Shaw (1956) are; (1) Tool life are affected by metallurgical differences more than by differences in cutting, (2) Generally, mist form water base fluids provided tool life results very similar to using flood of liquid, except for water since evaporation is large when a water mist is used, (3) The amount of liquid in the mist was not found to be critical, (4) The most effective direction for cooling is along the clearance face, (5) The effect of speed upon surface finish is far greater than the effect of using any water base fluids, and (6) While mist did not give quite as good a finish as a flood of liquid for the best fluids, the difference was far less than that for a good and poor lubricant. Thus, where it is more convenient to use mist lubrication at low speeds, where surface finish is the major problem. Water, when applied as a mist or as a flood of liquid, is not a good material where finish is of interest.

To aid dry cutting, researchers also introduce coating to help as lubricating agent and to provide strength to cutting tools, such as by particle vapour deposition of TiAlN (hard layer) and WC/C (lubricant layer) onto cutters by Derflinger et al. (1999). Being economical, yet functional, Ducros et al. (2003) used CrN/TiN and TiN/AlTiN for machining Inconel 718.

Following Shaji and Radhakrishnan (2002) and Gopal and Rao (2004), the latest technique is shown by Jianxin et al. (2009) in demonstrating the application of modified tool for dry cutting use. Molybdenum disulfide, a solid lubricant, was filled into the micro-holes on the rake and flank face of the cemented carbide (WC/Co) tools to form self-lubricated tools. During dry-cutting of hardened steel, the cutting forces, the tool wear and the friction coefficient at the tool-chip interface using the modified tool was found to be significantly lower when compared with the use of a conventional WC/Co tools. This was attributed to the self-lubrication action of the modified tool.

CUTTING FLUID

Cutting fluids, normally expected to act as a coolant helps to increase tool life by virtue of the reduced cutting temperature at the cutting edge. The temperature gradients generated are also brought down by this cooling effect, ensuring a lower thermal distortion to the work-piece. On the other hand the lubricating action of cutting fluids is mostly required as the prime consideration when heavy cutting load is expected in operations such as screw and gear cutting and broaching. Cutting fluid also flushes chips away during cutting, avoiding damaging the work-piece. In short, the application of cutting fluid ensures the longevity of tool life and a significant improvement of the surface finish of work-piece produced. During cutting, coolant is applied, according to the desired end result, in the form of flood, as mist, or not at all that is dry cutting.

However, recent studies and observations have shown serious repercussion of using cutting fluids (Cooper and Leith, 1998; D'Arcy, 1996; Hands et al., 1996; Leith et al., 1996a; Leith et al., 1996b; Lonon et al., 1999; Krystofiak and Schaper, 1996; Raynor et al., 1996; Suuronen et al., 2007; Thorne and DeKoster, 1996; Wilsey et al., 1996; Woskie et al., 1996). Fadlallah et al. (1997) has observed a significant decline in the concentrations of N-nitrosodiethanolamine (N DELA), a notorious mutagen, carcinogen and teratogen that can be seriously hazardous to human health in Metal-working fluids (MWFs) used in Canada.

Experimental research by Sutherland et al. (2000) in comparing between wet and dry machining reveals that wet turning produces 12 - 80 times more airborne particulate matter (cutting fluid mist) than cast iron dust in dry turning. The cutting fluid mist has high aerosol concentrations and can remain suspended in working environment for a long time and can be easily inhaled into the deep portions of the lungs. Speed, feed and depth of cut were all found to be significant factors in the formation of both cast iron dust and fluid mist. The mass concentration in all cases was found to increase with increasing values of speed, feed, and depth of cut, with the greatest levels recorded at the highest material removal rate.

Cutting fluids are harmful to the environment and an additional cost is needed for processing the waste before disposal. Klocke and Eisenblatter (1997) studies indicated the financial loss when deployed in cutting. Sheng et al. (1996) proposed a hierarchical part planning strategy for environmentally conscious machining to tackle this fatal issue. Due to the detrimental effects of the cutting fluids to the environment, safety and health, lots of researches were conducted towards minimizing or to totally avoid the use of cutting fluids altogether (Byrne and Scholta, 1993; Aronson, 1995; Klocke and Eisenblatter, 1997; Sreejith and Ngoi, 2000; Sales et al., 2001; Weinert et al., 2004). Sales et al. (2001) classified these two approaches distinctly as; (1) cutting without fluid (dry cutting) and (2) cutting with the addition of MQL.

Tolinski (2007) also noted that manufacturers has resorted to minimize cutting-fluid used during cutting due to the real ‘high’ costs of fluid use, hence, the concept of near-dry machining; especially the MQL approach becoming the 'in-thing' within the industry. Since the 1950’s, it has also been recorded the use of cryogenic gases, e.g. carbon dioxide or liquid nitrogen, for cutting and grinding fluids, to be one of the alternative solutions to the problems attributed to the cutting fluids (Silliman, 1992; Hong, 2001; Dhar et al., 2002).

When evaluating the performance of cutting fluid, De Chiffre and Belluco (2000) found that tests based on cutting forces have better repeatability and resolution, with test costing half when compared with test based on surface finish condition. Tests based on tool life fared the worst and are most expensive. While grinding using CBN tools, Tawakoli et al. (2007) has observed that oil performed better as a coolant compared to emulsion. However it was also noted that the use of other types of oil and emulsion might offer different results altogether.

