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Problems of Heat, Mass and Momentum Transfer in Manufacturing Processes: A Brief Review

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ABSTRACT

In machining processes the chip flows over the tool rake and carries heat away as it moves. This is a case of mass transportation with heat transfer. Similarly, during hot forging, upsetting or coining processes heat is transferred from the hot billet to the relatively cooler dies, punches or hammers with momentum transfer under high impact load. Also, in high energy rate fabrication (HERF) processes, such as electromagnetic forming, explosive forming, impact extrusion, etc. heat is generated almost instantaneously, in milliseconds, and its dissipation is a serious industrial problem due to the very short process cycle time. In the present paper some of the problems related to heat, mass and momentum transfer in the above mentioned manufacturing processes are reviewed and compared with experimental results.

1. Introduction

In most of the manufacturing processes the work and the tool materials essentially pass through three zones of transformation, namely, plastic deformation, friction and wear [1-3]. During materials removal processes like machining, grinding, shearing and even polishing, plastic deformation, friction and tool wear are very severe since the work-piece material has to pass beyond its ultimate shear strength as a result of physical separation of chips and burrs from the main body of the work-piece [4, 5]. During materials forming without chip or burr removal, such as rolling, forging, extrusion, drawing, etc., however, the work material only passes over its yield

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strength in order to facilitate plastic deformation, and thus deformation, friction and die or tool wear are not as severe as in materials removal processes [6-8]. Nevertheless, in all manufacturing processes heat is generated in each of the deformation, friction and wear zones, and industry's challenge lies in how to dissipate this heat effectively through heat sinks and coolants so that the thermal residual stresses and other thermal distortions in the component (final product), in the tool material and in the machine frame are kept at a low level [9, 10].

Several theoretical models [11-13] have been proposed from time to time, both in materials forming and in materials removal processes, that attempt to predict the phenomenological plasticity of materials a priori any laboratory experiment and/or mass scale industrial production. Unfortunately, as the strain rate in the material increases as a result of higher machine speeds - pushed by the demand for higher production rate - friction, wear and the rate of heat generation increase. One such example is the case of high energy rate fabrication (HERF) processes where the theoretical models do not quite fit into the real industrial panorama. Thus, the challenge of the academic research is to create more realistic models that can confidently predict the industrial situation without going through costly, laborious and awfully tedious laboratory experiments.

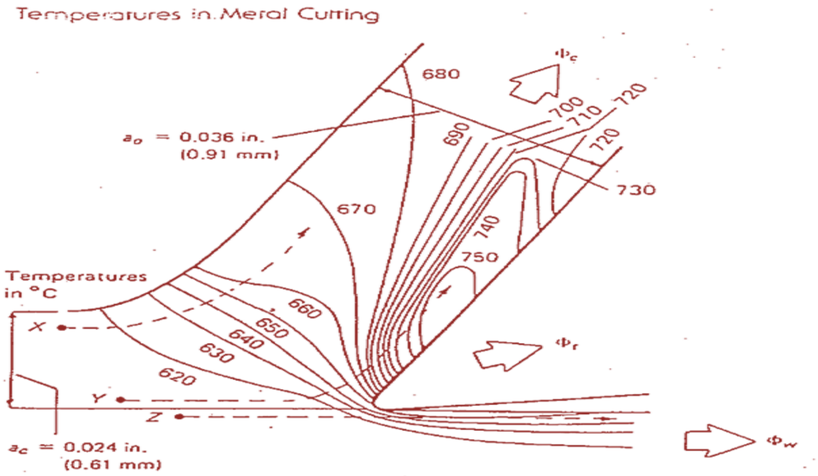

Figure1. Temperature distribution in the work-piece and chip in orthogonal cutting (obtained from an infrared photograph) for free-cutting mild steel where the cutting speed is 75ft/min (0.38 m/s), the width of the cut is 0.25in (6.35mm), the working normal rake is 30 Degrees, and the work-piece temperature is 611 C. (After Boothroyd [14])

2. Metal Cutting Processes:

While the work-piece material is passing through the primary deformation (shear) zone and the secondary deformation (friction) zone the resulting chip is considered as a moving heat source in a one dimensional heat transfer model [13]. According to this rather simplistic initial model the chip-tool interface temperature reaches its maximum at some distance up the cutting edge on the tool rake, and the chip leaves the interface at this maximum temperature. Critical laboratory experiments by Boothroyd [14] using a novel infrared photographic technique (Figure 1) show that the model agrees only qualitatively with the test results in orthogonal cutting of mild steel. He used a cutting speed of 0.38m/s (75ft/min), width of cut 6.35 mm (0.25 in) and a rake angle of 30 degrees. The maximum chip-tool interface temperature recorded was 750 C.

