Analysis of Wire EDM machining parameters on machining of Silicon material

[1]Raminder Singh, [2]Anish Kumar

[1]Department of Mechanical Engineering, Mullana College of engineering, Maharishi Markandeshwar (deemed to be University) Mullana- Ambala-133207

[2]Department of Mechanical Engineering, Mullana College of engineering, Maharishi Markandeshwar (deemed to be University), Mullana-Ambala 133207

Abstract: **The photovoltaic industry requires the cutting of Silicon ingots into wafers to facilitate the manufacturing of silicon with view to achieve higher productivity.. In this study the wire electric discharge machining process(WEDM) was[i]selected for machining of Polycrystalline silicon to study the effect of various input parameters like Pulse ON time, Pulse OFF time, peak current, wire feed, wire tension, spark gap voltage and water pressure on cutting rate, surface finish and kerf width. The experimental results showed that pulse on time, pulse off time, spark gap voltage, wire feed and water pressure have significant effect on cutting rate, surface finish and kerf width. The other machining parameters like wire tension and peak current did not have large effect on machining process. The experiments performed demonstrated that WEDM process can be applied to produce silicon wafers from polycrystalline silicon ingots. Hence the application of WEDM process to the manufacture of solar cells can bring significant enhancement in production efficiency of solar cells.**

Keywords: **photovoltaic industry, WEDM, silicon, solar cells.**

1. INTRODUCTION

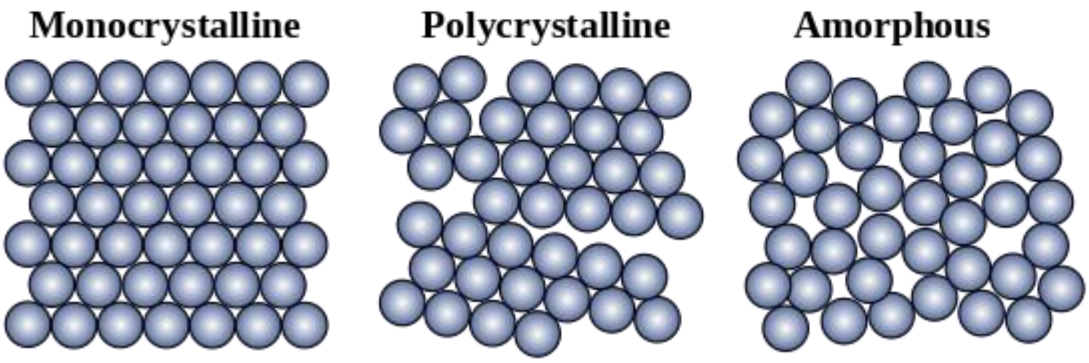

Fig 1: Schematic Polycrystalline grain structure

The silicon wafers are widely used in the manufacture of solar cells and microchip applications. So the photovoltaic industry requires the slicing of large diameter silicon ingots into ultra thin wafers at minimum kerf loss. At present inner diameter saw(ID) and abrasive wire saw methods were used for silicon ingot slicing but both these methods had limitations such as high kerf loss(35-40%) and lower thickness of sliced silicon wafers(250-350µm),(Barron,2010;Green, 2000 ;Kao et al1997 ;Peng and Liao,2003). The silicon wafers processed by above method showed greater kerf loss and to reduce this, the thickness of wafer was to be decreased. But the existent methods of silicon wafers involved greater tension in wire used so more effort was needed in developing new machining methods. WEDM method has been employed for machining of Polycrystalline silicon and this removes material using heat generated by electrodes made of conductive metal wires. The process involves non contact machining and hence can cut materials without residual stress as the work piece being machined bears no cutting pressure. This makes WEDM the best method for precision machining for ultra hard and complex work pieces. Lee et al (2009) studied WEDM process and found that pulse on time and open circuit voltage had great influence on cutting speed, machining groove width and surface roughness of work piece . Yeh et al (2013) studied the effect of various machining parameters on machining of polycrystalline silicon with resistivity (2-3Ω) and concluded that voltage was critical parameter to break insulation of Poly silicon material wherein pulse on time affected the cutting speed as per Sreejith et al (2001). The wire electric discharge machining process used Zn coated brass wire as electrode because it gives higher material removal rate as per Suresh et al (2017)

