Manufacturing Engineering: New Challenges from an Energy and Environmental Perspective

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Abstract. As the dominant paradigm for improving general living standards since the first industrial revolution, "economic development (ED)" is now regarded as unsustainable. The singular objective of ED, with an associated limited number of macro-economic indicators, has resulted in the depletion of natural resources of materials and energy, the destruction of natural ecosystems, pollution, and CO_2 emissions that have been related to climate change and global warming. The alternative paradigm, referred to as "sustainable development (SD)", demands a global approach and both "top-down" and "bottom-up" actions. The SD paradigm will be enabled by the paradigm "competitive sustainable manufacturing (CSM)" which requires new business models that deliver a product-service, provide a return to the business and are carbon-neutral and environmentally benign.

The role of the Manufacturing Engineer will change under the CSM paradigm, and this is being informed by research in networks such as CIRP, the International Academy for Production Engineering. Manufacturing Engineers are uniquely positioned to contribute to the realisation of the new paradigms given their responsibilities for "new product introduction" and "supply chain" processes. As such they will apply new "key performance indicators" such as the "embodied energy" in the product-service over multiple life cycles. By "following the energy" in the product life cycle(s) and, as discussed here, the manufacturing processes, some fundamental questions are posed. It is noted however that "total life cycle embodied energy" must be considered since functional specifications determined by the manufacturing process (dimensional tolerances, levels of surface finish and integrity) may affect embodied energy in other life cycle phases.

Introduction

As the dominant paradigm for improving general living standards since the first industrial revolution, "economic development (ED)" is now regarded as unsustainable. The singular objective of ED, with an associated limited number of macro-economic indicators, has resulted in the depletion of natural resources of materials and energy, the destruction of natural ecosystems, pollution, and CO_2 emissions that have been related to climate change and global warming. The "economic development (ED)" paradigm has been enabled by advances in science and technology, manifested as "Kondratieev cycles", and has delivered "on average" higher standards of living through innovation, new products and services and an increase in the aggregate levels and efficiencies of natural resource transformation. One indicator of the effectiveness of this paradigm is the rate of population growth with the current population of about seven billion set to increase to nine billion by 2040.

However, the implementation of the paradigm, based on a limited number of macro-economic indicators and class or nation-centred competitive development, has resulted in dysfunctional impacts on society and on the global environment. One of the global societal effects is the skewed distribution of resource consumption where 80% of the resources of the planet are currently consumed by 20% of the population [3]. In [2,4], other societal dysfunctions associated with the singular paradigm were indicated including; exclusion of individual and groups, loss of community, disconnect from the natural environment, uneven distribution of wealth and, more recently, the widening knowledge gap due to different levels of access to education.