Through grinding experiments complemented by computational fluid dynamics (CFD) prediction, Morgan et al. (2008) suggested for researchers to look at improving the cooling liquid delivery system in order to achieve the appropriate coolant velocity and flow-rate so as to eliminate waste and over-supply. Particular attention should be given to the nozzle position, design, flow-rate and velocity while the choice of cutter material and speed are considered. Preliminary study by Jin and Stephenson (2008) proved that the convection heat transfer coefficient (CHTC) values within the cutting zone can be estimated through theoretical analysis in combination with the experimental approach. CHTC was found to be influenced by the cutting speed and the cutting fluid film thickness within the contact zone. Other than the cutting parameters, the film thickness is greatly affected by the fluid system properties, namely; type, flow rate and nozzle size.

CLASSIFICATION OF CUTTING FLUID

Cutting fluids can be classified in various ways, but Sales et al. (2001) proposed for the fluid to be categorized as; (1) Air (or Gases, according to El Baradie (1996b)), (2) Water Based Cutting Fluids: water, emulsions (soluble oil), chemical solutions (or synthetic fluids), and (3) Neat Oils: mineral oils, fatty oils, composed oils, extreme pressure oils (EP), multiple use oils (Figure 2).

CRYOGENIC COOLING

Cryogenics is defined as a branch of physics that deals with the production and effects of very low temperatures (Merriam-Webster Online Dictionary, 2009). The Institut International du Froid / International Institute of Refrigeration (IIF/IIR) defined it as the science and technology of temperatures below 120K; the limit temperature of 120K which comprehensively includes the normal boiling points of the entire main atmospheric gases (Lebrun, 2007). TwoBritish chemists, Sir Humphry Davy and Michael Faraday, working with low-temperature physics (between 1823 and 1845), are credited as the pioneer to the development of cryogenics (Microsoft MSN Encarta Encyclopedia, 2009). Since the first liquefaction of air to 100K by the French physicist Louis Paul Cailletet and the Swiss scientist Raoul Pierre Pictet in 1877, the work in cryogenics today has progressed to the current lower temperature values of about 0.1 nK (Lebrun, 2003).

Cryogenics are used for large-scale production of oxygen and nitrogen from air, storage and transportation of liquefied natural gas, as nuclear particle detectors, for infrared devices, lasers, rocket fuel, etc. Cryogenic cooling is used in space telescopes. Compact cryo-coolers such as vortex tubes and spot coolers allow cryogenic temperatures to be used in an increasing variety of military, medical, scientific, civilian, and commercial applications, including infrared sensors, superconducting electronics, and magnetic levitation trains. Quantum phenomena such as superfluidity and superconductivity, chemical reactions and other properties of molecules are conducted and studied at cryogenic temperature. The latest development in cryogenics are Cryobiology - the study of life and life processes at very low temperatures, as well as the cryogenic preservation of biological and medical materials (Microsoft MSN Encarta Encyclopedia, 2009) (Figure 3).

RANQUE-HILSCH VORTEX TUBE (RHVT)

In 1930, Georges Joseph Ranque, a French physicist first discovered the vortex tube and patented it in 1932. However, it was only in 1946 that an American engineer, Rudolf Hilsch started to turn this phenomenal finding into practical, effective cooling solutions for industrial applications. Hilsch also published some basic construction details of the vortex tube with theoretical modelling and calculations (Cockerill, 1995; Kotelnikov, 2006). This Ranque-Hilsch vortex tube (RHVT) is a device with no moving parts that can produce from a high pressure input gas, two streams of gases at different temperatures, one

