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Studies on Recharging of Abrasives in Abrasive Water Jet Machining

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The objective of this work is to find the effect of the recharging of local garnet abrasives (origin: southern India) while cutting aluminium using abrasive water jet machining. The influence of the specially formulated optimised abrasive test sample, pressure, traverse rate, and abrasive flowrate, on the American Foundrymen's Society fineness number, depth of cut, top and bottom kerf width, kerf taper, and surface roughness are studied. The performance of the test sample has been compared with that of commercial grade abrasive with mesh size 80. Additionally, recharging studies are carried out after screening out particles of less than 90 μm. These tests help to determine the optimum recharging required.

Keywords: Abrasive water jet machining; Aluminium machining; American Foundrymen's Society fineness number; Garnet abrasives; Recharging; Surface roughness

1. Introduction

Abrasive water jet machining (AWJM) is becoming more widely used. Its industrial use depends on its cost effectiveness. In general, the overall cost of an AWJM system still remains high compared to that of traditional machining techniques, despite a move by the industry to reduce the equipment cost and increase the system reliability. System operating costs have been monitored and have held steady at a high level for many years [1]. The cost of the abrasive constitutes nearly 75% of the total operating cost. The high cost of the abrasive has restricted opportunities and use of this technology. Abrasive cost, however, must be considered along with abrasive performance. Good abrasive performance is more important than low abrasive cost, since any advantage in low abrasive purchase cost can be outweighed by the higher cutting speed achieved with a better-performing abrasive. Therefore, the cost of the abrasive should be weighed against its performance and the most cost-effective abrasive should be selected [2]. The cutting efficiency is influenced by the particle size, particle size distribution, and shape of the abrasive particles.

The abrasive particles disintegrate during the acceleration and focusing process, and also when cutting. The breakdown of particles occurs in two stages:

1. Particle/particle, particle/waterjet, and particle/wall collisions in the mixing chamber/focusing tube assembly.
2. Particle/particle and particle target collisions on the target cutting surface [3].

With proper cleaning and sorting, an important portion of sludge may be recycled as abrasive material and fed back to the cutting process. Only the remaining portion, the microchips of the workpiece material and the used abrasive material have to be disposed of [4]. By recycling the abrasives, the process will be more economical, effective, and ecologically friendly. Realising the importance of recycling, fully automated systems such as the Waterjet Abrasive Recycling Dispenser (WARD) [5] have been introduced recently into the market. The addition of fresh particles (recharging) is likely to improve the process.

Natural abrasives are often mined from riverbeds or sand deposits. Impurities are removed, since purity will influence the cutting performance. Then the mineral is sized. This is a multistep process where metal screens are used to remove very fine and oversized particles [2]. Garnet is frequently used as an abrasive, since it is relatively hard, sharp edged, has effectiveness, flow ability, availability and is of reasonable cost. It also has better performance than other abrasives such as aluminium oxide, silicon carbide, silica sand, copper slag, steel grit, steel shot, and glass beads [6,7]. However, different types of garnet, even when chemically and physically similar, perform quite differently [8]. In our work, garnet abrasives obtained from southern India are tested for usefulness. Preliminary work on these abrasives [9–11] has concentrated on depth of cut, kerf width, kerf taper, surface roughness, and fragmentation of abrasive particles (measured by AFS number) and recommendations have been made on their suitability for machining. It was also found that the commercial grades of mesh sizes supplied by various vendors vary in particle size distribution. A specially formulated test sample with five equally distributed particle sizes rather than a single or three

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Table 1. The details of equipment.

Item	Description
Abrasive water jet machining system	Injection type IP236-22, M/s WOMA, Austria
Power	22 kW, 50 Hz
Maximum discharge pressure	360 MPa
Abrasive feeding system	Vibratory conveyor with heating facility
CNC work table	Two-axis control ($X = 1000$, $Y = 1000$)
British standard sieves, mesh number	30, 36, 44, 52, 60, 72, 80, 100, 120
Surface roughness measuring equipment	Perthometer
Kerf width measurement	Optical microscope

equally distributed sizes is recommended by Krishnaiah Chetty et al. [11] based on optimisation studies. This paper reports on the recharging capabilities of this optimised abrasive test sample. The AFS number, depth of cut, top and bottom kerf width, kerf taper, and surface roughness achieved during recharging are reported. The results of this sample are compared with that of commercial grade mesh size 80. Additionally, recharging tests are conducted after screening out particles of less than 90 μm.

