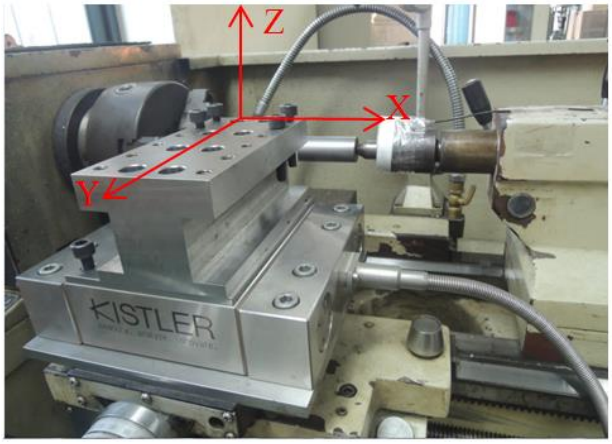
3.4 Measuring instrument

3.4.1 Surface roughness measuring instrument

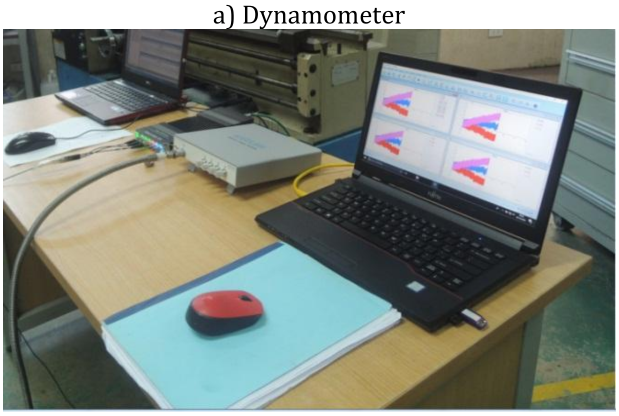
Surface roughness measuring machine SJ-301 from Mitutoyo (Japan) was used to measure the roughness of the test components (Fig. 3). Its order number, detector number and stylus tip radius are 178-953-2, 178-390 and 5 μm, respectively. Each sample had a standard length of 0.8 mm and was measured at least 3 times. The roughness value of each experiment is the average of the successive measurements.

Fig. 3. Surface roughness tester

3.4.2 Force measuring instrument



a) Dynamometer



b) The data-processing devices and computer

Fig. 4. Cutting force measuring instrument

The cutting force measuring device used in the study is a three-component dynamometer from KISTLER (Switzerland). Its model number is 9129AA. The device is capable of measuring up to 5kN for component forces in the X and Y directions and 30kN for component force in the Z direction. The dynamometer is fixed on carriage (Fig. 4). The data-processing devices were connected to the computer and they processed the results of the measurement of the component forces by the dynamometer. The value of the forces at each experiment is the average during the machining operation.

3.4.3 Determination of MRR

Material removal rate is defined as:

$$MRR = \frac{1}{60} \cdot n \cdot \pi \cdot d \cdot f \cdot t \qquad (mm^3/s) \qquad (7)$$

Where:
n is spindle speed (rev/min).
d is diameter of workpiece (mm).
f is feed rate (mm/rev).
t is depth of cut (mm).

3.5 Result and discussion

Experiment results are presented in Table 6. Pareto chart of the influence of input parameters on output parameters is shown in Figures 5 to 8.

Table 6. Result of the experiments

Trial No.	*Ra* (μm)	*Fx* (N)	*Fy* (N)	*Fz* (N)	*MRR* (mm^3/s)
1	1,344	94,749	218,941	94,964	10,790
2	0,968	184,704	307,095	85,576	45,791
3	1,030	626,367	1286.969	275,913	101,834
4	1,795	243,559	447,649	115,240	26,683
5	1,070	169,184	255,388	69,449	92,436
6	1,029	194,803	282,244	79,465	57,558
7	0,994	212,316	400,216	83,109	53,365
8	1,166	236,584	410,505	106,411	51,764
9	1,080	138,854	143,253	72.981	141,018