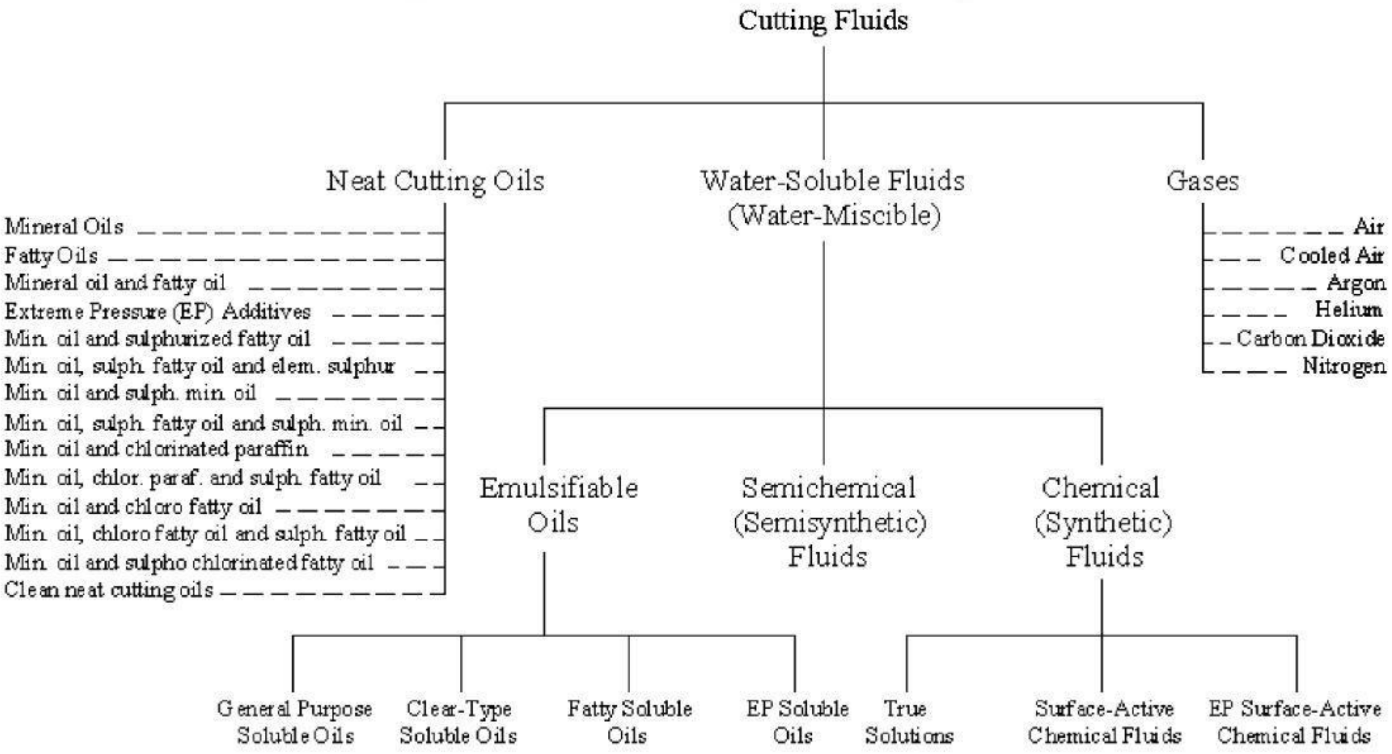

Figure 2. Classification of cutting fluid (El Baradie, 1996b).

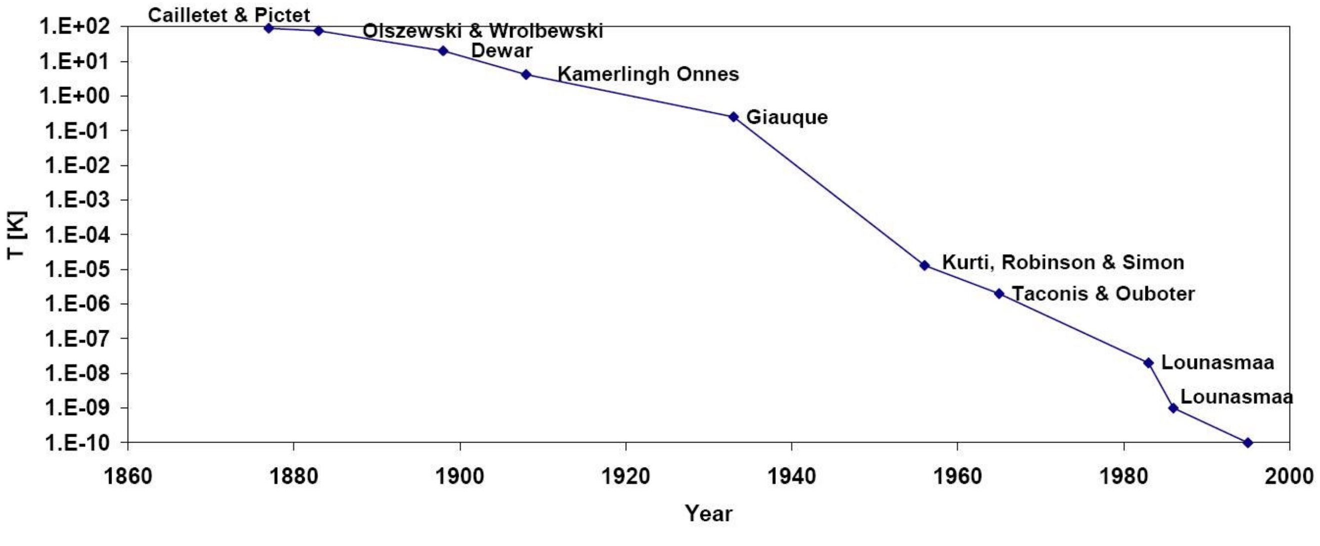

Figure 3. Progress of cryogenic studies (Lebrun, 2003).

hotter, and another colder. RHVT is used for low-cost refrigeration purposes. Even though the energy efficiency of RHVT is much lower than the conventional refrigeration cycle devices, it is very highly reliable. RHVT is suitable to be used when high pressure gas is readily available (Hellyar, 1979). Some patent based on RHVT and cryogenic cooling are such as by Nicol and Lane (2005) for Vortex Tube System and method for processing natural gas, Hong's cryogenic delivery mechanism (Hong, 1999) and Zurecki et al. (2002, 2004). RHVT works when the compressed air enters the tube which is exactly a cylindrical generator which causes the air to rotate. The rotating air is then forced down the inner walls of the hot tube at high velocity. At the end of the hot part of the tube, a small portion of this air exits through a needle valve as hot air exhaust. The remaining air is forced back through the centre of the incoming air stream at a slower speed. The heat in the slower moving air is transferred to the faster moving incoming air. This super-cooled air flows through the centre of the generator and exits through the cold air exhaust diffuser. Baffled rsearchers have tried to find qualitative explanations to the phenomena but no quantitative model for the Ranque-Hilsch effect has been established (Kotelnikov, 2006). Pourmahmoud and Akhesmeh (2008) and Akhesmeh et al. (2008) have introduced a steady axisymmetric computational fluid dynamics model (with swirl) that utilizes the standard k-ε turbulence model to predict the flow fields and the associated temperature separation within a Ranque-Hilsch vortex tube. A second-order numerical schemes was used. The model introduced was found to have good agreement with experimental data. The work has been carried out in order to provide an understanding of the physical behaviours of the flow variation of pressure and temperature in a vortex tube. It is worthy of note that when Eiamsa-ard and Promvonge (2008b) reviewed previous studies on temperature separation in RHVT, two important parameters were noted, the geometrical characteristics of the RHVT, and the thermo-physical parameters of the inlet gas. However, they still noted that even though many experimental and numerical studies on RHVT have been made, the physical behaviour of the flow is not fully understood due to its complexity and the lack of consistency in the experimental findings.