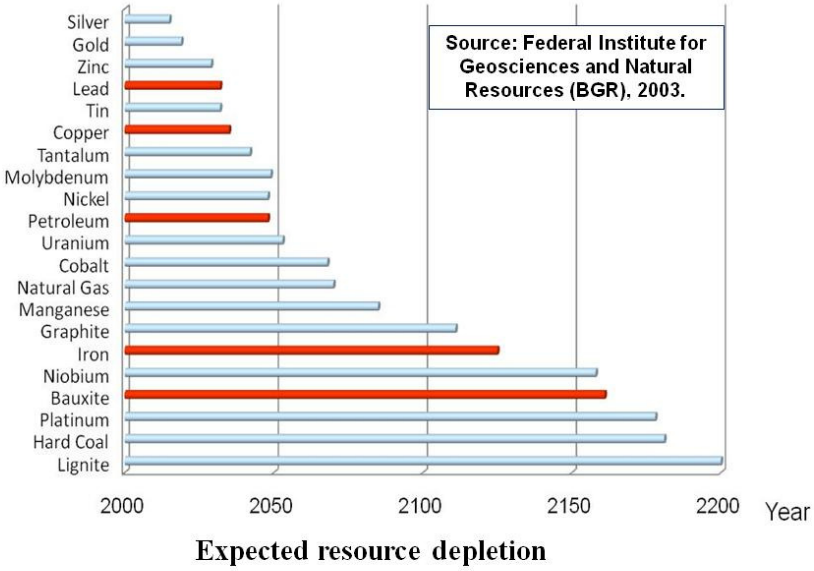


Fig. 1: Forecast depletion of mineral resources

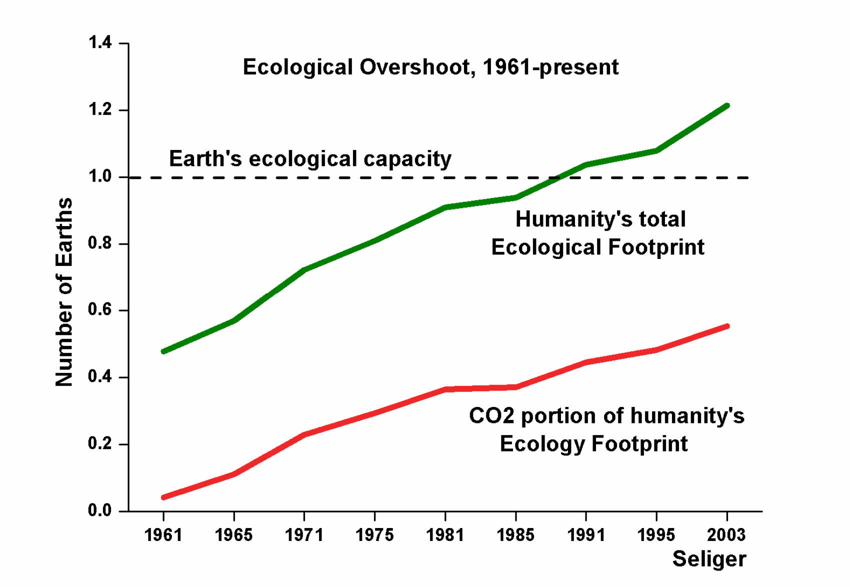


Fig. 2: Ecological footprint and capacity [2]

Of equal concern is the scale and imminence of threats to the sustainability of the ED model and, more importantly, the sustainability of life on the planet. Fig. 1 shows when mineral resources will be depleted on the basis of current levels of consumption; noting in particular the depletion of oil stocks by 2050 with prices expected to rise significantly before then. Fig. 2, from

Seliger [3], is based on a model that indicates the ecological footprint of humanity in relation to the constant capacity of the planet; it shows that the capacity of the planet was exceeded by 20% in 2003. Other than carbon dioxide emissions and the effect on climate change discussed later, the ED paradigm has also resulted in losses in both area and type of ecosystem, accumulating levels of waste, loss of bio-diversity, air and water-borne pollutants.

In the context of the threats as delineated, it is evident that a singular ED paradigm based on limited macro-economic indicators, cannot be sustained. This was recognised in the 1960's by the "Club of Rome" who reported on "the limit to growth" [5] and advocated the need for a sustainable model of development. The advent of "green" politics and political parties, especially in Europe, has ensured that economic and environmental sustainability is assimilated in policy at national and international levels. In that regard, some proponents of green politics have contributed publications of merit that advocate a more fundamental reappraisal of the ED paradigm [4].

