# Model Development and Sustainability Assessment of Minimum Quantity Lubrication Technique in Turning of 700/3 Austempered Ductile Iron

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***Abstract* – In manufacturing sectors, the effect of cutting fluid assign importance in human health hazard, disposal waste and environmental pollution in machining. This paper presents model the development for sustainability assessment of Minimum Quantity Lubrication (MQL) using environmental and energy rating. Machining of Austempered Ductile Iron using MQL technology seems to be a novel eco-friendly technique and hence a better manufacturing technology. It was observed that surface damage and tool wear was less in case of MQL than that of dry, and flood cooling environments. Thus proper lubrication and cooling effect of aerosols of MQL can be suitable to substitute flood cooling and dry application. From environment and energy sustainability assessment, it is found that use of MQL technique for biodegradable aerosols as lubricant and coolant in machining gives highest total overall product sustainability index of 85.41. Hence machining of 700/3 ADI under MQL technique is an ideal approach toward sustainable manufacturing practice.**

***Index Terms* – *MQL Technique, product sustainability index, 700/3 ADI, Turning.***

## I. Introduction

Sustainable development is severing urge requirement in cleaner and green manufacturing activity in social as well as in industrial era. It is necessary to achieve overall sustainability in all industrial sectors, arising due to lot of establishing and emerging causes: stricter regulations related to environmental and occupational safety/ health, increasing consumer preferences for environmental friendly products and dwindle non-renewable resources. The manufacturing sectors which lie at the core of industrial economies must be made sustainable in order to preserve the higher standard of living achieved by industrialized societies and to enable developing societies to achieve the same standard of living sustainably. Further, the sustainability improvement effort must yield benefits at all elemental levels involved: energy, economic, environmental and societal. At the process level there is an urge need to achieve technological improvements and process planning for reducing energy and resource consumptions, toxic wastes, occupational hazards etc. for improving product life by manipulating process-induced surface integrity [1].

Austenised and austempered heat treated austempered ductile iron is widely used in structural, automotive and fabrication components such as gears, connecting rod, crank shaft, cam shaft and railroad. It has high strength to weight ratio, fatigue strength, stiffness and flexibility in design characteristics [2]. The microstructures of elemental contaminants in 700/3 ADI plays important role in change of physical and mechanical properties of material. However, the elements which produce exception mechanical and thermal properties in alloys also responsible for making duel soft at core and hard at surface characteristics.

Some of researcher discussed on the sustainability index in machining /manufacturing and few of them developed sustainable model for their research challenges. Sakharkar et al. [3] were worked on CNC turning machine using 700/3 ADI with CNMG120408TN2000 cutting inserts. They report on comparative assessments of minimum quantity lubrication technique and flood lubrication which demonstrated effectiveness of MQL technique based on tool wear, surface finish and chip characteristics with help of cutting speed, feed rate and depth of cut. Sakharkar et al. [4] developed a sustainable assessment to minimise energy consumption in green machining and explain economy and environmental aspects of water vapour machining on Inconel 718. Pusavee et al.[5] reported in machinability of Inconel 718 using cryo lubrication machining which showing high potential in enhancing the overall machining performance and machined part quality with this sustainable alternative. G. Kadam and R. Pawade [6] developed comprehensive sustainable model for energy and economy for machinability of Inconel 718 using high speed turning operation. Rajemi et al. [7] analysed the sustainable machining of EN8 steel and suggested that when seeking cutting conditions that satisfy both minimum energy and minimum cost criteria, it becomes necessary to consider the energy footprint of cutting tools.

Deiab et al. [8] observed that in turning of Ti-6Al-4V alloy with use of vegetable oil as a machining lubricant in MQL and MQCL configuration was better sustainable alternative to the synthetic cooling in terms of tool wear, surface quality and cutting energy consumed. Yan et al. [9] model an extension theory-based methodology of evaluating sustainability performance of machining process referring to a consistent set of economic, environmental, and social impacts. Jayal et. al.[10] developed sustainable manufacturing modeling and optimization challenges at the product, process and system levels. Liu et al.[11] worked for green machining for P/M process and compared effective economy between machining processes and powder metallurgy process.

Sustainability principles are considering: manufacturing costs, energy consumption, waste management, environmental impact, operational safety and personal health. With the implementation of sustainability principles in machining processes, the machining companies of all sizes have potential to save money and improve their environmental performance even though the production stay on the same size or it is decreased.