2. Experimental Set-up and Procedure

An injection machine type IP236–22 supplied by M/s WOMA, Austria has been used for experimentation. The equipment details are given in Table 1. The constant process parameters are shown in Table 2. The levels of pressure, traverse rate, and abrasive flowrate and a specially formulated abrasive test sample containing particles of five different mesh sizes are selected, based on optimisation studies in machining aluminium by Krishnaiah Chetty et al. [11]. Commercial grade abrasive, mesh size 80, has been tested and the performance measured. The details of the test sample and mesh size 80 are shown in Table 3. A trapezoidal workpiece has been cut, and the depth of machining computed. The kerf width is measured at three locations on the cut length. The surface roughness (*Ra*) at the middle section of the workpiece is measured by a Perthometer.

Table 2. Constant process parameters.

Parameter	Description
Abrasive material	Local garnet (origin: Southern India)
Abrasive particle shape	Angular (random)
Primary nozzle diameter (mm)	0.25, sapphire
Secondary nozzle diameter (mm)	0.8, carbide
Secondary nozzle length (mm)	70
Stand off distance (mm)	3
Jet impact angle	90°
Work material	Aluminium 6063 T6
Pressure (Mpa)	225
Traverse rate (mm min^{-1})	50
Abrasive flow rate (g s^{-1})	1.5

To study the disintegration behaviour of abrasives, particles are collected at the exit of the focusing nozzle and also after cutting through a special catcher, consisting of a cylindrical drum with a screening cloth. The collected abrasives are cleaned (aluminium debris is dissolved by adding 20% sodium hydroxide solution), dried and sieved. The AFS numbers, average particle sizes, depth of cut, top and bottom kerf width, kerf taper, and surface roughness are measured. The average particle sizes are calculated based on the momentum method proposed by Guo et al. [12]. Recharging studies are undertaken. The abrasives collected after cutting are recharged with fresh abrasives at 20%, 40%, 60%, 80%, and 100% (the proportions of used abrasives and fresh abrasives are 1:0.2, 1:0.4, 1:0.6, 1:0.8, and 1:1) in order to study the influence of recharging. Additionally recharging studies are carried out after screening out particles of less than 90 μm. These tests help to determine the optimum recharging required. Tests were carried out with the test sample as well as with the mesh size 80.

3. Results and Discussions

3.1 AFS number/Average Particle Size

Table 4 shows the details of AFS numbers and average particle sizes of the test sample and mesh size 80 of the fresh abrasives, along with the recharged ones pertaining to nozzle entry, nozzle exit, and after cutting. The complex process of mixing within the mixing chamber and in the focusing nozzle results in an increase of the AFS number (reduction in average particle sizes) at the nozzle exit. It can be also observed from Table 4 and Figs 1 and 2 that tremendous disintegration occurs with the fresh abrasives (FA) in the mixing chamber and focusing nozzle, compared to the disintegration of the reused abrasives. This is to be expected, since fresh abrasives have particles of larger size. During the cutting process, further disintegration takes place and the AFS number increases (average particle size reduces) further. This increase in AFS number is found to be greater with the test sample compared to that with commercial grade mesh size 80 abrasive. The test sample contains more larger particles than the mesh size 80 abrasive and therefore the higher fragmentation, due to inter particle collisions, resulted in an increase in AFS number. The same phenomenon has been observed with the recharged particles at every stage. The increase in AFS number is (reduction in average particle size) partly compensated for (further recharged) by the addition of fresh abrasives in various proportions, hence the AFS number decreased (average particle size increased).

3.2 Depth of Cut

In general, the reuse of abrasives results in a decreased depth of cut, since particles disintegrate. However, with recharging, the depth of cut is expected to increase compared to that without recharging. Figure 3 shows the effect of recharging on depth of cut and compares the performance of the test sample

Table 3. Details of abrasive samples.