The CO_2 challenge

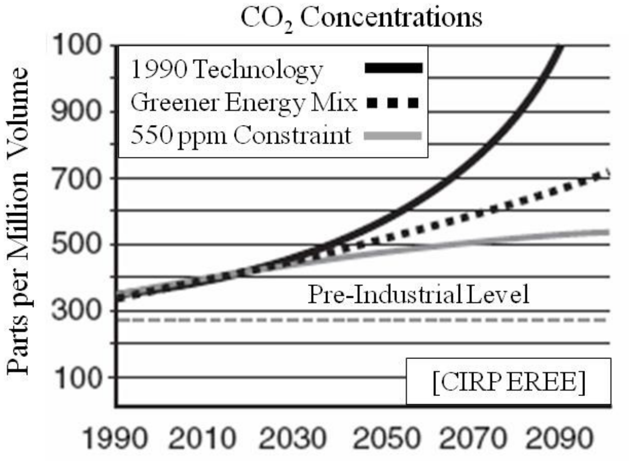


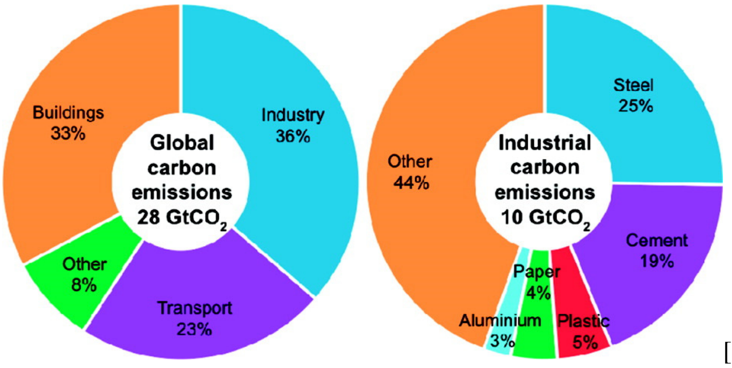
Fig. 3: CO_2 concentrations from 1990 to 2090

Fig. 3 shows that concentrations of carbon dioxide significantly exceed pre-industrial levels and are set to increase exponentially in the absence of effective countermeasures. The causal relationship between levels of carbon dioxide, global warming and adverse climate change has near-consensus in published scientific research. This has produced political consensus that a radical response is required and, implicitly, the need for a new paradigm as advocated by colleagues in CIRP [1,2]. The new paradigm is referred to as "Sustainable Development (SD)" and is to be enabled by the supporting paradigm; "Competitive Sustainable Manufacturing (CSM)" [1]. Clearly, the emphasis here is on "sustainability" defined by Seliger [3] as follows:

> *"Sustainability is directed at enhancing human living standards while improving the availability of natural resources and ecosystems for future generations"*

The proponents of CSM advocate that the paradigm must comply with the needs of nation states at varying levels of development and with different "ESET (economy, society, environment and technology)" contexts. Of course, global cooperation is a prerequisite for the sustainability of this shared planet.

While the scientific community confirmed the relationship between CO_2 emissions, climate change and global warming, the engineering community, who have a major role in developing solutions, require more "information for action". Thus fig. 4 is of initial interest as it presents an analysis of industrial sources of CO_2 which account for 36% of total global emissions. It can be seen that 56% of industrial emissions are due to just five materials - steel, concrete, plastic paper and aluminium. A key objective in this tops-down analysis is an identification of measures to meet multiple criteria (feasibility, investment cost, risk etc) including a maximum return in terms of CO_2 emissions reduction. This work by Allwood *et al* [6] is illustrative of a top-level analysis of global CO_2 emissions leading to more systemic type proposals.



[Allwood]

Fig. 4: Breakdown of global carbon emissions and emissions from industry [6]

On a meso scale, there are initiatives supported by public and private funding. In particular, there is a significant level of private interest in potential business opportunities in energy and the environment. Siemens commissioned a study by Byrne, Finn *et al*. [7] in University College Dublin based on the premise that 80% of CO_2 emissions and 75% of global energy consumption arises in urban areas. It was shown, as in fig. 5, that levels of CO_2 emissions per capita in Dublin were higher than other European cities surveyed and a near order of magnitude greater than the global target of 2 tonnes per capita for 2050. The objective of the study was to determine how technology can improve environmental sustainability in the Dublin area.