## II. DEVELOPMENT OF MODEL

Achieving the effective economy, environment and energy sustainability in manufacturing requires a holistic view of spanning not just the product but also the manufacturing process and safety involved. This requires to improved models, metrics for sustainability evaluation at the product and process levels.

TABLE I
SUSTAINABLE PARAMETRIC COMPONENTS AND THEIR FACTORS

| **Machining Environment** | **Machined Product** |
|---|---|
| Generation and supply | Part cleaning |
| Operator health and safety, emissions | Scrap disposal |
| Recycling and disposal | Surface roughness |
| | Tool wear |

The scores of influencing factors are recorded in each box of the matrix and PSI (Product Sustainability Index) is evaluated by proceeding across the matrix and summing up the scores of all influencing factors in each matrix category to calculate the percentage value. For example the product sustainability index for machining environment component can be calculated as:

$$PSI_{MENV} = \left\{ \frac{\sum_{i=1}^{n} IF_{MENV}}{n \times 10} \right\} \times 100\ \% \qquad \ldots (1)$$

where, $PSI_{MENV}$ = Product Sustainability Index for machining environment component,

$IF_{MENV}$ = Influencing factor rated on a scale of 0-10 for the machining environment component

n = Number of influencing factors considered.

Note: n = 3, since we have considered three influencing factors viz. generation and supply, operator health and safety, emissions, recycling and disposal.

Similarly, the sustainability index for the machined product component can be calculated as:

$$PSI_{MPRO} = \left\{ \frac{\sum_{i=1}^{n} IF_{MPRO}}{n \times 10} \right\} \times 100\ \% \qquad \ldots (2)$$

Where,

$PSI_{MPRO}$ = Product Sustainability Index for the machined product component,

$IF_{MPRO}$ = Influencing factor rated on a scale of 0-10 for the machined product component,

n = Number of influencing factors considered.

Note: For surface roughness as the main criteria, n = 3 since we have considered three influencing factors viz. part cleaning, scrap disposal and surface roughness. However for overall machinability as the main criteria, n = 4 since we have considered four influencing factors viz. part cleaning, scrap disposal, surface roughness and tool wear.

The overall Total Product Sustainability Index ($PSI_T$) for a machined product can be evaluated by averaging the PSIs of sustainability components in the horizontal column and hence can be calculated as:

$$PSI_T = \frac{\left| PSI_{MENV} + PSI_{MPRO} \right|}{2} \quad \ldots (3)$$

It has to understand that different applications demand the different surface integrity and tool wear requirements. Hence when the surface roughness is the main and only criteria in surface integrity, then in the above model, only surface roughness should be considered as influencing factor in machined product sustainability component; the other influencing variable, tool wear should not be considered. However, when an application demands overall machinability, then both surface roughness and tool wear should be considered when evaluating the model.

## III. EVALUATION OF MODEL

For our experimental work basically three machining environments viz. dry, flood coolant and MQL have been considered and the score level is considered based on saving of Energy, Economy and Environment.

### *A. Machining environment sustainability component*

1) Generation and Supply: dry environment does not require lubricant and cutting fluids. Hence maximum score of ‘9’ is given. But for flood cooling application it require in major amount. Before it, this fluid mixing and machining zone supply energy needs to be expended. Therefore for further supply, special accessories like pumps, motors, pipes, hoses, nozzles, filters, etc. are needed which incur costs. Thus considering all this, a low score of ‘6’ is given. As far as MQL concerned, in our case the compressed air required to mix lubricant for generation of aerosols in solenoid valve. However, for supplying aerosols also, accessories like pipes, hoses, nozzles, etc. are required and hence a score of ‘8’ is given.

2) Operator health and safety, emissions: dry machining is assuming safe due to absence of coolant and lubricant. Therefore it does not have emissions. Hence a score of ‘8’ is given. In case of flood coolant environment, during machining the operator comes in contact with cooling lubrication fluids which is highly toxic to the human body which causes health hazards. Hence a score of ‘5’ is given. In application of MQL, since MQL aerosols are composed of biodegradable liquid particles in suspension of air, it is not harmful to the operator. Also aerosols are escape out into the atmosphere freely due to low density. Hence a score of ‘8’ is given.