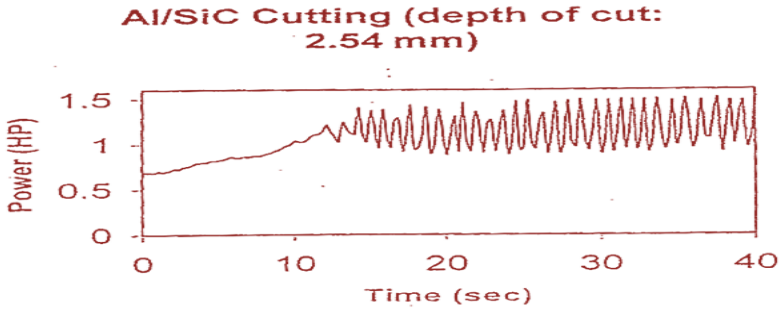

Figure 2. Cutting power versus time at constant depth of cut for Al/SiC specimen.

A more realistic two dimensional heat transfer model was proposed by Rapier [13] who assumed that the shear plane was a heat source of constant intensity and the thermal properties of the work-piece material were constant and independent of temperature. Because of the high speed of chip flow on the tool rake Weiner [13] assumed that the major heat transfer from the chip to the tool was by transportation, and hence the conduction part was neglected. This simplified the basic heat transfer equations of Rapier, and Weiner was able to solve them. Again, both Rapier and Weiner models overestimated the actual temperature rise in the friction zone as measured under the laboratory conditions by Boothroyd [14] and Nakayama [15]. The reason is that both the models assume the heat source as a 2-D plane while in reality it is a 3-D voluminous zone. Boothroyd [14] finally altered the previous models considerably, assuming that the frictional heat source was not just the chip-tool interface plane, but extended considerably into the chip itself. The analysis agrees with his experimental results on steel and brass work-pieces. Using acoustic emission technique while turning with diamond tools, Liu and Dornfeld [16] found new sources of rubbing and plowing energies in the tertiary zone on the tool flank where a rolling type forming rather than cutting takes place. This abnormal rubbing introduces more thermal energy in the tool flank, and if not properly dissipated this trapped energy creates additional thermal residual stresses in the final component. While end-milling Al/SiC composites with ceramics coated as well as HSS milling cutters, significant thermal distortion was evidenced by the non-uniformity of chip formation and chip flow, even at a relatively lower machine settings, such as cutting speed between 9 and 19 m/min, tool feed rate between 25 and 50 mm/min, and depth of cut between 0.3 and 2.6 mm [17].

During this experiment the total power consumption of the milling machine while cutting was traced against time, and its severe fluctuation was observed after only about ten seconds of cut (Figure 2).

It was postulated that the presence of 15 to 20 percent SiC in this aluminum based metal matrix composite (MMC) is the root cause for additional heat built up. Similar trends were observed while drilling and turning Al/SIC composites [18,19]. A brief review of the modeling of material removal with tools of well-defined geometry during conventional machining processes was given by Ehmann et al [20].

3. Grinding Processes:

Statistically random cutting tool geometry (Figure 3) as evidenced in grinding and polishing is often the prime source of high heat. In surface grinding [21-24] high negative rake angle on individual cutting grits, high normal force as compared to tangential (cutting) force at the wheel-work interface and pushing (compression) of the work material ahead of a grit rather than shearing (cutting) are the three major causes of high heat generated during the material removal process. Furthermore, like a milling cutter's tooth, each grit on the grinding wheel's active surface produces an impact load during each wheel rotation, and thus introduces more energy in the wheel-work interface, some of which manifests itself as heat. If the total heat coming from different sources is not dissipated by a proper combination of the three main aspects of a grinding fluid — its composition, concentration and way of application at the interface — thermal damages on the work-piece, on the wheel and on the grinding machine frame itself will invariably take place. Due to the statistical nature of this type of material removal processes as well as the involvement of so many hidden variables, mathematical modeling and numerical results do not tally with the real situation in grinding industries [25-28].

