Machinability Studies on Abrasive Water Jet Machining of Low Alloy Steel for Different Thickness

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Abstract. This paper reports some results of experimental investigation conducted on abrasive water jet machining (AWJM) of medium carbon low alloy (EN24) steel. EN24 steel samples of different thickness have been machined at various combinations of AWJM parameters. Three important AWJM parameters namely water jet pressure, nozzle traverse speed, and stand-off distance have been varied at three levels each. Three important responses i.e. material removal rate, kerf wall inclination, and surface roughness (average roughness) have been considered as the machinability indicators. The variation of these machinability indicators with a range of thicknesses of EN24 steel samples has been investigated. It is found that AWJM is capable to machine EN24 steel at very high MRR even at the increased thickness. But, surface finish deterioration is prominent with sample having higher thickness. Moreover, nozzle traverse speed is identified as the most significant parameter. It is concluded that the jet pressure of 240MPa with traverse speed of 20mm/min can produce good machinability for AWJM of EN24 Steel.

1. Introduction
In engineering materials, steel is the backbone for many engineering applications. The selection of steel material is based on the following primary factors: application of load, environment and cost. It has high impact on each and every operating condition of machineries. Steels are widely classified and most commonly used is medium carbon low alloy steels. Extensively articles are available to discuss on the properties and importance of steel [1]. The raw steel cannot be used as a final product in any conditions. It has to undergo some machining and finishing processes. Researchers have made an attempt to machine EN24 steel using conventional turning, milling and drilling process [2,3]. There are also such attempts where low alloy steels are machined by advanced processes such as electric discharge machining (EDM) based processes. But, carbide formation and white layers are some of the challenges occur while machining with EDM based processes.

Abrasive water jet machining (AWJM) is one of the important unconventional machining processes used to machine bulk and difficult to cut materials [5]. In recent years, the demand for abrasive based cutting has been increased due to the following reasons- no heat affected zone, good surface quality, less machining time, and low environmental footprints etc. The quality of machining highly depends on the selection of process parameter involved in AWJM process. Jet pressure, jet nozzle speed (traverse speed), stand of distance, and shape and size of abrasive particle are the main process parameters [6-8]. AWJM is a flexible and multi directional cutting process. Jai [9] reported that the
variation in orifice diameter in AWJM jet nozzle plays a vital role with significant effect while machining bulk material. Jet flow through nozzle decides the effect of depth of penetration to slice the material. That is the plastic deformation of material during machining is inversely proportional to the jet pressure and strength of material used [10]. While machining, jet pressure tends to cut the top surface of the bulk material and leads to the shallow cut throughout the thickness [11]. Subsequently the impact of nozzle traverse speed decides the amount of material to be removed while machining. The impact pressure jet allied with the traverse speed of the nozzle has high impact in making the variation in kerf wall inclinations [12]. Literatures are available to discuss about the influence of AWJM cutting process parameters on various machinability indicators [13, 14]. However, there is a scarcity of the research work on cutting of EN24 type of steel by AWJM, and effect of variation of thickness on machinability indicators etc. require future research attempts.

The research work reported in this article fulfils that gap where AWJM of low alloy steel with various thicknesses is conducted to gain more insights into it.

Surface roughness, material removal rate, and kerf wall inclinations were considered the important machinability indicators.

2. Experimental details

The medium carbon low alloy in the grade EN24 is used as a candidate material. The chemical composition of the material is given in Table 1. The highlight of the research is to focus on machining different section thickness of 5, 10, 15 and 20mm.

Table 1. Chemical composition of EN24 steel material used in the present work

| Element | C   | Si  | Mn  | S   | Cr  | Mo  | Ni  | Fe  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| Wt.%    | 0.4 | 0.3 | 0.5 | 0.04| 1.5 | 0.35| 1.5 | Balance |

The abrasive water jet cutter (Make: DWJ1313-FB) is used to perform experiments (Figure 1). The accuracy of the machine falls in the range of + 0.1mm and repeatability of the machining is + 0.005mm. The tip of the jet nozzle is 0.76mm. Garnet is used as an erodent, having multi sharp edges with an average particle size of 180-200µm. The machining studies are planned in nine combinations to study the influence of input process parameters. The level of input process parameters is given in Table 2.

Table 2. The level of abrasive water jet cutting input process parameters

| Parameters            | Unit  | Level 1 | Level 2 | Level 3 |
|-----------------------|-------|---------|---------|---------|
| Water pressure        | MPa   | 220     | 240     | 260     |
| Nozzle Transverse speed | mm/min | 20       | 30       | 40       |
| Stand-off distance    | mm    | 1       | 2       | 3       |
Optical microscopes are used to measure the kerf band gap of the machined surface. From the kerf geometry the kerf angle and material removal rate are empirically calculated using the following equations.

\[ \text{Kerf Taper} = \frac{W_t - W_b}{2t} \]  
\[ \text{MRR} = \frac{h_i d_i v_f}{t} \]

Where, \( W_t \) – top width, \( W_b \) – bottom width and \( t \) – thickness of the sample, \( d_i \) – diameter of focusing tube or nozzle \( [d_i = (W_t + W_b) / 2] \), \( v_f \) – traverse speed

Subsequently, the samples are sliced to individual pieces to find the surface roughness on machined area. Further the surface morphology of the machined surface is observed through scanning electron microscope. The wear morphology and the wear mechanism of the machined surface are studied in detail with respect to bulk thickness of the material.