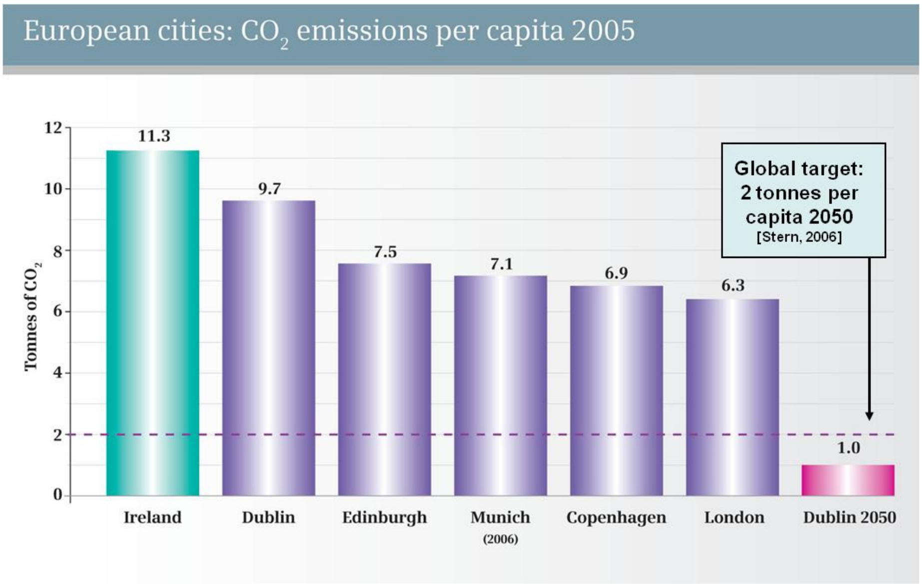


Fig. 5: Emissions per capita in European cities [7]

A global challenge requiring global solutions

It is evident that a reduction in CO_2 levels to meet the Kyoto targets is a global challenge requiring organisation on a global scale and based on a shared vision of a sustainable future. There is a basis for such global cooperation given the commitments to sustainable development indicated by the following international organisations and nation states realised through the dedicated divisions or instruments shown:

- The United Nations; Division for Sustainability Development (DSD)
- The Organisation for Economic Co-operation and Development
- The European Union: European Sustainable Development Strategy
- Japan; Japan Council for Sustainable Development
- USA: The Presidents Council for Sustainable Development
- China: "White Paper on China's Population, Environment and Development in the 21st Century"

The policy approaches will vary but "top-down" actions will be defined to realise goals of sustainable development. However, it is generally deemed that the Kyoto targets for CO_2 levels are unlikely to be met; not only in view of the outcome of the recent Copenhagen summit but also in view of feasibility studies, as above, which indicate that technology is currently not available to immediately realise the required levels of reductions.

There is also a need for organisation at the meso and micro (field) levels and the International Academy for Production Engineering (CIRP) has taken a leading role in that regard. Our main interest as researchers will be in advancing the enabling paradigm CSM. CSM is the broad domain of research for colleagues in CIRP and collaborative working groups (CWGs) have been established to enable networking on critical themes to the CSM paradigm. These include:

- Energy and Resource Efficiency and Effectiveness (EREE)
- Industrial Product-Service-Systems (IPS^2)
- "SPECIES" Production System Evolution

The collaborative working groups are linked to other international networks (for example, EREE is linked to CO2PE and IMS) while colleagues are involved in international initiatives such as "Manufuture" [2] in the European Union as well as large funded research projects.

Contributions are codified in CIRP publications; both specific research projects (volume 1 of the Annals) and comprehensive reports on the "state-of-the-art" (volume 2 of the Annals). For example, a keynote paper published in 2007 in the CIRP Annals by Jovane *et al* [1] provides a high level overview of the context for the SD paradigm and introduces "high added value" "knowledge-based" CSM as its main enabler. It further describes a "reference model for proactive action" by players in public administration, financial institutions, research, education and industry.

The colleagues in CIRP are thus contributing to the evolution of the CSM paradigm by involvement in both "top-down" and "bottom-up" initiatives. In the context of a new paradigm, there has been a fundamental reappraisal of the domain of manufacturing engineering and the role of the manufacturing engineer. This is still evolving but the next section will delineate some basic concepts from a "bottom-up" view.

The role of manufacturing engineering in competitive sustainable manufacturing

In order to discuss the impact of the CSM paradigm on manufacturing engineering, it is interesting first to review the definition of manufacturing engineering from the CIRP dictionary [8] as follows:

"Manufacturing engineering is an engineering activity / science which is concerned with all relevant functions within a manufacturing system. It involves:

- *design for production (or manufacturing; DFM)*
- *the design, operation and control of production processes and production methods*
- *the planning scheduling and control of production (stock control)*
- *quality assurance*

Further, it links with and uses such disciplines as mechanical, electrical, chemical, materials and systems engineering as well as management. Manufacturing engineering embraces all the technical aspects of management, i.e. the operation and control of production. It also involves human, legal and social aspects of work and working in manufacturing industry"