Abrasive sample	Percentage of abrasive, Mesh designation (particle size, mm)							AFS number	Average particle size (mm)
	44 (0.355–0.400)	52 (0.315–0.355)	60 (0.250–0.315)	72 (0.200–0.250)	80 (0.180–0.200)	100 (0.160–0.180)	120 (0.125–0.160)		
Test sample	20	20	20	20	20	–	–	52.80	0.282
Mesh size 80	8.3	29.1	36.0	1.1	23.7	1.4	0.4	53.76	0.281

Table 4. Effect of recharging on AFS number and average particle size (a.p.s.).

Recharging (%)	Test sample						Mesh #80					
	AFS number			a.p.s. (mm)			AFS number			a.p.s (mm)		
	Nozzle entry	Nozzle exit	After cutting	Nozzle entry	Nozzle exit	After cutting	Nozzle entry	Nozzle exit	After cutting	Nozzle entry	Nozzle exit	After cutting
FA	53	94	105	0.282	0.192	0.174	54	87	100	0.281	0.195	0.186
20	94	113	124	0.195	0.167	0.157	85	91	106	0.216	0.189	0.179
40	87	111	120	0.209	0.170	0.160	77	92	104	0.231	0.195	0.183
60	83	108	117	0.219	0.174	0.163	73	93	104	0.241	0.196	0.184
80	79	105	118	0.227	0.176	0.166	70	96	102	0.247	0.197	0.188
100	76	103	116	0.233	0.178	0.166	68	98	100	0.252	0.200	0.189

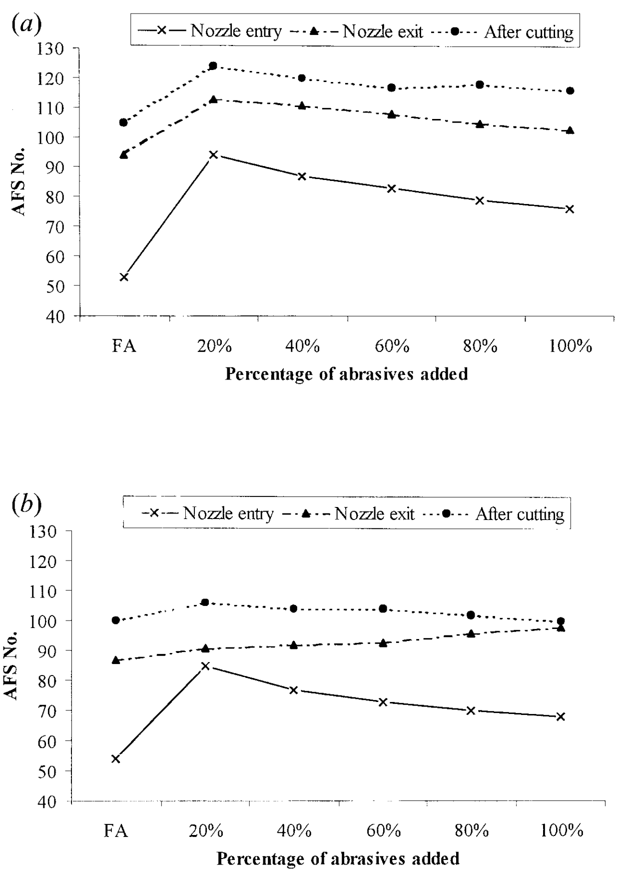

Fig. 1. The effect of recharging on AFS number of (*a*) test sample, (*b*) mesh size 80 sample.