Colgate and Buchler (2000) did experimental and theoretical study of the RHVT, which cannot be explained by a simple turbulent model, similar to the equally enigmatic and similar phenomenon in astrophysics of Keplerian accretion disk. There is already good experimental evidence to suggest that the cause of this enhancement is the formation of aligned vortices that swirl around the symmetry axes very much like virtual paddle blades. They theoretically link the plausible explanation of the RHVT to Keplerian accretion disk similar enhanced angular momentum transfer. The expected excitation of axially aligned ”Rossby” vortices has been predicted analytically and the linear growth has been modelled with numerical codes. The work is however, still without experimental proof which might offer further understanding of the Navier-Stokes equations.

The exergy-destruction rate and flow availability vortex tube energy separation was estimated by Saidi and Yazdi (1999). The equation derived for the rate of entropy generation was validated and a new approach to optimize dimensions and operating conditions of a vortex-tube using exergy analysis was proposed.

COMPUTATIONAL WORKS ON RHVT

Other than works previously indicated in the preceding paragraphs, various numerical computations have been performed to understand the RHVT better. Bezprozvannykh and Mott (2003) used FLUENT software with the Reynolds stress turbulence model and the Reynolds averaged Navier-Stokes (RANS) equations and managed to visualize the velocity and temperature fields inside the vortex tube in order to understand the details of fluid flow. It was shown that various levels of complexity in turbulence modelling were able to be simulated and no vortex effect was observed for incompressible flow. Raghavan et al. (2006) also used FLUENT.

Behera et al. (2005, 2008) performed both Computational fluid dynamics (CFD) (using k–ε turbulence model of the Star-CD software) and experimental studies towards optimizing the RHVT. Different types of nozzle profiles and number of nozzles are evaluated by CFD analysis. The swirl velocity, axial velocity and radial velocity components as well as the flow patterns including secondary circulation flow, which are difficult to obtain experimentally due to disturbance of flow by measuring probes have been obtained through the computation. The optimum cold end diameter (d(c)) and the length to diameter (L/D) ratios and optimum parameters for obtaining the maximum hot gas temperature and minimum cold gas temperature can be maximized by increasing the length to diameter ratio of vortex tube such that stagnation point is farthest from the nozzle inlet and within the tube. The studies also confirmed the presence of secondary flow for vortex tubes with low dc/D values, which may results in performance degrading for vortex tubes. Though the coefficient of performance (COP) of vortex tube is low when compared to the COP of Carnot cycle for the same temperature conditions, the vortex tubes can be used for modest heating and/or cooling requirements and when compressed air is available readily. Singh et al. (2004) proved this findings experimentally.

Using an algebraic Reynolds stress model (ASM) and the standard k-ε model, Eiamsa-ard and Promvonge (2006, 2007) performed numerical calculations to investigate the cold mass fraction’s effect on the temperature separation for vortex tubes. A TEFESS code, based on a staggered Finite Volume approach with the standard k-ε model and first-order numerical schemes, was used and results suggested that the use of the ASM leads to better agreement between the numerical results and experimental data, while the k-ε model cannot capture the stabilizing effect of the swirl.

Derksen (2005) performed large-eddy simulations (LES) of the turbulent flow in a swirl tube with a tangential inlet based on an experimental study by Escudier et al. (1980). A Lattice-Boltzmann discretization was used to numerically solve the Navier-Stokes equations in the incompressible limit. Flow features, such as vortex breakdown and laminarization of the vortex core, observed from the experiments were represented very well and this study confirmed the experimental observations that the average velocity profiles in the entire vortex tube are

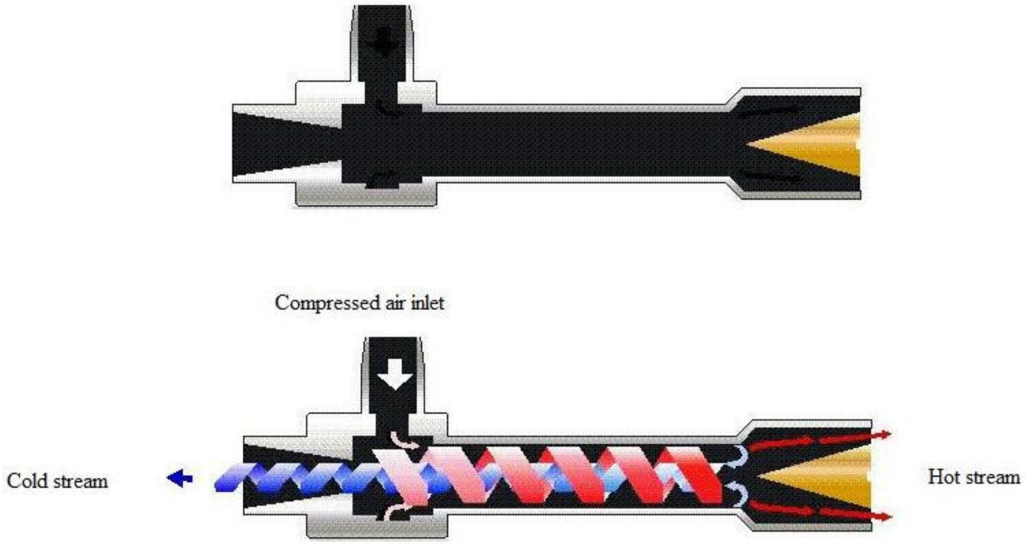

Figure 4. RHVT (Exair Corporation, 2007).