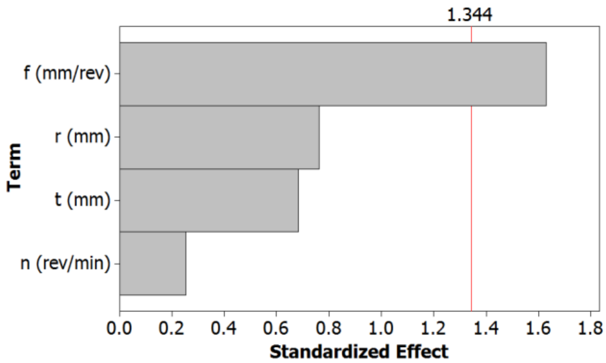


Fig. 5. Pareto chart of the influence of the input parameters on *Ra*

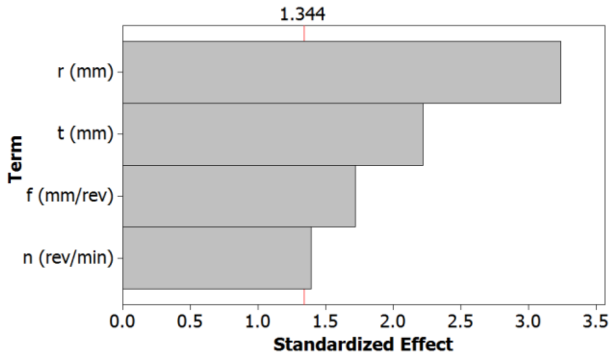


Fig. 6. Pareto chart of the influence of the input parameters on *Fx*

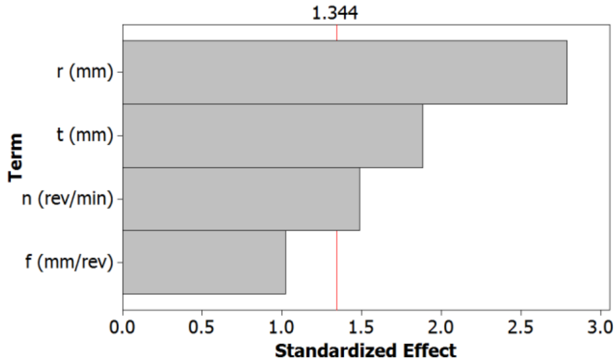


Fig. 7. Pareto chart of the influence of the input parameters on *Fy*

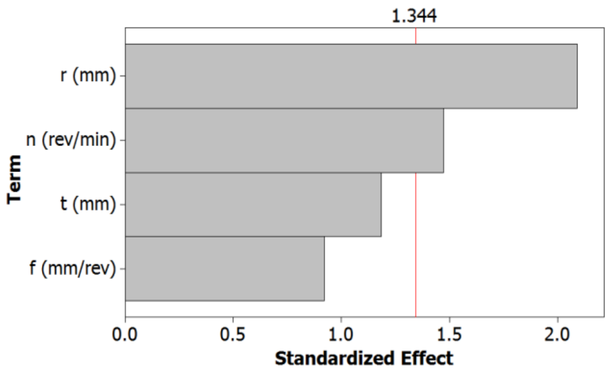


Fig. 8. Pareto chart of the influence of the input parameters on *Fz*

Figures 5 to 8 indicate that:

- The feed rate has a significant impact on surface roughness, while the other parameters are negligible to it (because the line showing their influence on surface roughness does not exceed across the red limit line in the Pareto chart). However, when considering in detail, effect of the tool nose radius on surface roughness is greater than depth of cut, while spindle speed is the parameter with the least influence.

- All four input parameters have a significant impact on the X-direction component force and the degree of influence decreases in order of tool nose radius, depth of cut, feed rate and spindle speed.

- Regarding component force *Fy*, the tool nose radius is the most influential, followed by depth of cut, spindle speed and feed rate is negligible to it.

- The tool nose radius and spindle speed both considerably affect the component force in the z direction, on which the impact of the tool tip radius is greater than the spindle speed. The other two parameters are not noticeable to *Fz*.
Since MRR is calculated based on (7), it is clear that all parameters of the spindle speed, feed rate and depth of cut influence on the MRR. Increasing the value of these parameters increases the MRR.

Analyses above show that the effects of the input parameters on the output parameters are not the same. For example, the tool nose radius is significant to all three component cutting forces but unimportant to surface roughness, while the feed rate has the greatest impact on surface roughness. The spindle speed is a parameter that negligibly affects surface roughness but greatly influences all three of component cutting forces, etc. The data in Table 6 reveals that the surface roughness are minimum at trial No.2; the component forces *Fx, Fy, Fz* have the smallest value in trial No.1, No.9 and No.5 respectively; the MRR reaches the highest value in trial No.9. Therefore, in order to identify the desired cutting parameters for achieving the "minimum" of surface roughness and cutting forces and the "maximum" of MRR, it is necessary to solve the multi-objective optimization problem, in which the spindle speed, the feed rate, the depth of the cut and the tool nose radius are parameters to be defined.

3.6 Multi-objective optimization of turning operation using Dear method

Based on the results in Table 6, the weights of the responses and the MRPI values in each experiment were defined by formula from (1) to (6), as presented in Table 7.