3. Results and discussion

The machining studies are carried out at different combination of input process parameters. After machining, the kerf band gaps are studied through optical microscope to calculate kerf angle and material removal rate. The Kerf value for individual input are studied in detail and for a single combination of process parameter, the kerf inclination and material removal rate are plotted in Figure 2 and 3. The graph infers the variation in kerf wall inclination for all the four thickness (5, 10, 15 and 20mm) machined at a traverse speed on 30mm/min at 2mm stand-off distance. The kerf inclination found neutral at average cutting pressure of 240MPa for all the sections. On other hand, the positive kerf was found with higher jet pressure for all the thickness and contraflexure in lower jet pressure. The kerf influence may be due to the hardness and strength of material possess. Figure 3 represents the variation in material removal with reference to jet pressure and section thickness of the bulk material machined at a traverse speed on 30mm/min at 2mm stand-off distance. In this case, the MRR reveals in incremental mode with respect to increase in thickness. At 5mm thickness, the MRR value is negotiable. While increasing the thickness of the bulk, the removal rate has a significant change on raising the jet pressure to a maximum. Therefore, if the bulk thickness of the machined material is increased, then the volume of material removal also increases for same machining condition (Fig.3).

![Figure 2. Kerf wall inclination of EN24 steel machined using AWJ cutting process](image)

![Figure 3. Difference in material removal rate with reference to change in bulk thickness](image)
measured. The surface roughness of the machined surface was observed in incremental mode with respect to bulk thickness. The major issue in machining thick section is that, the intensity of the jet penetration travelling from one level to another level will tough. At the same, the whirling / turbulence will make the sample to produce more roughness texture. To discuss in detail, the sliced samples observed with microscope and corresponding images were captured (Figure 5). After that, the cutting tracks are identified and studied in detail for each sample. From the wear scars / tracks a reference line has been marked to predict the angle of deviation in water jet cutting. The manually calculated trigonometrical relation has shown wide variations in cutting angle. At 5mm EN24 steel plate, the wear track angle is 2.9° and it has been increasing as 3.2°, 3.4° and 4.4° for the steel plate of 10, 15 and 20mm thickness respectively. This is the actual cutting mechanism involved while cutting same material with different section. To clarify in detail, the intensity of jet pressure is strong enough to machine the material. For better understanding, Figure 6 illustrates the basic cutting phenomenon in AWJM. When the travel speed increased, the variation in wear track is rapid and at low travel speed, the variation in wear track can be minimized. On controlling the travel speed, the material is susceptible to machine and overlapping of the erodent will produce good surface finish. The surface profile of the samples for 15mm and 20mm are studied, and results for the same are given in Figure 7. At these conditions, the surface profiles are very aggressive and reflects the wear morphology. If the travel speed found rapid, the machining of material will be difficult and the lagging distance may lead to produce uncut / improper machined surface. Therefore, the optimized machined conditions are highly recommended for machining thick sections.

![Figure 4. Surface roughness of the sample with different sections thickness](image1)

![Figure 5. Wear tracks made by abrasive water jet and manually calculated cutting angle for each sample](image2)

![Figure 6. Deviation in jet cutting intensity with continuous movement of jet nozzle at different thickness](image3)
Figures 8-10 show the contribution of input process parameters identified using analysis of variance. For material removal rate, the major contribution of the process parameter is travel speed. As discussed in the previous sections, the slow travel speed will be able to machine maximum material with perfection. The major contribution is 86-98% for jet travel speed. The jet pressure is the subsequent parameter followed by stand of distance. For kerf wall inclination, the two input parameters have to be considered. It has been proved that the travel speed has a major contribution in the range of 44-45% and jet pressure followed in the range of 35-36%. In this condition, the error rate is substantial because the kerf of the machined surface is not uniform for hard material. It is also part of interconnection with surface finish. For surface roughness the error percentage varied from 16-35%. The major input parameters are similar like kerf wall inclination. The contribution of jet travel speed is 37-44% and jet pressure with 26-37% for surface roughness. One more input parameter is there, that is stand-off distance (SoD). In a common practice, the SoD plays vital role. When the SoD is higher, the intensity of jet impingement will be reduced. But it is indirectly combined with the jet pressure used for machining. For all the three output, the maximum variation is 1-8% for SoD. Therefore, it is confirmed that the jet pressure of 240MPa with slow travel speed of 20mm/min can produce good machinability for AWJM of EN24 Steel.
4. Conclusion

Abrasive water jet machining of various sample thickness of EN24 medium carbon low alloy steel is reported in this paper. The following conclusions can be drawn from this research-

1. It is observed that EN24 steel samples of various thicknesses can be machined by AWJM process with good surface quality, geometric accuracy and process productivity.

2. Material removal rate and bulk thickness are directly proportional. It is possible to achieve higher MRR even while machining samples with increasing thickness.

3. Deterioration in surface finish with increased thickness is observed.

4. Overall, nozzle traverse speed or jet travel speed is identified as the most significant parameter followed by jet pressure.

In essence, it can be concluded that the appropriate combination of machining parameters can result in the desired machinability characteristics while cutting EN24 steel type hard material by AWJM. Future research avenues may include multi-performance optimization for ensuring better values of all conflicting responses, effect of some other AWJM parameters on machinability, sustainability assessment of AWJM process for machining EN24 type other steel variants etc.

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