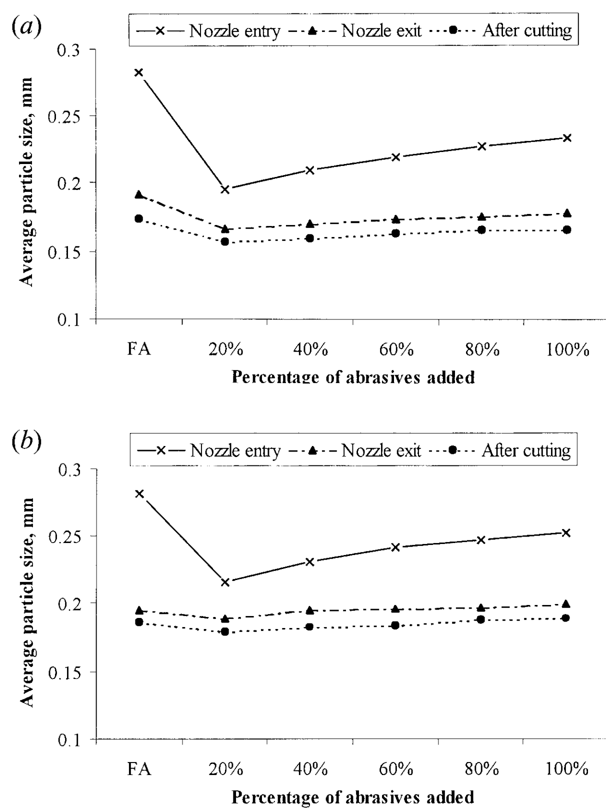

Fig. 2. The effect of recharging on average particle size of (*a*) test sample, (*b*) mesh size 80 sample.

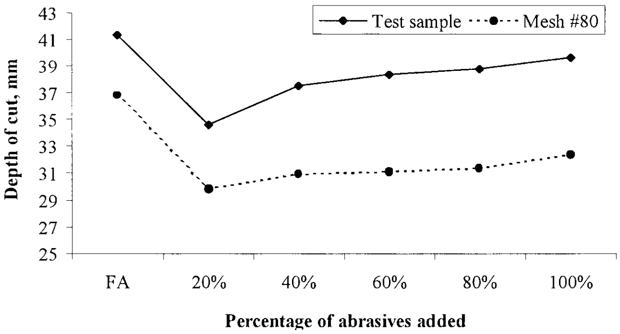

Fig. 3. The effect of recharging on depth of cut of test sample and mesh size 80 sample.

and the mesh size 80 sample. With an increase in percentage of recharging, the depth of cut has increased significantly up to 40% recharging and marginally thereafter, with both the test sample and mesh size 80 sample. Therefore, for greater depth of cut, recharging of the test sample and of the mesh size 80 sample by 40% is recommended. The depth of cut achieved with the test sample as compared to the mesh size 80 sample is higher by 12% to 24%. This indicates the superior performance of the test sample which may be attributed to the presence of the larger size particles added at every stage. Particle size distribution thus plays a key role in improving the cutting efficiency.

3.3 Kerf Widths and Kerf Taper

The average of three measurements of kerf parameters have been recorded. Figure 4(*a*) indicates the influence of recharging on top kerf width (kw_t), bottom kerf width (kw_b), and kerf taper (k_t) achieved with the test sample. It can be seen that the top kerf width as well as the bottom kerf width achieved with recharged abrasives are lower than those achieved with fresh abrasives. This is due to an increase in the AFS number (decrease in average particle size) of recharged abrasives compared to fresh abrasives. It may be recalled that fresh abrasives contains larger particles. The effect of recharging is found to increase the top and bottom kerf width marginally. So increases in recharging from 20% to 100% have resulted in marginal increases in top and bottom kerf width, both with the test sample and with the mesh size 80 sample. It is also observed that kerf taper reduces at every stage of recharging. Reductions in kerf taper obtained with recharged abrasives, are advantageous in machining because of the improvement in parallelisms of the cut surfaces.