2. EXPERIMENTAL SETUP AND PROCEDURE

The Polycrystalline silicon material is machined by WEDM to produce silicon ingots used in photo voltaic industry. In the present work the experiment was performed on CNC wire cutting machine of Electronic Machine Tools Ltd. (India). The machine with distilled water as dielectric was used for silicon slicing experiments. A 0.25mm diameter zinc coated brass wire was used as tool electrode(cathode) and a 5 inch square polycrystalline silicon ingot with resistivity of 0.5Ω was used as the work piece. The polycrystalline silicon ingot plate 150x150x10 mm size has been used as work piece material for present experiments. In order to identify the process parameters that may affect the machining characteristics of WEDM machined parts pilot study was done considering factors pulse on time, pulse off time, spark gap voltage, peak current, wire feed, wire tension and flushing pressure . The experimentation was done using one factor at a time approach, the one factor of machine varies keeping all factors constant. The purpose of these experiments is to study the variations of the WEDM process parameters on response variables such as cutting rate, kerf width and surface roughness. The experiments were conducted using CNC wire cutting machine of Electronica Machine Tools Ltd. (India). The machine with distilled water as a dielectric was used for the silicon slicing experiments. A 0.25 mm diameter zinc coated brass wire was used as the tool electrode (cathode) and a 5-inch square polycrystalline silicon ingot with a resistivity of 0.5Ω-cm was used as the workpiece. Figure 2 shows a picture of the experimental setup

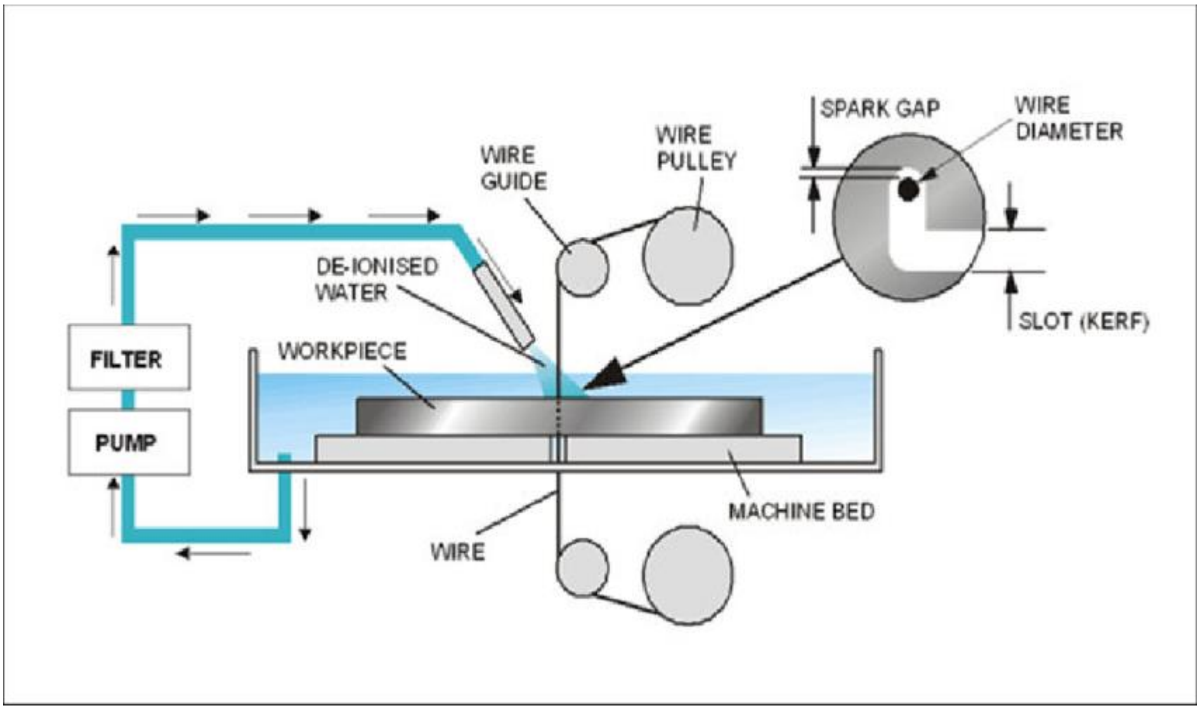

Fig 2: Experimental setup for WEDM process

The experiments were conducted using CNC wire cutting machine of Electronica Machine Tools Ltd. (India). The machine with distilled water as a dielectric was used for the silicon slicing experiments. A 0.25 mm diameter zinc coated brass wire was used as the tool electrode (cathode) and a 5-inch square polycrystalline silicon ingot with a resistivity of 0.5Ω-cm was used as the workpiece. Figure 1 shows a picture of the experimental setup

