INVESTIGATION OF DEBRIS PARTICLES DISTRIBUTION IN ELECTRICAL DISCHARGE MACHINING OF MICRO-HOLES ARRAY

B. C. XIE[a,b,*], J. G. LIU[a,b], H. X. CUI[a,b]
[a]*Key Laboratory of Advanced Manufacturing and Intelligent Technology, Ministry of Education, China*
[b]*College of Mechanical Power Engineering, Harbin University of Science and Technology, Harbin, China*

Micro-holes array and micro-electrodes array are widely used in biomedical industry, aerospace industry and micro-electromechanical systems. The machining of micro-holes array is a difficult problem for traditional machining technology. Currently electrical discharge machining technology (EDM) is an alternative machining technology for the fabricating of micro-holes array in high strength and hardness of metal material because of it is free from mechanical force. However, distribution and concentration of debris particles in the discharge gap easily leads to the intensive distribution of discharge positions, which significantly influences machining performance of EDM of micro-holes array. In this study, a three-dimensional flow field simulation model of ultrasonic assisted EDM of micro-holes array is proposed by FLUENT software. The effect of ultrasonic vibration and the depth-to-diameter ratio on debris particles distribution in ultrasonic assisted EDM of micro-holes array will be investigated by numerical simulation. It is shown that reducing the depth-diameter ratio and increasing the ultrasonic amplitude and frequency are beneficial to enhance the exhaustion of debris particles out of the discharge gap and decrease the concentration of debris particles in the discharge gap. In addition, machining experiments are carried out.

(Received September 17, 2019; Accepted January 11, 2020)

Keywords: Micro-holes array, Micro-electrodes array, Ultrasonic assisted EDM, Numerical simulation

1. Introduction

Micro-electrodes array and micro-holes array are widely used in biomedical industry, aerospace industry and micro-electromechanical systems. For example, micro-electrodes array are always used in brain-computer interface technology to receive signals, apply electrical stimulation to biological tissues and organs, and the aero-engine turbofan blade film holes array are applied as cooling holes [1-4]. Compared with traditional machining technology, electrical discharge machining (EDM) technology as a contactless machining technology has the advantages in machining micron scale structure in high strength and hardness of metal material because it is free

[*]Corresponding author: xiebaocheng@hrbust.edu.cn

from mechanical force. Therefore, EDM has replaced traditional machining technology as the preferred machining method of fabricating micro-electrodes array and micro-holes array [5-8].

In EDM of micro-holes array and micro-electrodes array, debris particles accumulated in the discharge gap easily give rise to the unstable discharge state and intensive distribution of discharge positions, which significantly influences machining performance of EDM. In order to improve machining performance of EDM, ultrasonic vibration assisted EDM of micro-holes array has been proposed by utilizing the cavitation and erosion effect of ultrasonic vibration [9-10]. However, ultrasonic assisted EDM is a complicated process which involves the distribution of flow field and debris particles. It is difficult to understand the transport process of debris particles in the gap flow field by experiment. To solve this problem, a lot of research has been done by computer fluid dynamics. Serkan CETIN et al. [11] analyzed the movement of debris particles in the gap flow field by numerical simulation. Zeng et al. [12] fabricated electrodes array and circular holes array by micro-WEDM and EDM. Albert et al [13] found that the ultrasonic assisted EDM had higher material removal rate. Bai et al. [14] studied the effect of electrode loss on the uniformity of the diameter of micro-spraying holes array by experiments. Chu et al [15] investigated the influence of tool jump on the concentration of debris particles and the discharge state between discharge gap electrodes. Although a lot of research has been done, the influence of ultrasonic vibration on movement and distribution of debris particles in ultrasonic assisted EDM should be further investigated.

In this study, a three-dimensional flow field simulation model of ultrasonic assisted EDM of micro-holes array is proposed. The influence of ultrasonic vibration on movement and distribution of debris particles in ultrasonic assisted EDM process will be investigated by computer fluid dynamics. In addition, machining experiments are carried out.

2. Experimental section

The machining experiment was carried out with RC power supply on micro-EDM machine tool developed by the Harbin University of Technology. The workpiece is contacted with ultrasonic generator. The vibration frequency of the ultrasonic generator is set to 20 kHz and the ultrasonic amplitude is 2 μm. The tool electrode is 3×3 tungsten electrodes array fabricated by reverse EDM. The workpiece is a tool steel. The experimental parameters are shown in Table 1. The SEM photo of micro-electrodes array and micro-holes array is shown in Fig.1. It is shown in the Fig. 1 that an average diameter of micro-holes array is 34μm.