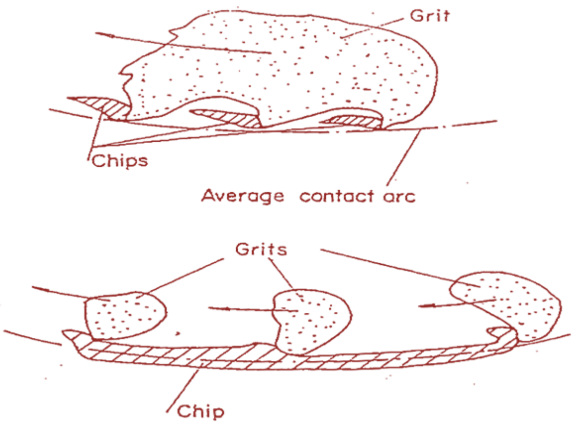

Figure 3: Alternative concepts in the chip formation mechanism with abrasive grits.

During the recent developments in creep-feed grinding (as compared to cross-feed grinding), where the grinding operation is completed in one pass with very low table feed rate and relatively very high wheel depth of cut, heat removal from the wheel-work interface is a major problem. How to avoid such thermal damages in grinding by efficiently controlling the grinding fluid flow at the wheel-work interface surface has been recently studied by many researchers [29-32]. Furthermore, development of new measurement sensors using modern electronics and electrical devices has helped studying and finding experimentally the ways of prevention against thermal and other damages in grinding [33-35]. Associated with heat transfer there is also mass and momentum transfer as each grit fractures out of the wheel periphery at a very high tangential speed, causing severe impact on the work-piece as well as on the grinding media, like the grinding fluid jet and the surrounding air. In other forms of abrasive machining processes, like abrasive water jet machining where the tiny abrasive particles of aluminum oxide, boron oxide or silicon carbide impinge on the work-piece surface with high impact velocity, mass and momentum transfer through transport phenomena interfere with heat transfer. This makes modeling problem of the real situation difficult to formulate precisely, and by far more complex to solve it. Notwithstanding these unavoidable difficulties in stating precisely the thermal boundary conditions, due to the statistical nature of grinding and other recently developed abrasive machining processes, attempts have been made to understand and deal with it in quasi-empirical fashion [36, 37].

During a test of flat surface grinding of mild steel and stainless steel work-pieces with cross-feed, coolant was not used in order to study the heat built up and the related thermal effect on the grinding forces. Figure 4 exhibits that as the idle time during the wheel over-run decreases, the horizontal component of the grinding force increases uncontrollably from pass to pass. Very similar trends were found for the vertical component. Thermal expansion causes the freshly ground surface to "bow out" like a bulge, introducing thereby more non-uniform grit depth of cut, more grit rubbing and hence more frictional heat. If this heat is not dissipated quickly enough by proper application of the grinding fluid as well as through the machine heat sinks, such as the machine table and the bed, grinding forces will keep rising causing more heat, more thermal expansion and rubbing and hence leading to more force increase, again like a vicious cycle, as seen in Figure 4. Due to the uncertainty of the system and for too many variables involved in the total process, mathematical modeling, simulation and prediction do not agree with the real experimental results, no matter in a laboratory set-up or in industry. The only way to cut this vicious thermo-mechanical cycle is an efficient grinding fluid; its composition, concentration and the way of application.