Figure 4(*b*) indicates the influence of recharging on kw_t, kw_b, and k_t achieved with the mesh size 80 sample. Though observations similar to those with the test sample have been made, top kerf width is found to be smaller than that with the test sample. The decrease in top kerf width in the present case is due to the increase in AFS number (decreased average particle size) compared with the test sample. However, the bottom kerf width is larger than in the test sample. The kerf taper is found to fluctuate. Jet instability at the bottom cut surface may be responsible for an increase in bottom kerf

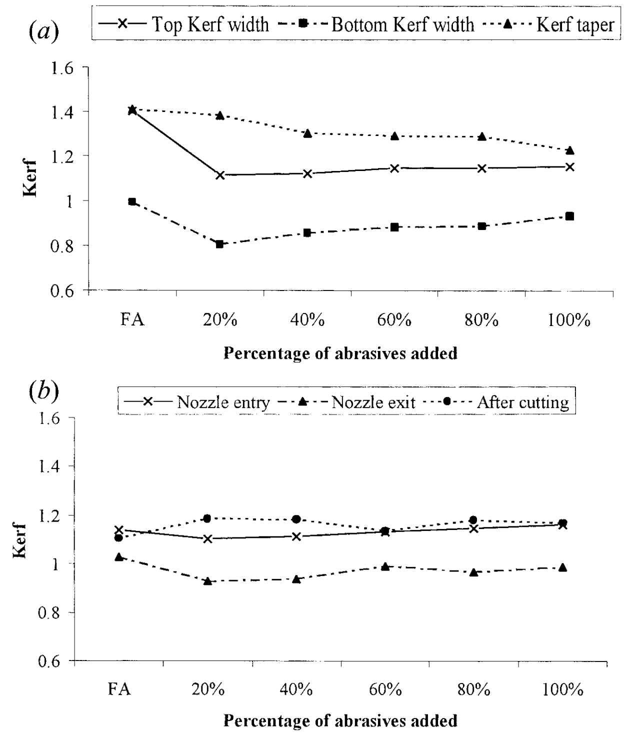

Fig. 4. The effect of recharging on kerf of (*a*) test sample, (*b*) mesh size 80 sample.

width and it also influenced the kerf taper. The variations observed in kerf taper confirm the jet fluctuations and may be attributed to the particle size distribution.

3.4 Surface Roughness

The surface roughness (*Ra*) at the middle section of the workpiece is measured by a Perthometer at three places and the average is recorded. Figure 5 indicates the influence of recharging on surface roughness both with the test sample and the mesh size 80 sample. Both the samples have resulted in decreased surface roughness after the first cut. The reduction in surface roughness can be attributed to an increase in AFS number (average particle size reduces) of the abrasive particles by fragmentation. It is also observed that the fresh abrasives

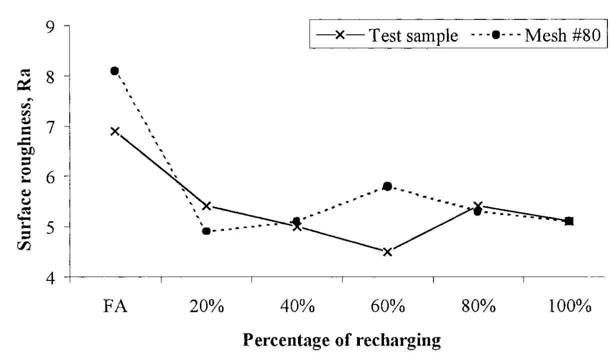

Fig. 5. The effect of recharging on surface roughness of test sample and mesh size 80 sample.

of the test sample produce decreased surface roughness as compared to the mesh size 80 sample, whereas the recharged abrasives with both the test sample and the mesh size 80 sample do not indicate any pattern of behaviour with regard to surface roughness. Although the AFS number of test sample and mesh size 80 sample decreases marginally with recharging (average particle size increases), the surface roughness is found to fluctuate widely. Hence, the particle size distribution seems to play a role in controlling the surface roughness. Minimum surface roughness is obtained with 60% recharging of the test sample, and hence this level of recharging is recommended. With the mesh size 80 sample, 20% recharging is recommended for minimum surface roughness.

4. Recharging with more than 90 μm

Workers [12–14] have preferred elimination of finer particles of less than 90 μm for improved cutting performance and repeated use. By removing these finer particles, there will be an increase in the average particle size, and it also avoids handling and dosing problems. The reuse of these abrasives can be increased by reducing the cost of the operation. Hence, recharging studies are carried out with particles of more than 90 μm.