This definition indicates the broad scope of the discipline and, depending on the manufacturing industry (nature and scale), the roles of the Manufacturing Engineer may be differentiated further. There are two differentiated roles that comply with a "process type" organisation structure; one in a "New Product Introduction (NPI)" process and the other in the "Supply Chain" process, including manufacturing. The measures of performance, or key performance indicators (KPI`s), in these roles conform with the process KPI`s. The new paradigm will both impose non-traditional KPI`s related to environmental, economical and social dimensions [3] on these value-creation processes and demand consistency of traditional ones. This will represent a "paradigm shift" for the roles of the engineer at the micro or field level as described.

This paradigm shift will be imposed by the change in the business model required to implement CSM. This will be most evident in the NPI process where both Design and Manufacturing Engineers will have particular responsibility for ensuring that the product to be designed not only provides the required functionality and enhances the service to be delivered, but is also consistent with the principles of "Design for the Environment (DFE)". This implies consideration of, not only the total life cycle phases of the product, but also reuse or remanufacture in multiple "life cycles" and analysis accordingly of all environmental impacts through estimation of related sustainability KPI`s such as: embodied energy / CO_2 emissions (including energy in use), materials depletion, toxic wastes etc. [9]. This clearly changes significantly the nature and scope of the design process and requires a fundamental reappraisal of principles and methodologies. It also has implications for the role of the manufacturing engineer in the supply-chain process where control and optimisation of process parameters (within design tolerances or uncertainty) will require reference to the effects on the total lifecycle.

Embodied energy in the product-service life cycle

The critical CSM key performance indicator (KPI), "embodied energy", will be considered as a basis for understanding the implication of the paradigm for manufacturing engineering. This is currently of particular interest to colleagues in the CIRP collaborative working group "Energy and Resource Efficiency and Effectiveness (EREE). The following definition of embodied energy (or "emergy") is an abbreviation of a definition taken from the "Embodied Energy and Embodied Carbon" database of the "Sustainable Energy Research Team" at the University of Bath [10]:

"The embodied energy of a (building) material can be taken as the total primary energy consumed (carbon released) over its life cycle. This would normally include (at least) extraction, manufacturing and transportation. Ideally the boundary would be set from the extraction of raw materials (including fuels) until the end of the product lifetime known as "cradle to grave". It has become practice to specify the energy from "cradle to gate", which includes all energy in primary form until the product leaves the factory gate.......etc"

Table 1: Estimated values for embodied energy of some common materials [10].

Material	Energy Cost (MJ/kg)	Production Process
Aluminium	227-342	metal from Bauxite ore
Cement	5-9	from the raw materials
Copper	60-125	metal from copper ore
Plastics	60-120	from petroleum products
Glass	18-35	from sand and other meterials
Iron	20-25	from iron ore
Bricks	2-5	baked from clay
Paper	20-25	from timber

Table 1 shows estimated values from the same source for the embodied energy of some common materials. The definition and values provided by the University of Bath are for common materials based on the “cradle to gate” boundary; noting that an evaluation of embodied energy based on the “total life cycle” is very product (life cycle) specific. There are clearly significant challenges to the development of an holistic (life cycle) model of embodied energy for a product-service as a function of parameters in the life cycle phases (design, manufacture, use, recycling or remanufacturing). However, a validated model is critical for decision making relating to strategies or measures to improve functional performance or further reduce life cycle embodied energy. For example, the model would indicate possible inverse correlations between reduced embodied energy in manufacturing and increases in energy consumption in use (and therefore a possible increase in overall life cycle embodied energy). Sutherland *et al* [11] present a model and analysis of “energy per unit” for initial manufacturing and multiple remanufacturing cycles of a diesel engine; considering the sensitivity to parameter changes including a material change from cast iron to aluminium. He indicates that the remanufacturing efficiency can significantly affect the “energy per unit” and this could determine the material selection decision.