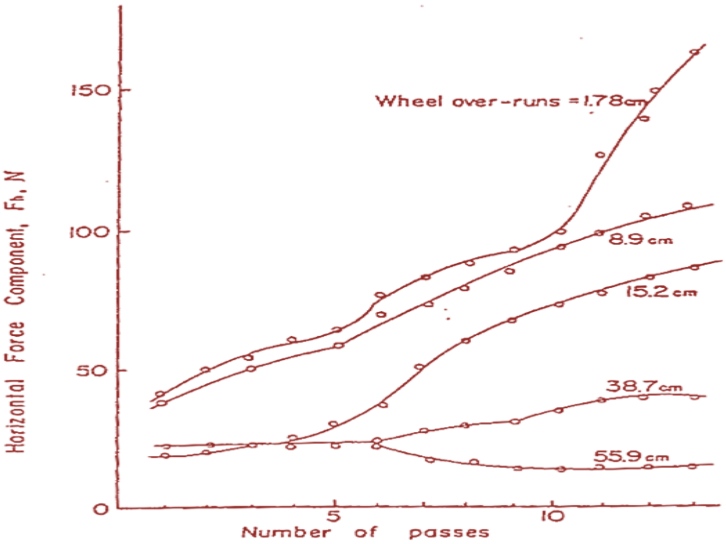

Figure 4. Force components versus number of passes for different wheels over-runs during dry grinding.

For both the cases of creep-feed grinding and cross-feed grinding thermal damages can be avoided by reducing the heat generation and increasing the heat removal activities. Using Cubic Boron Nitride (CBN) grits, instead of conventional Aluminum Oxide or Silicon Carbide ones, the wheel removes the heat faster from the wheel-work interface, simply because of higher thermal conductivity of CBN. Another way of faster heat dissipation is by using neat oil or water-based fluid under appropriate pressure such that the fluid enters in the grinding zone easily and leaves equally easily. In order to minimize the generation of heat the grinding wheel must be treated properly. For example, sharp wheel with soft grades should be employed and dressed frequently with coarse dressing rather than fine dressing techniques. Furthermore, optimum number of slots in the wheel, optimum wheel tangential (cutting) speed and optimum work speed do reduce heat generation and increase heat removal rates.

With the rapid advances in materials research as well as in monitoring and sensor systems, force control rather than feed control in grinding has become more convenient for bringing down heat during grinding. Thermal parameters are more directly and closely related to the actual force at the cutting zone than the grinding machine settings like wheel feed, table speed, etc. Super-abrasive grinding wheels, both single layer electroplated and deep layer bonded, have improved in structure for a better thermal function. Continuous monitoring and recording of wheel wear, grinding force and grinding temperature simultaneously are now possible by a DSP-based in-process telemetric data acquisition system as well as by Kalman filtering system. Artificial neuron network (ANN), including multivariable predictive neuronal control and fuzzy logic, has also been used in grinding plants.

4. Metal Forming Processes:

When material is not actually removed physically from the work-piece but reshaped by tensile, compressive, bending and torsion forces, the simplistic assumption that the total material volume remains invariant throughout plastic deformation works well for all practical, industrial processes of metal forming. The frictional forces at the die-work interacting surfaces, however, do not fall within similar simplistic assumptions like Coulomb friction, and hence the associated thermal phenomena arising from friction only remain to be solved as a complex issue. Besides friction, heat is also developed from other sources like redundant work done during plastic deformation (for example, internal friction at molecular level within the work-piece). Many authors suggest that almost all the energy consumed by the work-piece material during plastic (permanent) deformation is transformed into heat [38-40].

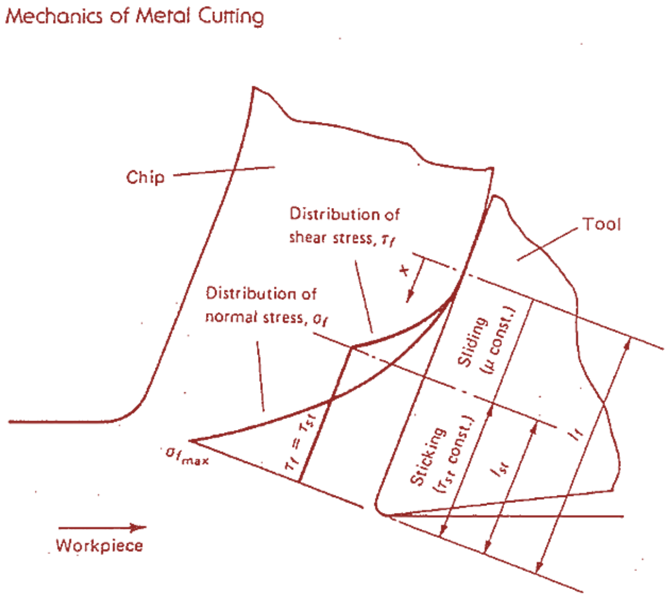

Figure 5: Model of chip-tool friction in the orthogonal cutting where $\sigma_{fmax} = maximum\ normal\ stress,\ \sigma_f = normal\ stress, \tau_f = shear\ stress,$ $\tau_\mu = shear\ strength\ of\ chip\ material\ in\ the\ sticking\ region,$ $l_f = chip - tool\ contact\ length$, and $l_{st=length\ of\ sticking\ contact\ region}$ (After Zorev.)