Table 1. Experimental parameters.

Process parameters	Set value
Tool electrode	3×3 tungsten electrode array
Workpiece	Tool steel
Capacitance	47
Working medium	kerosene
Voltage of open circuit (U/V)	40

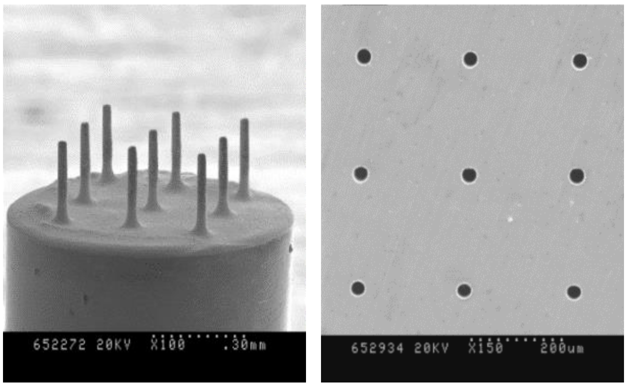

Fig. 1. SEM photo of micro-electrodes array and micro-holes array.

3. Three-dimensional flow field simulation model

Three-dimensional flow field simulation model of ultrasonic assisted EDM of micro-holes array is proposed by FLUENT software, as shown in Fig. 2. The model is meshed by tetrahedral mesh, and the discharge gap is refined to improve computational accuracy. In EDM process, part of tool electrode and workpiece are immersed in working fluid. Therefore, the VOF model is dealt with the two-phase flow problem of kerosene and air. The outlet pressure is the standard atmospheric pressure because of the upper boundary of the working fluid contacts air.

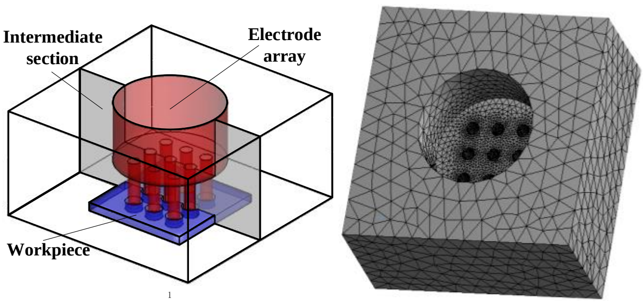

Fig. 2. Schematic diagram of EDM of micro-holes array.

Table 2. Parameters of discrete phase model.

Name of parameter	Value of parameter
Solving parameters of discrete phase	Coupled calculation, the maximum iteration step is 50000
Property of solid particle	Density: 7850kg/m^3, shape: spherical, diameter: 0.5um
Type of incident	Surface, each grid injects a particle at each step
Initial velocity and distribution	Initial velocity: 0, initial distribution: UDF
The step length of the incident time (t/s)	0.000001s
Incident time (t/s)	(3T/8+nT , 5T/8+nT), n=0,1,2….
Boundary Conditions of Wall (Electrodes)	Reflection, Collision Coefficient: Polynomial
Boundary Conditions of Wall (Workpiece)	Reflection, Collision Coefficient: Polynomial
Boundary Conditions for Exports	Escape

Dynamic Mesh Model is used to simulate the rapid vibration of tool electrodes and grid motion during ultrasonic vibration. User Defined Function is used to define the amplitude, frequency, the motion speed of ultrasonic vibration and starting and ending boundaries. In order to conveniently observe the EDM process of debris particles in EDM gap under the ultrasonic vibration of electrodes array, Discrete Phase Model in FLUENT was used to simulate the debris particles in the discharge gap. The parameter setting of discrete phase model is shown in Table 2.

4. Results and analysis of flow field simulation

In ultrasonic assisted EDM of micro-holes array, depth-to-diameter ratio, ultrasonic amplitude and ultrasonic frequency greatly affect movement and distribution of debris particles in discharge gap. Therefore, flow field of ultrasonic assisted EDM of micro-holes array (3×3) is conducted by FLUENT software. The influences of depth-to-diameter ratio, ultrasonic amplitude and ultrasonic frequency on debris particles distribution in the discharge gap are investigated by numerical simulation.

4.1. Effect of depth-to-diameter ratio on debris particles distribution

The influences of depth-to-diameter ratio on debris particles distribution in discharge gap are investigated through flow field simulation. The ultrasonic frequency of ultrasonic vibration is set at 40 KHz, the ultrasonic amplitude is set at 8 μm, and the depth-to-diameter ratio is set at 0.5, 1 and 2, respectively. After 36 cycles of ultrasonic vibration, the debris particles distribution of micro-holes array in ultrasonic assisted EDM process are simulated numerically, as shown in Fig. 3.