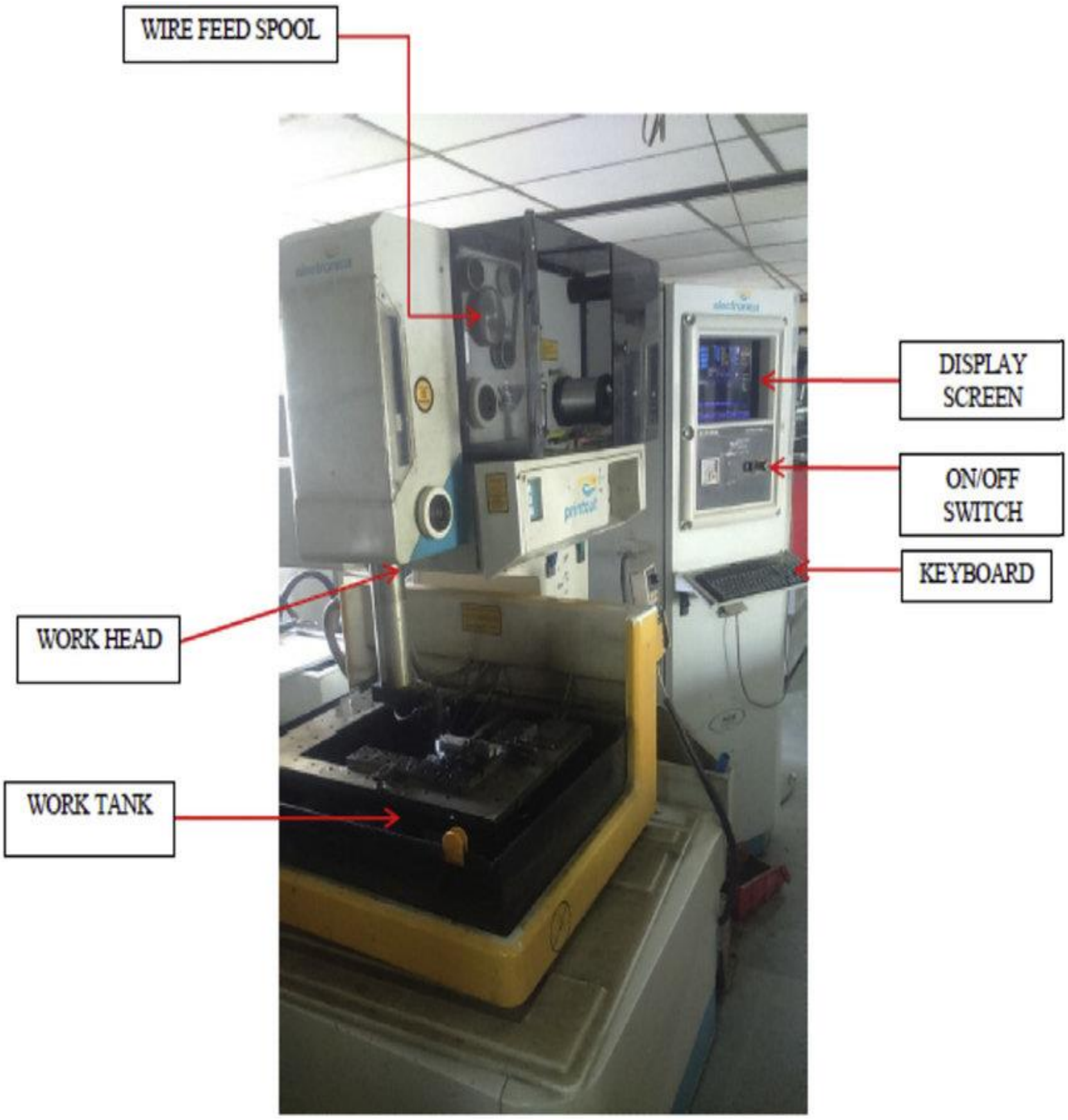

Fig 3: WEDM machine tool

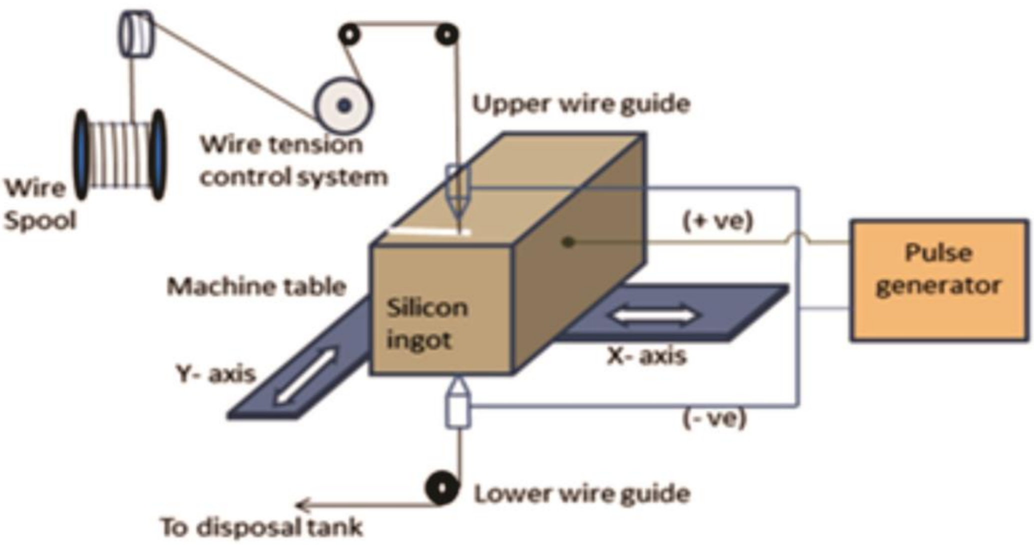

Fig 4(a) Schematic diagram of experimental apparatus

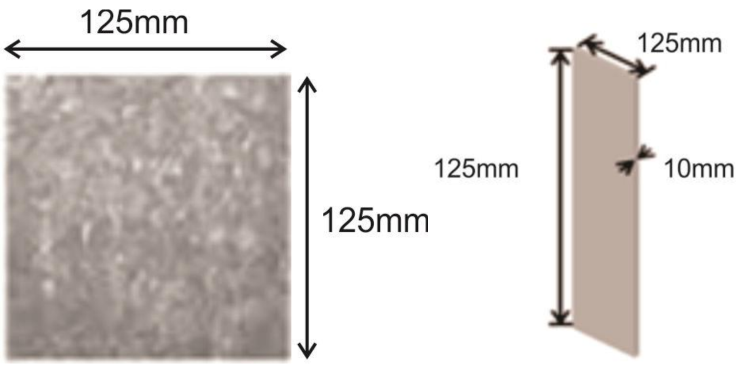

Fig 4(b) Fig 4(c) 125mmsquare polycrystalline silicon ingot

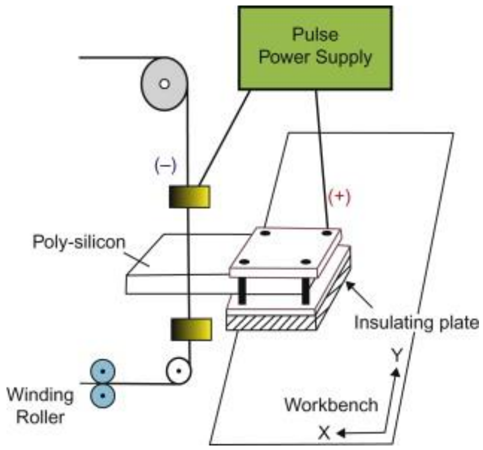

Fig 4(d) Schematic diagram of experimental apparatus

The range of parameters selected are given in table below

Table 1

S No.	Name of Parameter	Symbol	Range
1	**Pulse on time**	T_{ON}	**110-130μs**
2	**Pulse off time**	T_{OFF}	**45-55μs**
3	**Peak current**	**Ip**	**20-60A**