A mixture of sticking and sliding friction occurs at the die-work or tool-work interfaces during almost all materials forming processes. In rolling, the friction at and near about the entrance plane of the roll-billet or roll-ingot contact arc is basically that of slipping (sliding) in nature, and thus obeys the simplistic Coulomb's law that the frictional force is proportional to the normal force at the interface contact surfaces. As the billet enters more into the roll the transition from sliding to sticking friction starts to occur, and as the billet crosses the neutral plane the friction becomes mainly sticking and remains so till the billet leaves the exit plane [40-42]. Similar ideas were proposed for forging, arguing that the friction between the dies and the billet is of sliding in nature near the edge of their contact surfaces, and then slowly changes to its sticking nature as the geometry changes from the periphery towards the center of the billet [43-44]. Phenomenological observations suggest that in all the above mentioned processes, both in forming and machining, there is no specific boundary or line of demarcation but a zone of transition from sliding to sticking friction. Zorev [45] quite successfully created a model for this type of slide-stick transition for machining, as sketched in Figure 5, which was later applied by many researchers [46-48]. Many others [49-51] proposed similar models for forging, coining, upsetting and other forming processes where friction is associated with compressive bulk deformation.

Heat generation models in metal forming are abundant in literature, but only a few obey experimental results and industrial practice. As mentioned earlier, one part of the heat generated in the manufacturing processes is due to friction and the other part is from bulk deformation. Plastic deformation of the work-piece occurs not only within the bulk material but also at its surfaces in contact with the dies during forging , or with the rolls during rolling. Such superficial plastic deformation takes place mainly at the tip of an asperity in a typical peak-to-valley type work-piece surface configuration. In a recent study Chang et al [52] applied a frictional-heating model and an asperity deformation heating model in calculating temperature distribution during rolling. Their theoretical calculations were supported by experiments. The results show that the heat from asperity deformation largely dominates the frictional heat, but their ratio is sensitive to surface finish, surface hardness and slide-to-roll ratio.

Unlike rolling, forging is usually associated with an impact load, and in hot forging the average billet temperature at the time of impact is well above its re-crystallization temperature. The impact strain-rate is also significantly higher than that in rolling, and its interaction with elevated temperature makes theoretical modeling cumbersome and difficult. Most of the useful studies are, therefore, based on actual measurement of temperature in laboratory or in an industrial set-up [53-55].

In some of these papers numerical calculations based on some quasi-empirical/ semi-theoretical models are shown in order to justify the experimental results [56-58]. Finite element, finite difference and finite volume analyses have been applied to forging, upsetting, coining and other examples of axial compression with impact load. Such modeling and simulation must represent close proximity to a real industrial situation. Keeping this in mind 2-D and 3-D computer simulations of hot forging of parts like a connecting rod, were conducted. Using a software package called DEFORM-3D, modeling and simulation were performed on two forging stages, like mold and finish, that included the intervening heat transfer analysis as the work-piece was transferred between the two stages and rested within the dies.

5. High Energy Rate Fabrication (HERF) Processes:

The necessity and the demand for high industrial productivity lead to the invention of many novel manufacturing processes that increased the production rate without sacrificing the product quality. Some such processes are electromagnetic forming, explosive forming, impact extrusion, high speed forging, high speed machining, creep-feed grinding, abrasive water-jet machining, etc. Due to high machine speed, for example, some of these processes impose high strain rate on the work-piece. The elevated speed also dissipates high kinetic energy into the work-piece material. Part of this energy manifests itself in the form of heat, and hence increases the temperature of the work-piece, the tools, the dies and the machine frame. Besides, the high speed often introduces high localized straining and local heating within the bulk material of the work-piece, as evidenced by the adiabatic shear bands in it. Very sharp strain and temperature gradients within the bulk material, due to their non-uniform and localized concentration, often cause the material to fail prematurely, long before the onset of plastic instability in a normal forming process [59-61].