3) Recycling and disposal: dry machining does not use any fluid; therefore, there is no problem of recycling and disposal. Hence a score of ‘9’ is given. In case of flood coolant environment, large amount of coolant required. Therefore flood coolant becomes very costly and hence intended to be used multiple times. For it, frequent cleaning and filtering is required after each cycle. For it accessories like filters, pumps, motors, etc. are required. The disposal requires special procedures to be followed and also incurs additional costs. Considering all this, a score of ‘6’ is given. In case of MQL environment, there is no need of recycling and special disposal. It is because the aerosols are directly gets exhausted out into the atmosphere. Hence a score of ‘9’ is given to the MQL environment.

### *B. Machined product sustainability component*

1) Part cleaning: dry machining does not required part cleaning and hence a score of ‘9’ is given. But for the flood coolant application, thorough part cleaning is required as it contains a deposition of fluid over the part and hence a score of ‘7’ is given. In case of MQL application, aerosols escapes out into the atmosphere, therefore part is clean and hence no external cleaning is required due to which a score of ‘9’ is given.

2) Scrap disposal: In machining, the scrap is generated in the form of chips. The scrap disposal basically means handling, storing and recycling of scrap. Since 700/3 ADI is a ductile cast iron produced very small (elemental) chips which are difficult to control and collect. Therefore preference should be given to control and collection of scrap.

In dry machining, the scrap is free from the fluid and hence a score of ‘9’ is given. In case of flood coolant environment, the scrap has deposition of fluid over it. Therefore rapid corrosion will occurred due to oxidation and chemical affinity of cast iron. Hence special treatments like washing and heating may be required to make it fluid free which incurs heavy costs. Hence a score of ‘6’ is given. In case of MQL environment, as aerosols escapes out into the atmosphere, the scrap is free from any fluid and hence no special treatment is required. Hence a score of ‘9’ is given.

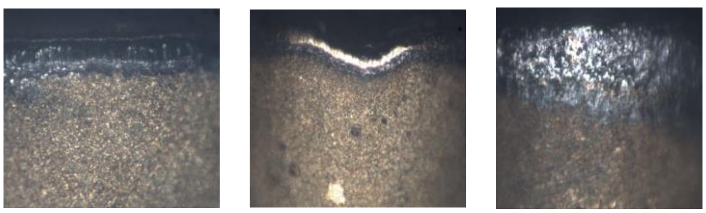
3) Surface roughness: For the surface roughness, the values obtained from experimental investigations have been considered. The values have been graded from low to high. Further the scoring has been done conversely, i.e. low grades have been given highest score and vice versa. Thus a low surface roughness indicates a good surface finish giving high score and vice versa.

4) Tool wear: The wear is graded based on its length of flank wear ($V_B$). The catastrophic nose wear has lowest score rate and increase in score rate to reduction in abrasive flank wear length.

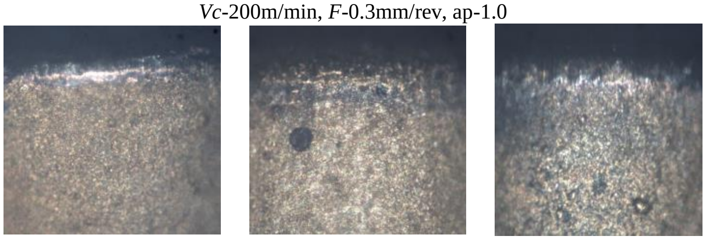
Overall machinability: For considering the overall surface integrity, both the scores of surface roughness and tool wear have been considered.

TABLE II
EXPERIMENTAL TEST MATRIX

| Expt No | *Environ-ment* | *Vc* m/min | *F* mm/rev | $a_p$ mm | Surface roughness µm | Tool wear µm |
|---|---|---|---|---|---|---|
| 1 | Dry | 50 | 0.1 | 0.1 | 4.03 | 30.19 |
| 2 | Dry | 125 | 0.2 | 0.55 | 3.25 | 38.23 |
| 3 | Dry | 200 | 0.3 | 1.0 | 1.78 | 71.69 |
| 4 | Flood | 50 | 0.1 | 0.1 | 2.81 | 39.31 |
| 5 | Flood | 125 | 0.2 | 0.55 | 3.02 | 39.78 |
| 6 | Flood | 200 | 0.3 | 1.0 | 3.39 | 41.79 |
| 7 | MQL | 50 | 0.1 | 0.1 | 1.67 | 27.53 |
| 8 | MQL | 125 | 0.2 | 0.55 | 1.86 | 30.01 |
| 9 | MQL | 200 | 0.3 | 1.0 | 2.23 | 49.02 |