5. Results and discussion

5.1 AFS Number/Average Particle Size

Table 5 and Figs 6 and 7 indicate the details of AFS numbers and average particle sizes of the test sample and the mesh size 80 sample at nozzle entry, nozzle exit, and after cutting. Higher fragmentation occurs initially with fresh abrasive at the mixing chamber and focusing nozzle, and as a result the AFS number increases (average particle size reduces). During the cutting process, further disintegration takes place and the AFS number further increases (average particle size further reduces). The increase in AFS number is partly compensated for by recharging as well as by the removal of finer particles. This is expected to help to improve machining. Table 5 indicates that the AFS number increases more with the mesh size 80

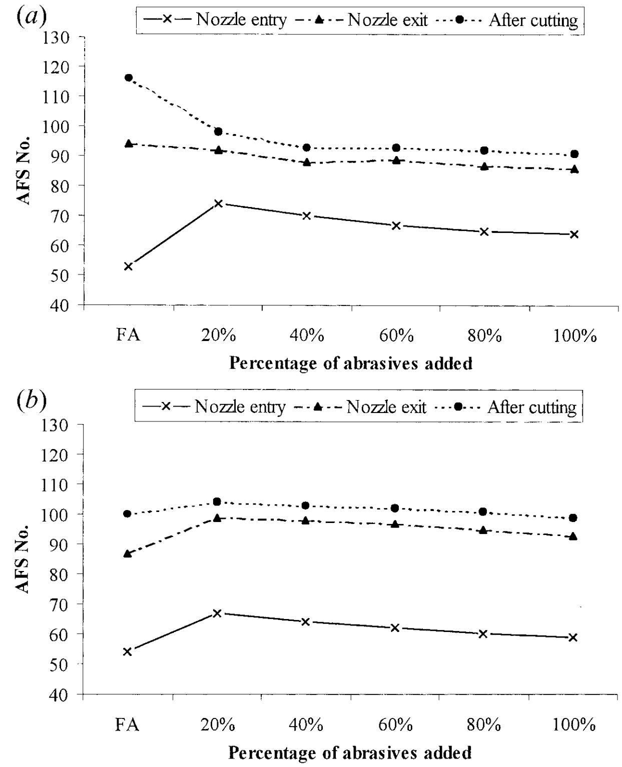

Fig. 6. The effect of recharging on AFS number of (*a*) test sample, (*b*) mesh size 80 sample with particles of more than 90 μm.

sample as compared with the test sample at the nozzle exit and after cutting. Because the test sample contains more larger particles, when the fresh abrasives are added the AFS number decreases (average particle size increases).

5.2 Depth of Cut

Figure 8 shows the effect of recharging on the depth of cut with abrasive particles of more than 90 μm, both with the test sample and the mesh size 80 sample. With an increase the in percentage of recharging, the test sample shows that the depth of cut has increased significantly by up to 40% of recharging, and marginally thereafter; whereas in the mesh size 80 sample

Table 5. Effect of recharging on AFS number and average particle size (a.p.s.) with more than 90 μm particles.

Recharging (%)	Test sample						Mesh size 80					
	AFS number			a.p.s. (mm)			AFS number			a.p.s. (mm)		
	Nozzle entry	Nozzle exit	After cutting	Nozzle entry	Nozzle exit	After cutting	Nozzle entry	Nozzle exit	After cutting	Nozzle entry	Nozzle exit	After cutting
FA	53	94	116	0.282	0.192	0.171	54	87	100	0.281	0.195	0.186
20	74	92	98	0.212	0.178	0.176	67	99	104	0.229	0.185	0.178
40	70	88	93	0.225	0.185	0.181	64	98	103	0.242	0.186	0.175
60	67	89	93	0.234	0.190	0.188	62	97	102	0.250	0.192	0.179
80	65	87	92	0.240	0.195	0.184	60	95	101	0.256	0.193	0.183
100	64	86	91	0.245	0.196	0.182	59	93	99	0.259	0.194	0.180