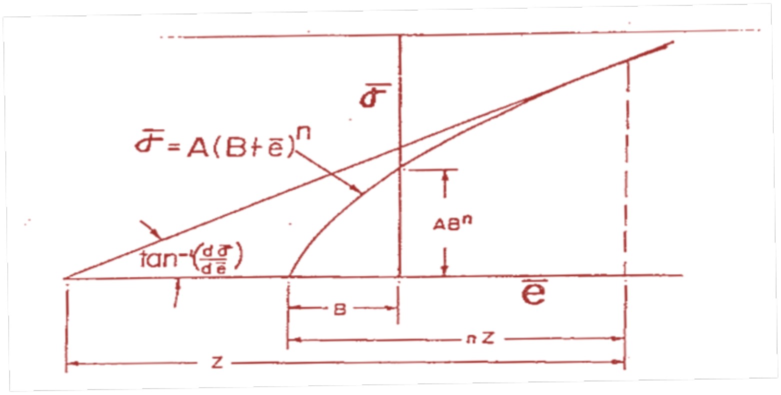

Figure 6. Critical Sub-tangent to Swift's Empirical Curve

Depending on the work-piece material properties, strain hardening and thermal softening can occur simultaneously in HERF processes, and there is a break-even point regarding the effects of these two mutually opposing phenomena on the strength of the final product. This can be detected from the true stress-strain curve of the work-piece material leading to the resulting product. The length of the critical sub-tangent (Z) to this curve (Figure 6) at the onset of a normal plastic instability (wrinkling type) is unity in case of a standard tensile test specimen.

In comparison, if a thin-walled cylinder is expanded or squeezed radially (Figure 7) with an electromagnetic force by passing a high current through a coil for a very short duration, in the order of milliseconds, the value of this sub-tangent is 2/3 (= 0.666).

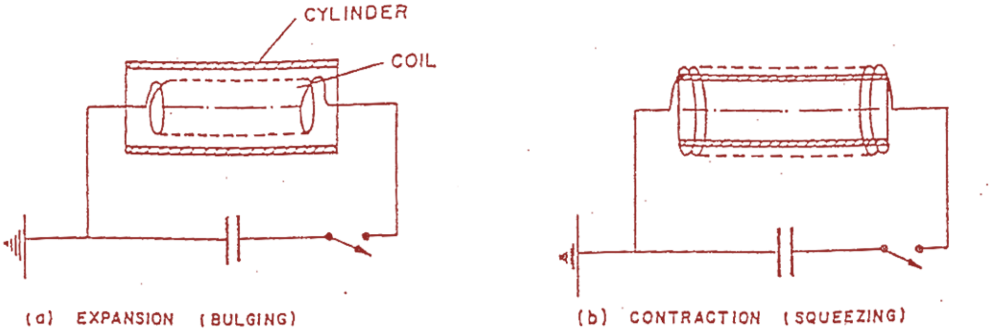

Figure 7. Schematic Diagram of Electromagnetic Bulge Forming.

This means that due to the high speed arising from the electromagnetic force the material will become unstable at a true strain which is one third (0.333) less than that in case of uniaxial tension of a solid bar of the same material [62]. Combining the thermal effect with high strain rate, however, the situation becomes more complex. Thermal residual stresses are introduced in the work-piece material as a result of high kinetic energy dissipation in it. Theoretically, the length of the critical sub-tangent (Z) no longer remains a simple number as before but a function of the cylinder geometry (wall thickness, length/diameter ratio) and the thermal properties of the work-piece material. Further study on electromagnetic forming of an aluminum sheet metal suggests a temperature rise of 200 C when the sheet is impinged on an external die at a speed of 900 m/s, and up to 783 C at a speed of 2000 m/s [63].

Although in some cases of electromagnetic forming, such as the free radial expansion of a thin cylinder, when there is no physical contact between the work-piece and the die, heat is generated from the elevated electric current only due to the Joule effect as well as from very short time of the process cycle, in the order of milliseconds, for the plastic (permanent) deformation of the cylinder wall to occur. More experimental as well as theoretical studies are currently conducted in Boeing Laboratories and other places [64, 65] in order to find the thermal and the mechanical effects arising from high inertia forces associated with the HERF processes.