*Vc*-200m/min, *F*-0.3mm/rev, ap-1.0



*Vc*-50m/min, *F*-0.1mm/rev, ap-0.1

Dry Flood Coolant MQL

Fig. 1. Effect of machinability parameters on tool wear

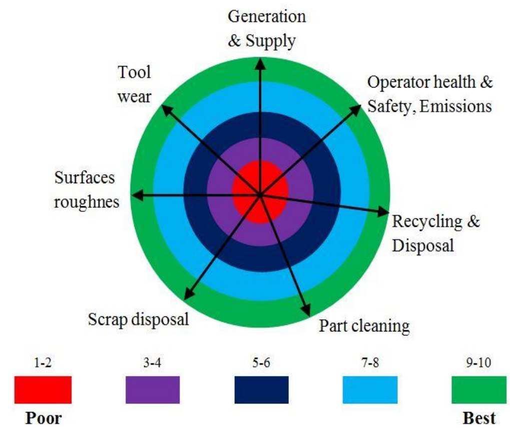



Fig. 2.Representation of the scoring criteria for the influencing factors of the sustainability components for product sustainability evaluation

## IV. RESULTS AND DISCUSSION

### A. *Sustainability main criteria for surface roughness*

This model has been formed by considering surface roughness as the main criteria. The appropriate scoring has been done and product sustainability index been found as given in Table 3. Further, the total product sustainability index ($PSI_T$) for the respective conditions (experiments) has been systematically represented in Fig.3. From the above model, the conditions which give higher values of total product sustainability index ($PSI_T$) are the best which support sustainable energy in machining. It is recommended to implement them in practice to achieve sustainability in turning of 700/3 ADI. Further, as seen from Table 3 and Fig. 3, the highest total product sustainability index ($PSI_T$) of 84.83% is found in case of MQL environment (#Expt. No. 7,8). Hence it is suggested that turning of ADI under MQL environment at *Vc* = 50-125 m/min, f = 0.1-0.2 mm/rev, ap = 0.1-0.55 mm be carried out as it is the better operational condition under sustainable regime which shows minimum energy source consumption in operations.

TABLE.III
SUSTAINABILITY EVALUATION CONSIDERING SURFACE ROUGHNESS AS MAIN SURFACE INTEGRITY PARAMETER

| Condition | Machining Environment | | | $PSI_{MENV}$ | Machined Product | | | $PSI_{MPRO}$ | $PSI_T$ |
|---|---|---|---|---|---|---|---|---|---|
| | Generation and supply | Operator health and safety, emissions | Recycling and disposal | | Part Cleaning | Scrap Disposal | Surface Roughness | | |
| Dry condition 1 (#Expt.1) | 9 | 8 | 9 | 86.66 | 9 | 9 | 4 | 73.33 | 79.99 |
| Dry condition2 (#Expt.2) | 9 | 8 | 9 | 86.66 | 9 | 9 | 4 | 73.33 | 79.99 |
| Dry condition 3 (#Expt.3) | 9 | 8 | 9 | 86.66 | 9 | 9 | 6 | 80.00 | 83.33 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Flood Coolant 1 (#Expt.4) | 6 | 5 | 6 | 56.66 | 7 | 6 | 6 | 63.33 | 59.99 |
| Flood Coolant 2(#Expt.5) | 6 | 5 | 6 | 56.66 | 7 | 6 | 5 | 60.00 | 58.33 |
| Flood Coolant 3(#Expt.6) | 6 | 5 | 6 | 56.66 | 7 | 6 | 4 | 56.66 | 56.66 |
| MQL Environment 1(#Expt.7) | 8 | 8 | 9 | 83.33 | 9 | 9 | 8 | 86.66 | 84.83 |
| MQL Environment 2(#Expt.8) | 8 | 8 | 9 | 83.33 | 9 | 9 | 8 | 86.66 | 84.83 |
| MQL Environment 3(#Expt.9) | 8 | 8 | 9 | 83.33 | 9 | 9 | 7 | 83.33 | 83.83 |