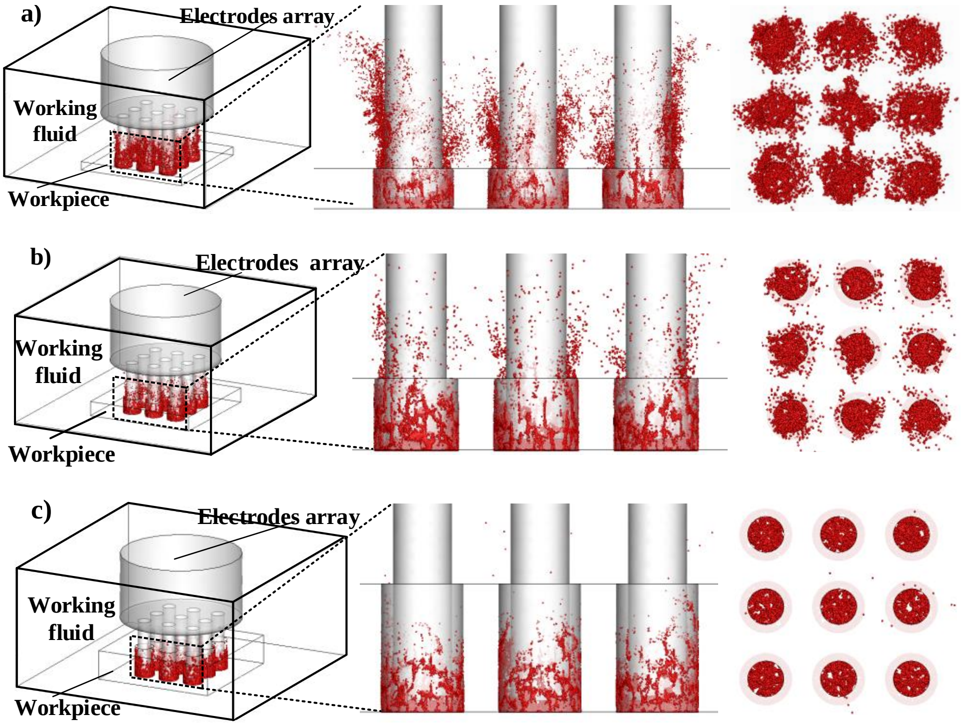

Fig. 3. Debris particles distribution with different the depth-to-diameter ratio: (a) 0.5, b) 1, (c) 2.

It is shown in the Fig. 3 that under the condition of constant ultrasonic frequency and ultrasonic amplitude, plenty of debris particles are exhausted out of the hole with depth-to-diameter ratio of 0.5, a few debris particles are exhausted out of the hole with the depth-to-diameter ratio of 1, and little debris particles are exhausted out of the hole with the depth-to-diameter ratio of 2. Therefore, it can be concluded that the increase of depth-to-diameter ratio is not conducive to the exhaustion and distribution of debris particles. As shown in Table 3, the number of debris particles exhausted to outside of the hole with the different depth-to-diameter ratio is given.

Table 3. The number of debris particles with different the depth-to-diameter ratio.

Depth-to-diameter ratio	Total of debris particles	Number of debris particles outside of hole	Proportion of debris particles outside of holes (%)
0.5	75800	9338	12.32
1	75800	935	1.23
2	75800	17	0.02

It is shown in the table 3 that the proportions of debris particles exhausted to outside of holes are 0.02%, 1.23% and 12.32% with the depth-to-diameter ratio of 2, 1 and 0.5, respectively. The larger the depth-to-diameter ratio, the less the debris particles exhausted from the discharge gap under the condition of constant ultrasonic amplitude and frequency because the longer the path of the debris particles exhausted from the holes array, the more difficult it is to exhaust.

4.2. Effect of ultrasonic amplitude on the distribution of debris particles

The influences of ultrasonic amplitude on debris particles distribution in discharge gap are investigated through flow field simulation. The ultrasonic frequency of ultrasonic vibration is set at 40 KHz, the depth-to-diameter ratio is set at 0.5 and the ultrasonic amplitude is set at 2 μm, 4 μm and 8 μm, respectively. After 48 cycles of ultrasonic vibration, the debris particles distribution of micro-holes array in ultrasonic assisted EDM process are simulated numerically, as shown in Fig. 4.