3. RESULTS AND DISCUSSIONS

1. Effect of pulse on time on cutting speed and Kerf width

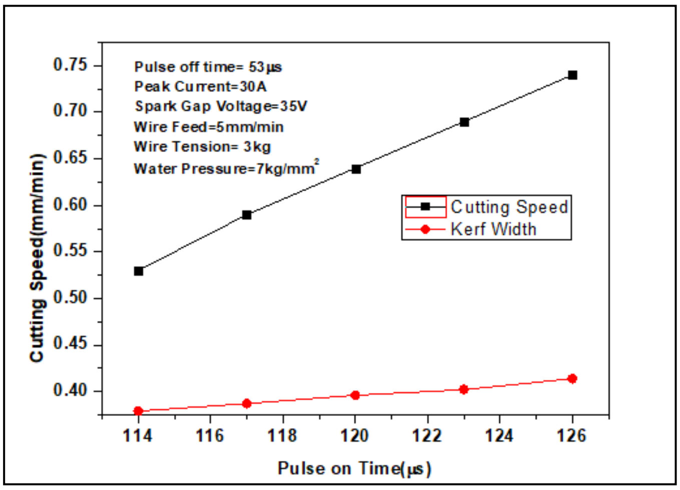

Fig 5: Pulse on time Vs Cutting Speed and Kerf Width

The experimentalresults show with increase in pulse on time (114-126µs) the cutting speed increases from (0.53-0.74mm/min) Basically pulse on time is the duration of time(µs)the current is allowed to flow per cycle and with higher values of pulse on time greater energy is applied and hence higher the material removal process causing higher cutting speed. But with longer periods of spark duration the resulting craters will be broader and deeper and therefore surface finish will be rough so short spark duration helps to achieve fine surface finish. Moreover it is observed that cutting speed is directly proportional to energy applied which is controlled by peak current and pulse on time. It was not possible to perform cutting beyond T_{ON}>130 because of the frequent wire breakage.

2. Effect of pulse off time on cutting speed and kerf width

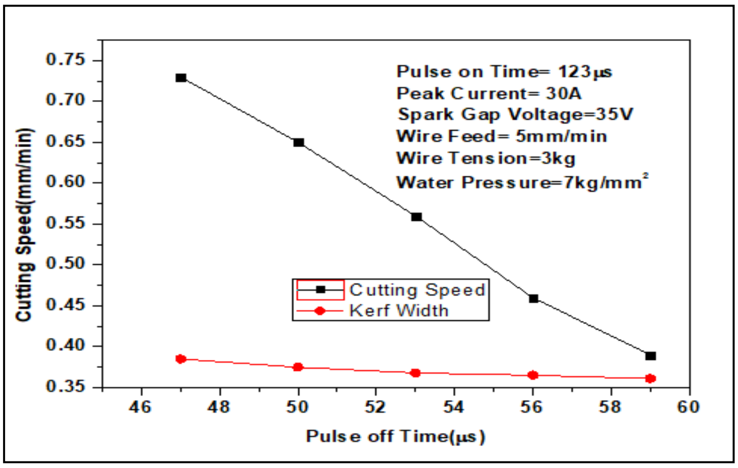

Fig 6: Pulse off time Vs Cutting Speed and Kerf Width

The experimental results show that with lower values of pulse off time(59-47µs) there is increase in cutting speed. Basically the pulse off time is the duration of time between two successive sparks when the discharge is turned off thus it is the duration of the rest pauses required for the reionization of the dielectric and this time allows the molten material to solidify and washed out of the gap. With lower values of pulse off time the number of discharges within given period become more and this results in higher cutting speed but the surface accuracy becomes poor with large number of discharges. on the other hand when the off time is insufficient as compared pulse on time it will cause erratic cycling and retraction of advancing servo motors thus slowing down the operation. The pulse off time must be low for having high cutting speed but insufficient pulse off time can lead to inefficient flushing and does not provide enough time for dielectric to recover its strength . The experimental results have showed that machining beyond this range can lead to wire breakage using very low T_{OFF} values i.e. below 58µs can causes wire breakage.