Table 7. Weights of the responses and the MRPI values in each experiment

Trial No.	Weight					MRPI
	Ra	*Fx*	*Fy*	*Fz*	*MRR*	
1	0.12829	0.04509	0.05835	0.09660	0.39412	30.64574
2	0.09240	0.08791	0.08184	0.08705	0.09287	53.16138
3	0.09832	0.29811	0.34299	0.28065	0.04176	709.9278
4	0.17134	0.11592	0.11930	0.11722	0.15937	99.70661
5	0.10214	0.08052	0.06806	0.07064	0.04601	40.27302
6	0.09822	0.09271	0.07522	0.08083	0.07388	50.06805
7	0.09488	0.10105	0.10666	0.08454	0.07969	75.51397
8	0.11130	0.11260	0.10940	0.10824	0.08215	87.44938
9	0.10309	0.06609	0.03818	0.07423	0.03016	24.42696

MRPIs of the initial cutting parameters were determined. They are the summation of MRPI of each parameter at the respective levels, shown in Table 8.

Table 8. Summation of MRPI at each level of cutting parameters

Par.	Levels			Max-Min
	1	2	3	
n	793.7349	190.0477	187.3903	606.3446
f	205.8663	180.8838	784.4228	603.5390
t	168.1632	177.2949	825.7148	657.5517
r	95.34572	178.7434	897.0838	801.7381

The data in Table 8 show that the MRPI of spindle speed, feed rate, depth of cut and tool nose radius are minimum at level 3, 2, 1, 1 respectively. In the DEAR method, the value of input parameter corresponding to the minimum *MRPI* is the most optimal [25, 28]. Thus, the optimal input parameters include *n* (910 rev/min), *f* (0.194 mm/rev), *t* (0.2 mm) and *r* (0.2 mm). The greatest "Max – Min" value of MRPI is 801.7381, which is also the tool nose radius. Furthermore, the input parameters corresponding to the maximum of "Max-Min" of *MRPI* have the greatest influence on the efficiency of the entire turning process [25, 28]. Thus, when assessing the turning process by considering surface roughness, cutting force in three directions (X, Y, Z) and *MRR*, the tool nose radius is found to be the most influential parameter, followed by depth of cut and spindle speed. The feed rate affects the turning operation least.

3.7 Experiments using the optimal cutting parameters

The above optimal values of the input parameters are used for the turning process (910 rev/min of *n*, 0.194 mm/rev of *f* , 0.2 mm of *t* and 0.2 mm of *r*). Surface roughness and component cutting forces are measured in each test, *MRR* is also defined in each case. The result is presented in table 9.

Table 9. Output parameters with optimum values of input parameters

Trial No.	Ra (μm)	Fx (N)	Fy (N)	Fz (N)	MRR (mm^3/s)
1	0.985	114.522	162.852	80.772	51.764
2	1.022	113.560	160.288	82.288	51.764
3	0.981	109.922	159.386	78.776	51.764
Mean	0.996	112.668	160.842	80.612	51.764

The comparison of data between table 9 and table 6 shows that the value of the output parameters is significantly improved when the optimal of the input parameters is applied.

4. CONCLUSION

In this study, experiments of turning AISI 1055 steel with a titanium coated cutting tool are performed. In each test, surface roughness and three component cutting forces are measured and *MRR* is identified. The combination of the Taguchi and DEAR method determines the value of the input parameters for reaching the "minimum" of surface roughness and component cutting forces and the "maximum" of MRR. Some conclusions are drawn as follows:

- The feed rate is the parameter that has a significant impact on the surface roughness, while the spindle speed, depth of cut and tool nose radius have negligible effects on it.

- All four of the input parameters are considerable to *Fx*, in which the tool nose radius is the most influential, followed by the depth of cut and the feed rate. The least is the spindle speed.

- The tool nose radius greatly impacts on *Fy*, followed by depth of cut and the spindle speed. Meanwhile, the feed rate has a limited influence on *Fy*.

- Regarding *Fz*, the tool nose radius has the greatest effect on it, followed by the spindle speed. The depth of cut and feed rate are inconsiderable to *Fz*.

- The optimal cutting parameters include spindle speed *n* (910 rev/min), feed rate *f* (0.194 mm/rev), depth of cut *t* (0.2 mm) and tool nose radius *r* (0.2 mm).

- Among these four parameters, the tool nose radius is the most influential parameter in the turning process (considering the output factors, including surface roughness, three component cutting forces and *MRR*).

- When machining with the optimum parameters, the output is significantly improved.

- Apparently, the algorithms of the DEAR method are successfully applied for multi-objective optimization of not only turning operation in this study, but also other machining processes.

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