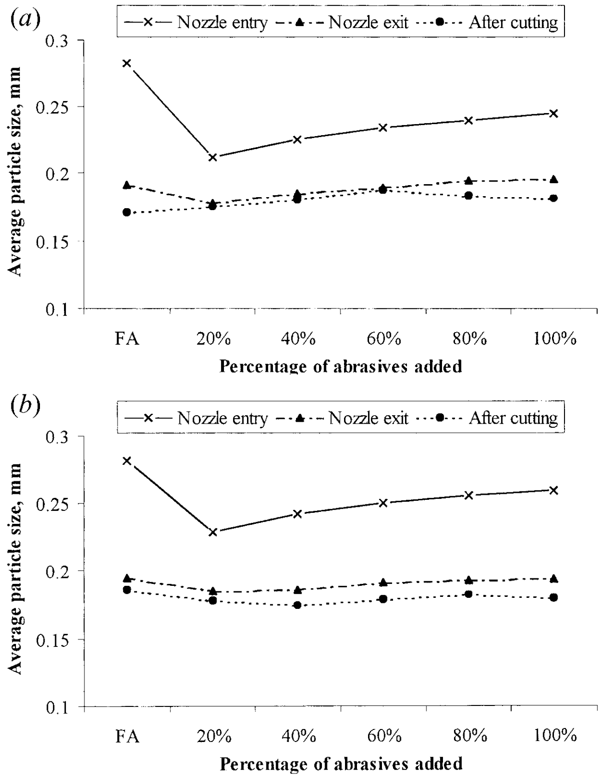

Fig. 7. The effect of recharging on average particle size of (*a*) test sample, (*b*) mesh size 80 sample with particles of more than 90 μm.

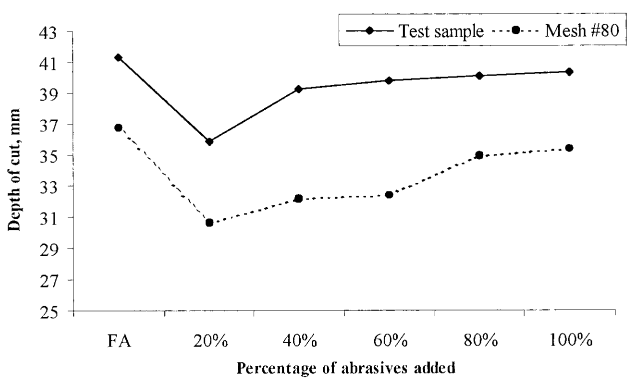

Fig. 8. The effect of recharging on depth of cut of test sample and mesh size 80 sample with particles of more than 90 μm.

the depth of cut has increased significantly up to 80% and marginally thereafter. The depth of cut achieved with the test sample as compared to the mesh size 80 sample is higher by 12%–23%. A marginal improvement in depth of cut is achieved with the removal of particles of less than 90 μm with both the test sample and the mesh size 80 sample (Fig. 3).

5.3 Kerf Widths and Kerf Taper

Figure 9(*a*) shows the influence of recharging on kw_t, kw_b, and k_t achieved with the test sample. It can be observed that the top kerf width achieved with recharged abrasives is lower than that with fresh abrasives, while the bottom kerf width increases with recharged abrasives. This is due to an increase in the AFS number of the recharged abrasives as compared to fresh abrasives. The effect of recharging is found to increase the top and bottom kerf width marginally. This may be attributed to the fact that fresh abrasives contain larger particles. It is also observed that kerf taper reduces with up to 40% recharging, and then fluctuates.

Figure 9(*b*) indicates the influence of recharging on kw_t, kw_b, and k_t achieved with the mesh size 80 sample. The top and bottom kerf width are found to be lower in size than with the test sample. The decrease in top and bottom kerf width is due to the decreased size of the average particles. The kerf taper is found to increase at every stage of recharging.