3. Effect of peak current on cutting speed and kerf width

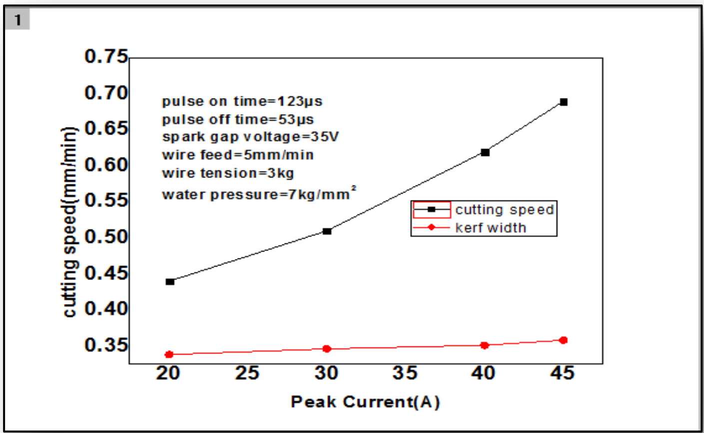

Fig 7: Peak current Vs Cutting Speed and Kerf Width

The experimental results show that with higher values of peak current (20-45A) the cutting speed initially increases. This is because higher values of peak current leads to increase in discharge energy across the electrode resulting in high melting and evaporation of material thus leading to higher cutting speed. Moreover with increase in peak current the impulsive force in spark gap also increases resulting in higher cutting speed. It is also observed that with higher values of peak current(Ip>45) the wire breaks because that higher the value of peak current greater is the discharge energy associated with machining process.

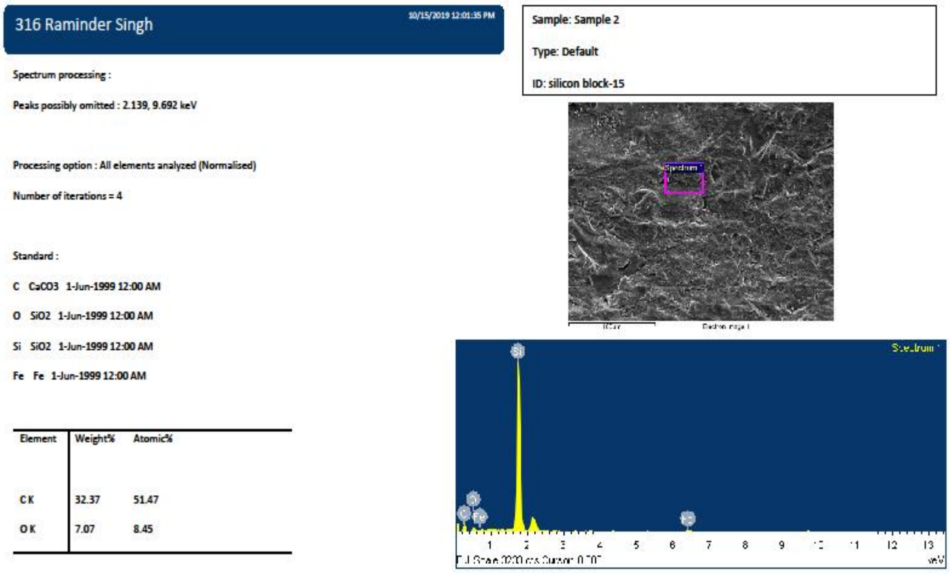

Fig 8: SEM & EDX view of sample for Pilot study

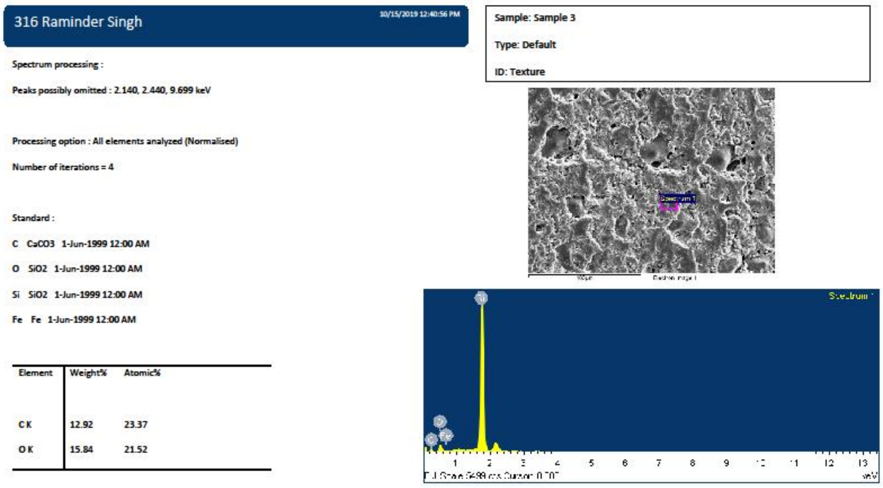

Fig 9: SEM EDX view of sample for Pilot study

4. CONCLUSIONS

This study discusses the influence of WEDM parameters on the machining of Polycrystalline silicon material. The conclusions are as follows

1. The cutting speed increases with the increase in pulse on time. With increase in pulse on time the energy supplied also increases so more particles will strike to the work piece and thus the particles penetrate more deeply due to increase in energy as a result the thick recast layer will be observed.