This demonstrates the need for methodologies to expedite model development and this will be enabled by the application of advanced statistical analysis methods to multiple data-sets collated and correlated over more extended phases of the product life cycle (“data mining” approaches). The potential of this approach is enabled by integrated data management systems and developments in sensor technologies and monitoring systems applied to both processes and products.

The life cycle embodied energy will be significantly determined during the design process by application of methodologies such DFE as described in [9]. The design of the product, the manufacturing processes and the production system requires a significant input from manufacturing engineers including now specialist knowledge and expertise in environmentally friendly materials, manufacturing processes, remanufacturing, reuse or recycling and ultimately green disposal. DFE generally complements modern design methodologies [12] in particular other “Design for” methodologies based on the objective of reducing resources in design and subsequent service provision; the outcome is generally a reduction in embodied energy but this needs to be refined by DFE and the context of reuse and remanufacturing.

Process and production system selection is determined as part of the NPI process. However, depending on the business model, and in particular the product volume-variety mix, the production system type will normally vary over a range from “continuous to project”. The paradigm of lean manufacturing is generally most consistent with the CSM paradigm in view of the basic principle of the elimination of all non-value activities in the supply chain (including the manufacturing process chain) and the inclusion of the concept of “just-in-time” for delivery of the product-service to the customer. Many of the colleagues in CIRP have been developing production system concepts "beyond lean" including: mass customisation [13], production in networks [14], reconfigurable manufacturing systems [15] and reconfigurable machine tools [16].

Embodied energy in manufacturing processes

Total life cycle models require basic information on the levels of embodied energy in core manufacturing processes. This is being addressed holistically by colleagues in CIRP in the CWG EREE but there is also an interest by the CIRP technical groups in embodied energy and the environmental impact of core manufacturing processes [17]. It should be noted here, as a "bottom-up" view, that embodied energy in these processes is a recent interest driven by the "top-down" CSM agenda and now, increasingly, by our industrial partners. A goal of this research may be regarded as the provision of comprehensive guidelines, models or tables of specific values for embodied energy arising in a process as a function of material, stock, form-finish specifications, process types and process parameters. Notwithstanding the specific nature of these requirements, the general goal of reduction in embodied energy elicits some fundamental questions about the nature our manufacturing processes.

In particular, it is interesting to consider the energy efficiency of manufacturing processes and to describe the energy flows in terms of productive and non-productive transformations of the input energy. Processes involving mechanical removal of material (by defined and undefined edge tools) are indicative. However, before considering transformation of the energy in "work done" by the tool on the material, it is noted that there are other sources of energy loss in the machine tool and ancillaries and these can be relatively significant. In general, these sources include; work done in accelerating masses, overcoming friction in driving masses, electrical resistance losses and energy consumed by ancillary equipment (tool changer, coolant pumps etc).

In terms of embodied energy for a specific fixed machining operation (for example, turning), and omitting for now any reference to micromachining, the embodied energy (E_m) is given by:

$$E_m = e_c * V_w \qquad (1)$$

where e_c is the specific cutting energy for the material (in JM^{-3}) and V_w is the volume of material to be removed for the particular component. The transformation of energy is from "work done by the tool" to plastic deformation in the shear zones (1-5) and friction at the tool-work interfaces (2-4) as indicated in the simplified orthogonal model of cutting shown in fig. 6. The friction energy can be reduced by the use of cutting fluids but most of the energy is used in deforming the material to be removed. This may be regarded as the "productive" consumption of energy in terms of the input energy to the machine tool as it is the energy that finally removes material. However, a more fundamental question may be posed here as to a definition of the ideal minimum energy in cutting and why it is necessary to deform <u>all</u> the material to be removed when the objective is to remove a layer of material which could (theoretically) be realised by separation of bonds at an interface (at depth h) in a controlled "cleavage" type mechanism?