extremely sensitive to the exit pipe diameter. Very high average velocity gradients were encountered for the narrowest exit pipe considered and show the most pronounced effects of spatial resolution and subgrid-scale modelling. LES was also adopted by Farouk and Farouk (2007).

A computational study of the RHVT by Oliver (2008) showed the capability of CFD software, ANSYS CFX 10 to predict the highly complex flows contained within a RHVT. The predictions compared favourably with all the previous works of Fröhlingsdorf and Unger (1999) (CFX software, using k-ε model and adapted formulation), Colgate and Buchler (2000), Aljuwayhel et al. (2005) (using FLUENT software with two standard models, k-ε model together with a turbulent Prandtl number equal to unity and the RNG (Random Number Generation) k-ε model), Behera et al. (2005, 2008), Promvonge and Eiamsa-ard, 2005, Skye et al. (2006) and Eiamsa-ard and Promvonge (2008a). This work also confirmed the presence of secondary flow and locating the stagnation point with-in the flow. Attempts were also made through CFD studies by Choi and Chung (2008).

COOLING THEORY

Lewins and Bejan (1999) noted that the RHVT is an intriguing device in which a stream of high pressure gas swirls to split into two low pressure streams, one higher than at entry temperature and the other lower. The drop in pressure more than accounts for this apparent breach of the Second Law of Thermodynamics, which never-the less puts a limit on its performance. At a pressure drop ratio of 5 and ambient temperature, temperature differences of 30K (or 10% of ambient) are easily obtained, sufficient for simple refrigeration. The lack of moving parts, electricity etc., make the device attractive for a number of specialized applications where simplicity, robustness, reliability and general safety are desired, either as a supply of hot or, more likely, cold gas. For any given cut or fraction of the cold stream, the best refrigerative load, allowing for the temperature lift, is nearly half the maximum loading that would result in no lift. The second optimization shows that the optimum cut is an equal division of the vortex streams between hot and cold.

How does it work

High pressure gas is fed into the 'T' shaped device at the stem and the gas exits at both 'arms' of the 'T'. The inlet stem is tangential to the inner wall of the device. The gas, leaving the inlet nozzle, travels down the end of the hot tube in a vortex. A fraction of the inlet gas can be forced to flow through and orifice (diaphragm) inside the hot tube using an adjustable valve. The slower velocity through the small opening becomes chilled, due to the heat being taken away by the faster flowing hot stream travelling to the hot end, exits at the other end, the cold outlet. This schematic is from the original design of the RHVT and is also called as 'counter-flow' vortex tube (Figure 4). There are also other not so popular types of vortex tube in the market such as the design by Torocheshnikov in 1958, and in 1971 by Lewellen as well as Linderstrom-Lang (Hellyar, 1979).

When reviewing the existing theories of the Ranque effect and noting their inherent inconsistencies in the interpretation of some experimental data, Gutsol (1997) proposed for new approaches to the vortex effect are formulated. A unified explanation of all the experimental data available would be achieved. This must be performed theoretically, experimentally and numerically.

Performance

Hellyar (1979) noted that the relative temperatures of the two hot and cold streams of RHVT are determined by the ratio of mass flow of the two opposing stream and its geometrical parameters, while it was reported by Boswell and Chandratilleke (2009) that Gulyaev has experimented in 1966 and found that the minimum ratio of the length of the tube to that of its diameter were thirteen.

Alhborn et al. (1994) conducted experiments using vortex tube with inner diameter, D of 18 mm. The length was 23D. Compressed air was injected into a single circular inlet orifice of surface area, A_o = 14.5 mm^2. The hot air was released through four-symmetrically-arranged large wall-holes with a total cross section of A_h = 1520 mm^2 and the cold air was extracted through a hole of A_c = 33 mm^2. Alhborn's proposed model provided an upper limit of hot temperature of $(T_h - T_o)/T_o \ll X(\gamma - 1)/\gamma$ and the lower limit of cold temperature of $T_c \gg T_o(1 - X)^{\gamma-1/\gamma}$, with X being the normalized pressure drop between the inlet and the cold outlet, $(P_o - P_c)/P_o$. With the maximum inlet Mach number of 1, it was noted that the internal dynamics of the vortex tube will only have an optimum value of X at 0.7, a sub-sonic flow. With X being a function of relative pressure difference, it was predicted that vortex tubes can be operated in a much wider pressure range than previously used.

Experimentally, Nimbalkar and Muller (2009) noted that even though there is an optimum diameter of cold end orifice for achieving maximum energy separation, the maximum value of energy separation was always reachable at a 60% cold fraction irrespective of the orifice diameter and the inlet pressure.

The experimental study of the temperature separation phenomenon in a counter-flow type vortex tube by Promvonge and Eiamsa-ard (2005) showed that the insulated vortex tube with 4 inlet nozzles and cold orifice diameter of 0.5D yielded the highest temperature reduction (temperature separation) and isentropic efficiency at about 30°C and 33%, respectively.