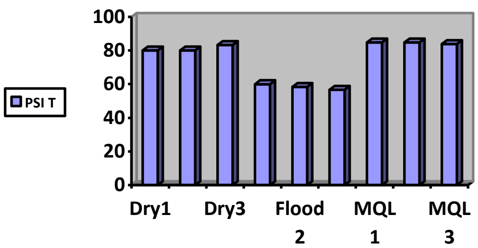



Figure 3.Total product sustainability index ($PSI_T$) for different conditions (experiments) considering surface roughness as the main criteria for product sustainability evaluation

### *B. Sustainability overall criteria for machinability*

According to this, the model has been formed considering both surface roughness and tool wear as it encompasses overall machinability. The appropriate scoring has been done and product sustainability index been found as given in Table 4. Further, the total product sustainability index (PSIT) for the respective conditions (experiments) has been systematically represented in Fig. 4. From this model, the conditions which give higher values of total product sustainability index ($PSI_T$) are the best which support sustainable manufacturing. It is highly recommended to implement them in practice to achieve sustainability in machining of 700/3 ADI. Further, as is evident from Table 4 and Fig. 4, the highest total product sustainability index ($PSI_T$) of 85.41% is found in case of MQL environment (#Expt. no. 7,8). Hence it is suggested that machining of under water vapour environment at $V_c$ = 125 m/min, $f$ = 0.2 mm/rev, $a_p$ = 0.55 mm be carried out as it is the best operational condition under sustainable regime.

TABLE IV
SUSTAINABILITY EVALUATION CONSIDERING OVERALL MACHINABILITY

| Condition | Machining Environment | | | $PSI_{MENV}$ | Machined Product | | | | $PSI_{MPRO}$ | $PSI_T$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | Generation and supply | Operator health and safety, emissions | Recycling and disposal | | Part cleaning | Scrap disposal | Surface Roughness | Tool wear | | |
| Dry condition 1 (#Expt.1) | 9 | 8 | 9 | 86.66 | 9 | 9 | 4 | 8 | 75 | 80.83 |
| Dry condition2 (#Expt.2) | 9 | 8 | 9 | 86.66 | 9 | 9 | 4 | 6 | 70 | 78.33 |
| Dry condition 3 (#Expt.3) | 9 | 8 | 9 | 86.66 | 9 | 9 | 6 | 3 | 67.5 | 77.08 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Flood Coolant 1 (#Expt.4) | 6 | 5 | 6 | 56.66 | 7 | 6 | 6 | 6 | 62.5 | 59.58 |
| Flood Coolant 2(#Expt.5) | 6 | 5 | 6 | 56.66 | 7 | 6 | 5 | 6 | 60 | 58.33 |
| Flood Coolant 3(#Expt.6) | 6 | 5 | 6 | 56.66 | 7 | 6 | 4 | 5 | 55 | 55.83 |
| MQL Environment 1(#Expt.7) | 8 | 8 | 9 | 83.33 | 9 | 9 | 8 | 9 | 87.5 | 85.415 |
| MQL Environment 2(#Expt.8) | 8 | 8 | 9 | 83.33 | 9 | 9 | 8 | 9 | 87.5 | 85.415 |
| MQL Environment 3(#Expt.9) | 8 | 8 | 9 | 83.33 | 9 | 9 | 7 | 4 | 72.5 | 77.915 |

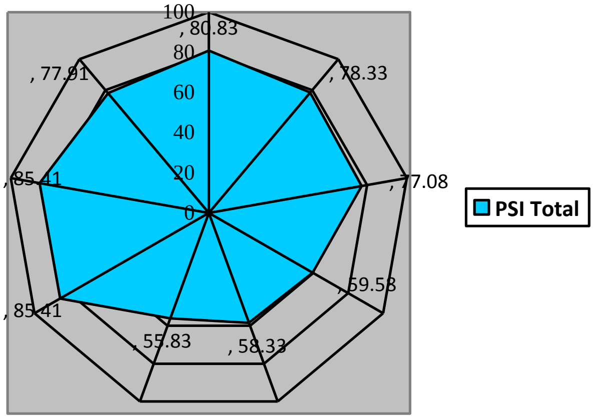



Fig 4. Total product sustainability index ($PSI_T$) for different conditions (experiments) considering overall surface integrity as the main criteria for product sustainability evaluation

Thus in general it can be concluded that machining under MQL environment seems to be one of the best practice towards sustainable green manufacturing with highly appreciating results for minimum energy consumptions. Hence MQL as a coolant and lubricant in machining of 700/3 ADI may be followed as a practice by machining firms who wish to achieve sustainability in their operations.

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