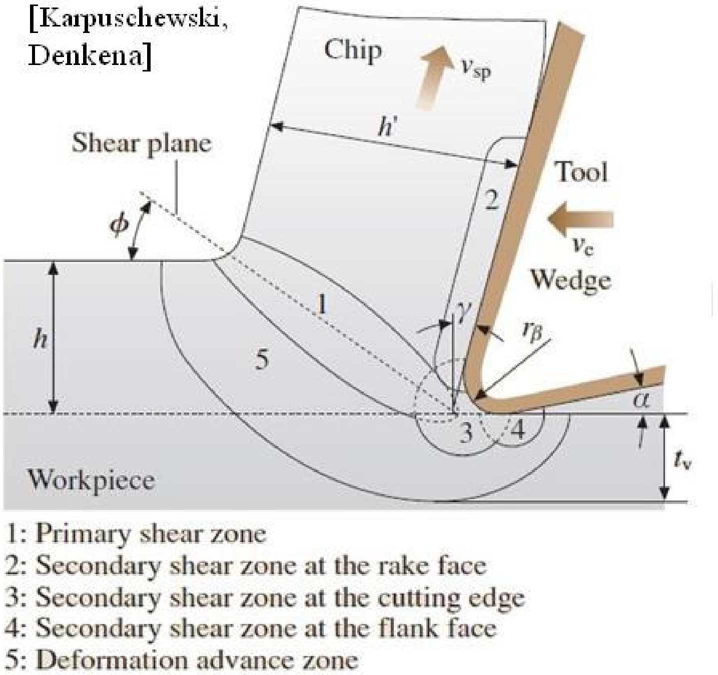


Fig. 6: Orthogonal cutting of ductile materials showing shear zones

The energy efficiency of micro and ultra-precision machining procesess, motivated by demands for higher levels of precision, is also a possible theme for future research. Improvements in general levels of precision due to developments in process technologies were codified by Taniguichi *et al* [18] in the diagram of his namesake shown fig. 7. In the context of embodied energy, it has been established that levels of “specific energy” in mechanical micro-cutting generally increase with reductions in the unit removal; a phenomenon referred to as the “size effect” [19]. According to one hypothesis, the specific energy increases as the undeformed chip (*h*) thickness reduces below the finite tool edge (best-fit) radius dimension. This leads to a significant increase in the size of the primary shear zone and the energy involved in plastic or irreversible deformation. A second hypothesis advocates that the density of defects (dislocations in particular) reduces with scale so that the yield strength of the material effectively increases. The outcome is a more energy inefficient process at the tool-work interface exacerbated also by relatively higher rates of tool wear. Of course, it should also to be noted that micromachining, and high precision processes in general, require temperature controlled environments thus adding to process embodied energy.

The levels of process efficiency in microcutting are nonetheless expected to exceed the levels in form and finish grinding where similar mechanisms apply. In fact, the term “size effect” originally referred to grinding to describe the increase in specific energy with reduced undeformed chip thickness. Additionally, in grinding, many particles do not remove material but only generate friction by elastic contact or elastic-plastic deformation without material removal. In a particular grinding operation, Komanduri *et al* [20] further indicated that only 0.15 % of particles actually remove material with 3-4 % making contact and generating friction and the remainder not engaging at all (static particles). The grinding process is also beset, in most applications, by the effects of abrasive particle (flank) wear leading to progressively increasing levels of specific grinding energy.