5.4 Surface Roughness

Figure 10 indicates the influence of recharging on surface roughness, *Ra*, both with the test sample and the mesh size 80 sample after screening out abrasive particles of less than 90 μm. Both samples resulted in a decreased surface roughness after the first cut. The reduction in surface roughness can be attributed to an increase in AFS number (average particle size reduces) by fragmentation. It is also observed that fresh abrasives of the test sample caused a decrease in surface roughness as compared to the mesh size 80 sample at every stage in recharging. It may, however, be pointed out that test sample yields the same level of finish with fresh abrasive as well as with recharged 100% fresh abrasives. It should be noted that the performance of the test sample is more predictable when

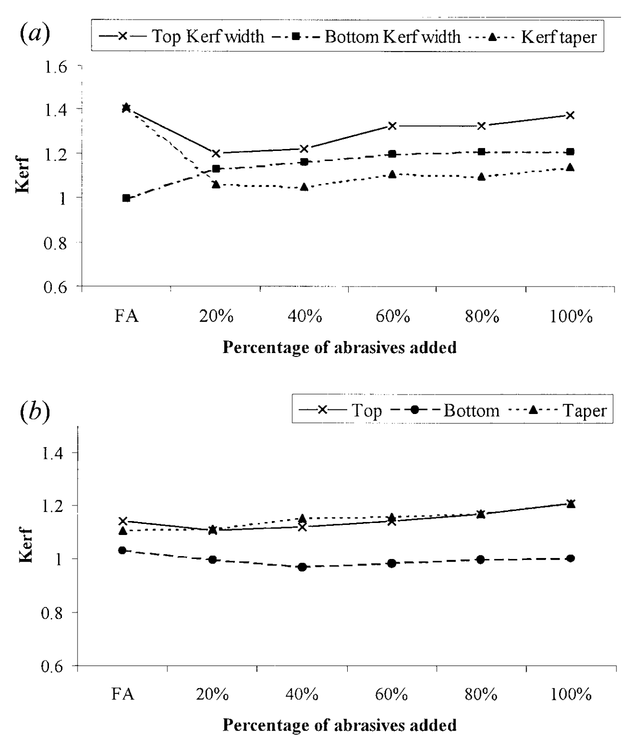

Fig. 9. The effect of recharging on kerf of (*a*) test sample, (*b*) mesh size 80 sample with particles of more than 90 μm.

the finer particles are removed. This is due to the addition of more and more fresh abrasive. A decreased surface roughness is obtained when 60% of fresh abrasives are added. Therefore, for a better surface, recharging of the test sample as well as with the mesh size 80 sample by 60% is recommended after screening out abrasive particles of less than 90 μm.

6. Conclusions

The cost of abrasives contributes significantly to the machining cost in abrasive water jet machining. Recharging of abrasives is expected to result in cost reduction. This paper reports the findings of research on garnet abrasives available in southern India. Tests conducted on Aluminium using an optimised abrasive test sample, pressure, traverse rate, and abrasive flowrate indicate the behaviour of abrasives. The results obtained with a mesh size 80 sample are compared. Our findings are as follows:

The depth of cut increases significantly with up to 40% recharging and marginally thereafter, both with test sample and mesh size 80 sample. Hence, this level of recharging is recommended.

Top and bottom kerf widths increase marginally both with test sample and with mesh size 80 sample.

Surface roughness is found to be a minimum with 60% recharging of test sample. Hence this level of recharging is recommended. While with the mesh size 80 sample, 20% recharging is recommended.

Recharging of test sample as well as of the mesh size 80 sample by 60% is recommended after screening out abrasive particles of less than 90 μm to achieve better surface roughness.

The numerical values reported are specific to the abrasives under study. The behaviour/trend, however, can be generalised to represent any garnet abrasive.

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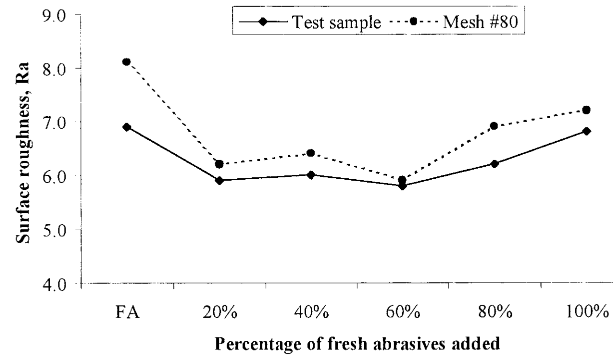

Fig. 10. The effect of recharging on surface roughness of test sample and mesh size 80 sample with particles of more than 90 μm.

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