2. The cutting speed decrease with increase in spark gap voltage however it should be noted that the spark gap voltage which actually prevails during sparking is different from the set voltage. The instantaneous gap voltage measurement facility is available on the machine and should be noted that the voltage applied between anode and cathode determines the total energy of the spark and with high voltage can cause poor surface finish and can also cause wire breakage. Before current can flow, the open gap voltage increases until it has created an ionization path through the dielectric Once the current starts to flow the voltage drops until it stabilizes at the working gap level. The preset voltage determines the width of the spark gap between the leading edge of the electrode and workpiece. High voltage settings increase the gap, which improves the flushing conditions and helps to stabilize the cut.

3. The cutting speed increases with increase in wire feed because the new electrode wire comes in contact rapidly with work piece and there is higher penetration of electrode wire in material . Though low wire speed tends to cause breakage of the wire. But with increase in wire feed, the consumption of the wire increases and hence the machining rate also increases.

4. The increase in dielectric water pressure improves the cutting speed because higher value of dielectric fluid pressure results in greater distribution of dielectric fluid in the spark gap so removal of gaseous and solid debris becomes fast and easy. Moreover it also helps to maintain dielectric temperature below the flash point.

5. The cutting speed increases with increase in peak current because there is increase in discharge energy which is caused due to higher peak current that will result in increase in heat density. Higher value of heat density will result in high cutting speed due to greater erosion and melting of material but at higher values of peak current the electrode wire breaks.

REFERENCES

[1] Moller,H. J. Funke, c; Rimo M.; Scholz, S. Multicrystalline silicon for solar cells,thin solid films 2005, 487(1-2) 179-187

[2] Moller,H. J. Wferin of Silicon crystals physics status solids A-application and material Science 2006 203(4),659-669

[3] Kung K. Y.; Chiang K. T. Modelling and analysis of machinability evaluation in Wire electric discharge machining(WEDM) process of Aluminium oxide based ceramic Material and manufacturing process 2008 23 (3-4) 241-250

[4] Luo Y. F. ; Chen C. G. ; Tong Z. F. Investigation of silicon wafering by wire EDM. Journal of material science 1992, 27(2) 5805-5810

[5] Green M. A. ; Photovoltaic technology overview. Energy policy, 2000 ; 28, 989-998

[6] Suresh T. ; Avinash P. ; Guraserkha S. Comparison of brass and Zn coated wire electrode using wire cut EDM concerning MMR of machining SS304 International journal of innovative Research in science and Engineering technology, Vol. 6, Issue 3, Mar(2017)

[7] Peng, W. Y., Liao, Y. S., Study of electrical discharge machining technology for slicing silicon ingots Journal of Materials Processing Technology 2003,140 274-279

[8] Dongre, G.G.; Vesvikar, C.; Singh, R.K.; Joshi, S.S. (2010) Efficient dicing of silicon ingots for photovoltaic applications. 35th IEEE Photovoltaic Specialists Conference (PVSC), 20–25 June 2010, Hawaii.

[9] Green, M.A. (2000) Photovoltaics: Technology overview. Energy Policy, 28: 989–998.

[10] Green, M.A. (2001) Crystalline Silicon Solar Cells. In Clean Electricity from Photovoltaics;

[11] Archer, M. D.; Hill, R., Eds., World Scientific, London. Kao, I.; Prasad, V.; Li, J.; Bhagvat, M. (1997) Wafer slicing and wire saw manufacturing technology. In NSF Grantees Conference, pages 239–240, Seattle, Washington, USA, January 7–11, 1997.

[12] Kunieda, M.; Lauwers, B.; Rajurkar, K.P.; Schumacher, B.M. (2005) Advancing EDM through fundamental insight into the process. CIRP Annals-Manufacturing Technology, 54(2): 64–87.

[13] Lee, J.; Lakshminarayan, N.; Dhungel, S.; Kim, K.; Yi, J. (2009) Optimization of fabrication process of high-efficiency and low-cost crystalline silicon solar cell for industrial applications. Solar Energy Materials & Solar Cells, 93: 256–261.

[14] Liao, Y.S.; Yu, Y.P. (2004) Study of specific discharge energy in WEDM and its application. International Journal of Machine Tools & Manufacture, 44: 1373–1380. Luo, Y.F.;

[15] Chen, C.G.; Tong, Z.F. (1992) Investigation of silicon wafering by wire EDM. Journal of Materials Science, 27: 5805–5810.