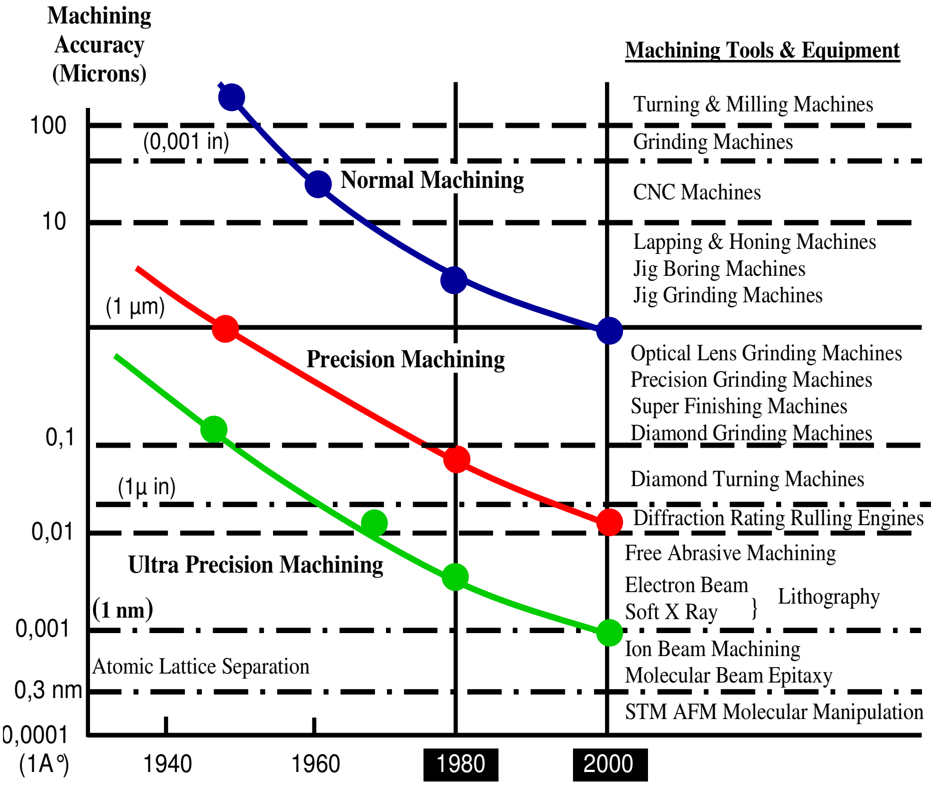


Fig. 7: Taniguchi diagram after McKeown [18]

It is thus evident that these basic production processes are inherently energy inefficient and the level of inefficiency seems to increase with a reduction in scale of the “unit removal” as generally required for higher levels of precision. It is proposed that there is significant scope for improved process understanding and improvement, including a reduction in embodied energy, by more fundamental studies based on the energy transformations at the tool-work interface. In that regard, the transformation of work-done into thermal energy was not discussed above. Some recent studies have shown that favourable thermo-mechanical coupling at very high speeds can reduce the specific energy in cutting even under dry (environmentally friendly) conditions. Furthermore, in grinding of brittle materials it is well known that “brittle machining” is much more energy efficient (lower specific grinding energy) than ductile-mode machining which applies when the undeformed chip thickness reduces below the critical “brittle-ductile transition” value. Again, it proposed that there is significant scope for optimisation from an “embodied energy” perspective.

Finally, it should be noted again that reductions in embodied energy in the manufacturing processes must be in the context of the “total life cycle” model for the product-service. Thus, in the context of the observations on micro-machining, the drive for miniaturisation of components would probably be a superior consideration for realising reductions in embodied energy. It is also possible to generalise in relation to the importance of the surface as a critical functional feature in engineering components with increasing importance for high precision and micro components, where the structural integrity increasingly depends on the surface integrity. Similarly, the production of tribological surfaces will require levels of surface form, finish and integrity to ensure part longevity and reduced friction energy in use. Thus, the challenge in relation to embodied energy in the manufacturing process will be to reduce energy while maintaining or improving surface finish and integrity.

Summary and Conclusions

The “sustainable development (SD)” paradigm requires a global approach and both “top-down” and “bottom-up” actions. The SD paradigm will be enabled by the paradigm of “competitive sustainable manufacturing (CSM)” which requires new business models and conforming processes. The role of the Manufacturing Engineer (ME) will change under the CSM paradigm with responsibility for new “key performance indicators” including the “embodied energy” in the product-service over multiple life cycles. In product and production system design (in the NPI business process), design methodologies and databases will be developed to ensure “design for the environment” as well as enhancing the product-service to ensure competitive advantage. The Manufacturing Engineer should also take responsibility for development of predictive models relating all KPI’s to key product and process parameters over all life cycle phases. This will be facilitated by the use of integrated data management systems, embedded product and process sensors and techniques such as “data mining”. ME’s should also be continuously informed about research through networks such as CIRP, the International Academy for Production Engineering.

The new paradigm will also require a reappraisal of current manufacturing processes and related technology roadmaps. It is shown here that even a cursory analysis of the “embodied energy” or “energy efficiency” of a core manufacturing process, leads to some fundamental questions and potential new areas for research, development and innovation. However, it also shows that the “embodied energy” in a single process must be considered in the context of the total life cycle embodied energy model.

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