Like high speed forging where momentum is transferred from the ram to the billet, in electromagnetic forming also the momentum is transferred, but in the reverse order, from the work-piece to the external die or the internal mandrel on which the material is slammed. The current trend from the standpoint of the work-piece material properties is to study the effect of the electromagnetic field accompanied with the dynamic load. Theoretical studies include developing equations between the electromagnetic field intensity and the electric current density in the material undergoing thermoplastic deformation under high strain rate. Parallel experimental studies with tubular specimens over a range of length, diameter and wall thickness, using steel, brass, copper and aluminum alloys show that the onset of plastic instability (limiting deformation) depends on a number of electromagnetic, mechanical and thermal factors, such as discharge power and frequency, wall thickness as well as thermal and mechanical properties of the work-piece material. For example, the frequency of magnetic discharge-induced successive pulses affects the intensity of plastic deformation as measured by the total true strain. Formability is improved by high strain rate in aluminum alloys, and thus promotes its application in automotive and aerospace industries, like shearing, shaping and joining of Al-Mg alloy tubes by electromagnetic forming. It was also found that increasing the electromagnetic field strength improves the work-piece material's microstructure by refining the grains for the same formability, as given by the total true strain before the onset of plastic instability. This is very attractive to all metalworking industries [64-68].

6. Closing Remarks:

In this brief review of thermal considerations in manufacturing processes - both material removal and material forming - theoretical as well as experimental studies are analyzed in the light of thermal and mechanical effects on the work-piece material properties. Plastic deformation-induced heating as well as heat arising from tool-work friction need to be removed appropriately from the interface surfaces and sub-surfaces in order to reduce thermal residual stresses in the component (final product), minimize tool and die wear, and also eliminate thermal distortion of the machine tools structure. During material removal processes like machining and grinding a great portion of the total heat developed is transferred through mass transportation of the chips, burrs and grits, apart from conduction.

While machining with single and multi-point tools with well defined cutting geometry, computer simulation studies tend to agree to some extent qualitatively with the laboratory experiments for geometrically well-defined cutting tools. But the "statistical cutters" like the grits of a grinding wheel are too unpredictable in their cutting geometry (such as, grit size and shape, rake angle on a grit, grit-chip contact geometry, etc.) to construct a theoretically deterministic thermo-mechanical model for any useful computer simulation. The same is true for polishing, sand blasting and abrasive water-jet machining.

During materials forming with steady load, like rolling, drawing, hydrostatic extrusion and bulge forming, there is no mass transfer or transportation; heat is propagated by conventional means. When the load is dynamic, however, such as in impact extrusion, high-speed forging, etc., the momentum is transferred from the ram to the work-piece, and additional thermal effects due to high impact have to be considered. A considerable amount of the kinetic energy is converted to heat, and the flash temperature is high in these processes. Often this temperature is localized and concentrated in a small zone and the thermal gradient is steep enough to cause thermal residual stress and localized strain as evidenced by the formation of adiabatic shear bands within the bulk of the material. This is especially true in high energy rate fabrication (HERF) processes like electromagnetic, electro-hydraulic and explosive forming processes where the speed of impact is very high. Even without any physical contact between the tool or die and the work-piece in electromagnetic processes, for example, temperature rises only from the Joule effect of high intensity electric current dissipation. The work-piece material undergoes strain hardening from high impact and thermal softening from temperature rise. A balance between these two mutually opposing behaviors of the work-piece material affects the properties of the final product.

In sum, during the macro-manufacturing processes, both conventional and unconventional, a significant amount of heat is lost through the tools and dies, the chips, burrs and grits as well as through the machine tools structure, for instance, lead screw, spindle, tool post, carriage, frames, tables and columns. Heat is transferred by conduction and transportation. Besides, there is mass transfer between the raw material and the final product during chip formation in material removal processes, and during shape change in material forming processes. Furthermore, there is momentum transfer associated with high impact, dissipation of high kinetic energy and the inertia forces during the high energy rate fabrication (HERF) processes, such as, explosive forming, electromagnetic forming, etc., both in the production of components and their assembly. Due to the complexity of too many variables involved during these processes, as mentioned here, academic studies — analytical and computational — need to be verified and validated by experimental results, both in laboratory environment as well as in life size prototype tests, in order to facilitate further industrial research.

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