[16] US Patent No. 8,138,442. (2012) Wire electrical discharge machining method, semiconductor method, and solar battery cell manufacturing method, by Sato et al., assignee: Mitsubishi Electrical Corporation, March 2012.

[17] Montgomery, D.C. (2009) Design and Analysis of Experiments (Third ed.). Wiley, New York.

[18] Peng, W.Y.; Liao, Y.S. (2003) Study of electrical discharge machining technology for slicing silicon ingots. Journal of Materials Processing Technology, 140: 274–279.

[19] Puri, A.B.; Bhattacharyya, B. (2003) Modelling and analysis of the wire-tool vibration in wire-cut EDM. Journal of Materials Processing Technology, 141: 295–301

[20] Son, S.; Lim, H.; Kumar, A.S.; Rahman, M. (2007) Influences of pulsed power condition on the machining properties in micro EDM. Journal of Materials Processing Technology, 190: 73–76

[21] . Takino, H.; Ichinohe, T.; Tanimoto, K.; Yamaguchi, S.; Nomuraa, K.; Kunieda, M. (2004) Cutting of polished single-crystal silicon by wire electrical discharge machining. Precision Engineering, 28: 314–319.

[22] Takino, H.; Ichinohe, T.; Tanimoto, K.; Yamaguchi, S.; Nomuraa, K.; Kunieda, M. (2005) High-quality cutting of polished single-crystal silicon by wire electrical µdischarge machining. Precision Engineering, 29: 423–430.

[23] Uno, Y.; Okada, A.; Okamoto, Y.; Hirano, T. (2000) High performance slicing method of mono crystalline silicon ingot by wire-EDM. In Proceedings of the 2000 APSE Annual Meeting, 22: 172–175.

[24] Sreejith P. S.; Udupa G., Ngoi B. K. (2001), Recent advances in machining of silicon wafers for semiconductor applications [J] International Journal of advance Manufacturing Technology , 17: 157-162

[25] Takion H., Ichinohe T., Tanimoto, K., (2007) Contouring of polished single crystal silicon plates by wire Electrical discharge Machining. Precision engineering, 31(4), 358-363

[26] Rakwal et al.(2009) research was done on slicing of germanium wafers from single crystal wire using saws method to produce wafers of thickness 350µm with the use of 75µm and 100µm Molybdenum wire to examine surface profile and texture and it was concluded that wastage of material was minimum when WEDM was used in combination with thin wire diameters.

[27] Lee et al. (2009) the machining of Poly Silicon semiconductor material was done using wire electrical discharge machining and it was found that pulse on time and open circuit voltage had great effect on cutting speed, machining groove width and surface roughness of the work piece.

[28] Yu P. H., Lee H. K., Lin Y. X., (2011) Machining characteristics of Polycrystalline silicon by wire electrical Discharge machining [J] Journal of materials and man, 26: 1443-1450

[29] Zhidong et al.(2012) research was done to study the damage caused polycrystalline silicon and concluded that there were four kinds of damage forms of damaged layer surface of monocrystalline silicon during the machining process using wire electrical discharge machining.

[30] Yeh et al.(2013) wire electric discharge machining (WEDM) of polycrystalline silicon was done with use of to dielectrics and concluded that phosphorus dielectric with addition of water and sodium pyrophosphate increased working efficiency and infiltration of phosphorus element on the surface.

[31] Huijun et al.(2013) studied the reasons and mechanism for existence of small holes on monocrystalline surface during cutting by wire electric discharge machining and found that the small holes caused the surface to heat up resulting in thermal stress and crack propagation.

[32] Punturat et al.(2014) studied the influence of major process parameters on the cut surface characteristics and damage caused during machining of silicon using density and small duty cycles caused poor surface quality and the comparison of EDM parameters and cut surface technology can affect damage free processing of semiconductors materials.

[33] Ding et al.(2015)studied the process of multi cutting technology used by wire electric discharge machining to cut semi conductor monocrystalline silicon with specific crystal orientations and concluded that multi cutting technology by WEDM can improve the surface quality of silicon with few cracks and low deterioration of layer thicknes.

[34] Mai et al.(2015)studied the concept of new wire electrode method to machine polycrystalline silicon ingots into wafers at higher machining rate while slicing across large areas and avoiding kerf loss during machining and this improved method was used for machining of 150mm square ingot at machining rate of 343mm^2/minute.