In an experiment study conducted by Gao (2005) and Gao et al. (2005) on the RHVT, it was proven that the process inside the RHVT system is highly irreversible. By modifying the Ahlborn's model, the performance was predicted. After validating the simulation and theoretical results against the experimental results, it was noted that to improve the performance of RHVT, exhaust velocity has to be increased while keeping the pressure drop over the inlet nozzle small. All experiments showed a secondary circulation flow within the RHVT and the turbulence level to be very strong in the centre and near the wall of the RHVT.

Aydın and Baki (2006) conducted an experimental study investigating the design parameters and performances of RHVT. Using different inlet pressures, the thermal performance as a function of the length of the vortex tube, the diameter of the inlet nozzle and the angle of the control valve were observed for three different working gases; air, oxygen and nitrogen. It was revealed that the inlet pressure and the cold fraction are the important parameters influencing the performance of the RHVT. Xue and Arjomandi (2008) had experimentally shown that the vortex angle played an important role in both the separation of cold and hot flows and the vortex tube performance. A smaller vortex angle demonstrated a larger temperature difference and better performance for the heating efficiency of the vortex tube. However, small vortex angles resulted in better cooling efficiency only at lower values of input pressure. The better performance of the vortex tube can be seen at higher input pressure and the highest efficiency can be found when the input pressure is around 4 bars.

When modelling, Dincer et al. (2008) found that artificial neural networks (ANN) can be reliably used in investigating the effect of length to diameter ratio and nozzle number on the performance of a counter-flow RHVT and it was proven through the experimental investigation of his team (Dincerk et al., 2009).

Wu et al. (2007) had proposed three innovative technologies to improve the energy separation efficiency of RHVT, namely: a new nozzle, a new intake flow passage of nozzles and new kind of diffuser. Their experimental results indicated that these modifications remarkably improve the performance of the RHVT. Recently, at the Chinese academic database at http://www.ilib2.com/, very aggressive researches have been reported in various local journals in China, with multiple patents being registered at People's Republic of China State Intellectual Property Office. Zhang and Lee (2006) further emphasized various works of RHVT there.

CRYOGENIC COOLING WORKS IN METAL CUTTING APPROACHES

Four cryogenic cooling approaches are attempted by researchers; pre-cooling the workpiece (Ding and Hong, 1997), indirect cryogenic cooling, cryogenic spraying with jet and direct cryogenic treatment (of cutting tools) (Yildiz and Nalbant, 2008). Being environmentally-friendly, liquid nitrogen is the most commonly used medium. Other cryogenic fluids are Helium, Hydrogen, Neon, Air and Oxygen (Lebrun, 2007).

Workpiece pre-cooling

After cooling by the refrigerated gases (works done by Olson, Pahlitzsch, Wister and Axer as indicated by Shaw (1956)), Busch (1969) proposed for metals which are difficult to machine to be first frozen and while in the frozen state are cut to shape. Busch also proposed cryogenics treatment in chilling aluminium castings prior to machining, can prevent the castings from moving during and after machining.

Indirect cryogenic cooling

Hong and Ding (2001), Wang et al. (1996), Wang and Rajurkar (1997, 2000) and Ahmed et al. (2007) has used this technique where the cutting tools are cooled indirectly with no physical contact between them. Cooling is only attempted at cutters or inserts and no attempt were made on the workpieces.

Cryogenic spraying with jet

De Chiffre et al. (2007) carried out experimental investigations which showed cryogenic CO_2 applied at 6 g/s performing as an efficient coolant for threading AISI 316L stainless steel as well as for parting/grooving AISI 304L stainless steel. Although the gas can act alone, best performance was obtained when 6 ml/min vegetable oil (with no additive) was added to the gas. It was also noted of the mandatory requirement to add oil at 10 ml/min to the gas when parting/grooving to prevent sudden tool failure. Inoue and Aoyama (2005) also proved experimentally that grinding of cutting tool using cooled-air with MQL ensured longer tool life and the surface roughness is lower when compared with oil-based grinding.

Ko et al. (1999) used a vortex tube for cooling ejected air, and liquid coolant misted by the air. Taguchi's method was used for optimization and eventually the group manage to conclude that it is possible to machine hard materials at a lower cost using TiN coated tools instead of expensive CBN tools when cooling is aided by RHVT.

Boswell and Chandratilleke (2009) when attempting turning using air cooled by RHVT found that the temperature recorded was found to be 40°C cooler than that obtained during traditional wet machining and 210°C cooler than dry machining. They concluded that dry machining incorporating cooled air being directed onto the tool interface is a possible alternative for harmful liquid-based cooling. However, the low convective heat removal rates associated with conventional air-cooling methods meant that a suitable improved cooling methodology still needs to be established.

Direct cryogenic treatment of cutting tools

When AISI M2 and AISI H13 steel were subjected to cryogenic treatment by Molinari et al. (2001), cost reduction of about 50% was gain because of the increases in high speed steels' hardness; bringing about a lower tool consumption and equipment thereby reducing time.

EFFECTS OF CRYOGENIC COOLING

Yildiz and Nalbant (2008) reported that in machining incorporating cryogenic cooling, workpiece material properties, cutting temperature, tool wear and life, work-piece surface roughness and dimension, tool/ workpiece friction ratio and cutting forces were affected.

Effect on workpiece material properties

Hong and Zhao (1999) found that when alloys were subjected to cryogenic cooling, the hardness increased retaining most of their mechanical properties, making them a very good choice as cutting material. However, Silva et al. (2006) and some other researchers have noted little difference when the same cryogenic treatment is applied on high-speed steels and other cutters. Hong et al. (1997, 1999), Hong and Zhao (1999) and Hong and Ding (2001) agreed that different treatment attempted by different researchers has contributed to the difference in the results of material properties being reported. Hong and Zhao (1999) further recommended that the best approach is by having simultaneous cooling of both workpiece and cutting tools would be an ideal effective cryogenic cooling strategy.

Effect on cutting temperature

All the works by Hong et al. (1999), Wang and Rajurkar (2000), Hong and Ding (2001), Dhar et al. (2002a, 2002b) and Dhar and Kamruzzaman (2007), reported a varying degree of cutting temperatures depending on the different cryogenic approach taken.

Effect on tool wear and life

Molinari et al. (2001)'s work showed that cryogenic treatment on cutting tools increases their hardness. Tool wear period is extended, lengthening tool life.

Effect on workpiece surface roughness and dimension

Risbood et al. (2003) and Azouzi and Guillot (1997) noted that dimensional accuracy are greatly influenced by the cutting machine system and the applied depth of cut. Surface roughness reductions are attributed to the reduction of auxiliary flank wear as a result of tool hardness being kept by the lower cutting temperature (Dhar et al., 2002a, 2002b, 2006; Dhar and Kamruzzaman, 2007; Paul et al., 2001). Wang and Rajurkar (1996, 2000) and Wang et al. (2003) however noted that the surface roughness can be improved using indirect cooling instead.

Effect on tool/workpiece friction ratio

Works by Hong (2001, 2002, 2006) and by Hong et al. (2001, 2002) has shown that the jet cooling also offered some cushion during cutting hence lowering the friction between the cutters and the workpieces.

Effect on cutting forces

Wang and Rajurkar (2000) noticed that cryogenic cooling do not significantly affect the cutting forces in machining. This might be due to the restriction of the cooling to the cutting insert and the workpiece was not affected at all. Hong et al. (2001) noted that generally cutting forces increases when cutting at lower temperature, materials being cut are harder and stronger, hence the higher force felt. However, some other researchers found the inverse condition occurring, which could be explained by the use of different materials and conditions during their experiments.

MOLD AND DIE STEELS (M AND DS)

In Malaysia, AISI D2 is the most extensively used cold work tool steel in the tool and dies industries (Kamely et al., 2007). For plastic mold, ASSAB 718 (modified AISI P20) is the most commonly used material while ASSAB 8407 (AISI H13 premium) is normally considered for hot work purposes.

In the UK, forging dies are normally the AISI H13 hot work tool steel (48-52 HRC). Plastic injection mold tool steel are normally made from AISI P20 (30-55 HRC), AISI D2/D3 (55-62 HRC), AISI H13 and stainless steel. Die casting material are AISI T2, M2 (52-62 HRC) and AISI H13 (Urbanski et al., 2000).

Fallbohmer et al., (2000) noted that in the U.S., in addition to AISI H13 steel; H11, H12 and FX steels with hardness ranging from 45-60 HRC are also commonly used. The most common mold material is AISI P20 at 30 HRC. It is then case-hardened to 50-55 HRC. S7, H13 and A2 are also used. For die-casting, AISI H13 is mainly used as well as S7, 4140 and P20 (46-50 HRC). For stamping dies, mainly GM241 cast iron, D2 and A2 steels are used.

Traditional technique for cutting M and DS

More than half of the companies involved in manufacturing injection molds surveyed by Fallbohmer et al. (1996) in Germany, Japan and the United States are mainly catering towards the need of the automotive industry, consumer electronics and household appliances industries. More than 60% are independent enterprises employing less than 100 people. The Japanese companies are the largest and fastest producer of dies and molds, followed by the German and the American (Figure 5).

Other observations includes; (1) Forging dies, die casting dies, and injection molds are mainly produced through milling and electrical discharge machining (EDM), or a combination of both. Dies for sheet metal forming processes are mainly machined by milling and grinding. Non-conventional machining methods are also being explored, (2) German and American companies gives low emphasizes on roughing, finishing and polishing but Japanese companies put more emphasize on polishing, spending little time on roughing and finishing. Further development of HSM technology in Japan and Germany will mean that EDM use for finishing and polishing will decrease. However, EDM is still heavily applied in the United States, (3) Manual polishing still is the most used method to achieve the required surface finish, especially in Japan and the U.S. Regarding automated polishing, the Japanese companies focus on mechanical machining methods whereas the Germans and the Americans prefer EDM, and (4) Japanese and German tool makers focus on their field of expertise and acquire outside contractors to do machining work, more so than their American colleagues. The focus of the Japanese and German helped to save time and further enhance the quality of the product.

Fallbohmer et al. (1996) also indicated that the way to reduce the lead-time in the manufacture of mold and die is by employing near net shape (NNS) manufacturing processes. Their prediction that contract work will become a typical phenomenon in the die/mold industries has been proven true, and so was their vision of HSM being employed within the NNS manufacturing approach, in order to achieve the faster production rate.

Carbide is the most common cutting tool material for M and DS (Fallbohmer et al., 2000). Although tough, hard coatings are added to improve its poor hardness. Ceramics such as AlO, SiN, cermet and polycrystalline diamond are also used. Tool diameter ranges from 1.5 to 0.5 inch. The normal way to produce molds and dies are by the use of standard support components such as cavity and core inserts so that machining can be concentrated to produce the core and cavity or the punch and the die.

M AND DS CUTTING RESEARCHES CONDUCTED BY OTHERS

Urbanski et al. (2000) conducted a research to demonstrate the appropriateness of employing HSM for the production of hardened steel molds/dies for the NNS manufacture of forgings, plastic injection moldings and die-castings. Three different tool materials were tested at

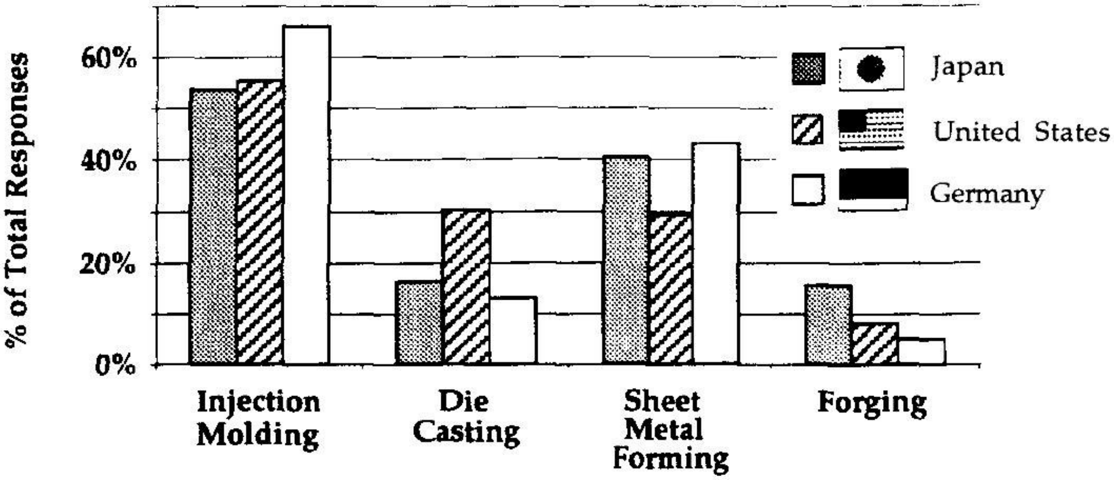

Figure 5. Types of Dies/Molds Produced (Fallbohmer et al., 1996).

spindle speed of 200 - 20 000 rev/min. Wear and cutting force were observed on tests performed according to ISO 8688-2, 1989 standard. It was concluded that TiCN coated carbide insert performed longer than uncoated cermet and TiAlCrYN coated insert. The tool life of TiAlN was observed to be four times higher than TiCN coated tools. The surface roughness averaged at 1 - 4 µm Ra and the cutting force was noted to be higher. This contributed to a relatively large axial depth of cut of 1 mm and negative rake angle of -10°.

In implementing NNS manufacturing approach, the die or mold tooling consumes considerable resources in terms of cost, time and expertise; sometimes accounting to over 25% of the total product cost and development time (Nagahanumaiah et al., 2005). It has always been intimated that manufacturing work such as machining is an experience-based industry and the process development has always been performed through trial and error approach by skilled craftsmen who picked their experience through apprenticeship (Woody and Smith, 2006). The die and mold development procedure varies for different parts and materials and is not very well documented (Nagahanumaiah et al., 2005). In this work, a flexible hybrid die and mold cost estimation model was developed by Nagahanumaiah et al. (2005), where a feature based approach, activity based costing and parametric costing methods were integrated to the input from the experience of the cost appraiser as well as the project-specific complexity indicators. The methodology has been implemented and tested at 13 industrial examples in India with the result showing an average deviation of 0.40% only.

Kamely et al. (2007) looked at the effect of cutting on residual stress of AISI D2, a regular cold work tool steel in the tool and die industry. Residual stresses was found to be more compressive as multiple pass cutting is applied and more compressive residual stress were found using worn tools compared to the new tools. It was also concluded that tool wear and multiple pass cutting have significant effects on the plastic deformation and at the surface. Different cutting speeds do not have any significant effect to the surface finish.

Fallbohmer et al. (2000) reviewed the implementation of HSM in M&DS manufacturing for the recent years and has proposed the following advances to ensure a cost effective implementation. They are; (1) Machine tools structure must be rigidly enhanced, (2) Coolant-through capability spindle and tool holders, (3) High data transfer controllers with good NC programming strategy, (4) Tool geometry, materials and coatings to be improved further to achieve longer tool life, (5) Deep process knowledge understanding and repeated reliability to be achieve for high level of machine performance and un-manned machining can be attempted safely, and (6) More accurate and true-to-life prediction of stress and temperature by process modelling.

CONCLUSION

The proposed future HSM incorporating cryogenic cooling on mold and die research work needs to adopt simulations of the cooling devices at the initial stage of the investigation in order to identify the best location and direction of cryogenic air jet. The cutting experiments can be based on tool life since a standard has been established, the ISO 8688-2:1989. To reduce the number of experiments, design of experiments, such as the robust Taguchi optimization (Ghani et al., 2004) can be adopted. Few different tools and materials regularly used in the local industry must be considered, in the case of Malaysia AISI D2, ASSAB 718 and ASSAB 8407. For better comparison, different mode of cryogenic cooling application method should also be explored.

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