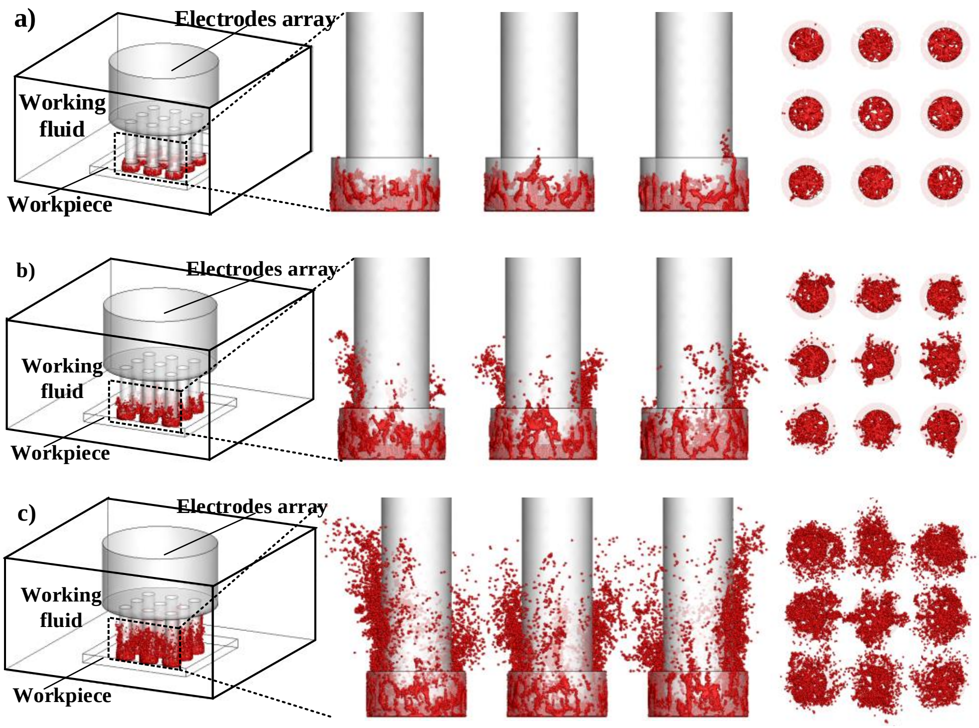

Fig. 4. Debris particles distribution with different ultrasound amplitudes: (a) 2 μm, (b) 4 μm, (c) 8 μm.

It is shown in the Fig. 4 that under the condition of constant ultrasonic frequency and depth-to-diameter ratio, plenty of debris particles are exhausted out of the hole with ultrasonic amplitude of 8, a few debris particles are exhausted out of the hole with the ultrasonic amplitude of 4, and only a little debris particles are exhausted out of the hole with the ultrasonic amplitude of 2. Therefore, it can be concluded that the increase of ultrasonic amplitude is benefit to the exhaustion and distribution of debris particles. As shown in Table 4, the number of debris particles exhausted to outside of the hole with the different ultrasonic amplitude is given.

Table 4. The number of debris particles with different ultrasonic amplitudes.

Ultrasonic amplitude(μm)	Total of debris particles	Number of debris particles outside of hole	Proportion of debris particles outside of holes (%)
2	126300	15	0.01
4	126300	1825	1.44
8	126300	14788	11.71

It is shown in the table 4 that the proportions of debris particles outside of hole are 0.01%, 1.44% and 11.71% with the ultrasonic amplitude of 2μm, 4μm and 8μm, respectively. As shown in Table 4, the larger the ultrasonic amplitude, the more the debris particles exhausted from the discharge gap under the condition of constant ultrasonic frequency and depth-to-diameter ratio because the larger the ultrasonic amplitude, the stronger the ultrasonic vibration intensity in the same time. The strong ultrasonic vibration intensity contributes to enhance the cavitation and pumping effect of the ultrasonic vibration. Therefore, the large ultrasonic amplitude is help to exhaustion of debris particles out of the discharge gap.

4.3. Effect of ultrasonic frequency on the distribution of debris particles

The influences of ultrasonic frequency on debris particles distribution in discharge gap are investigated through flow field simulation. The ultrasonic amplitude of ultrasonic vibration is set at 4 μm, the depth-to-diameter ratio is set at 0.5 and the ultrasonic frequency of ultrasonic vibration is set at 20KHz, 40KHz, 60KHz, respectively. After 60 cycles of ultrasonic vibration, the debris particles distribution of micro-holes array in ultrasonic assisted EDM process are simulated numerically, as shown in Fig. 5.

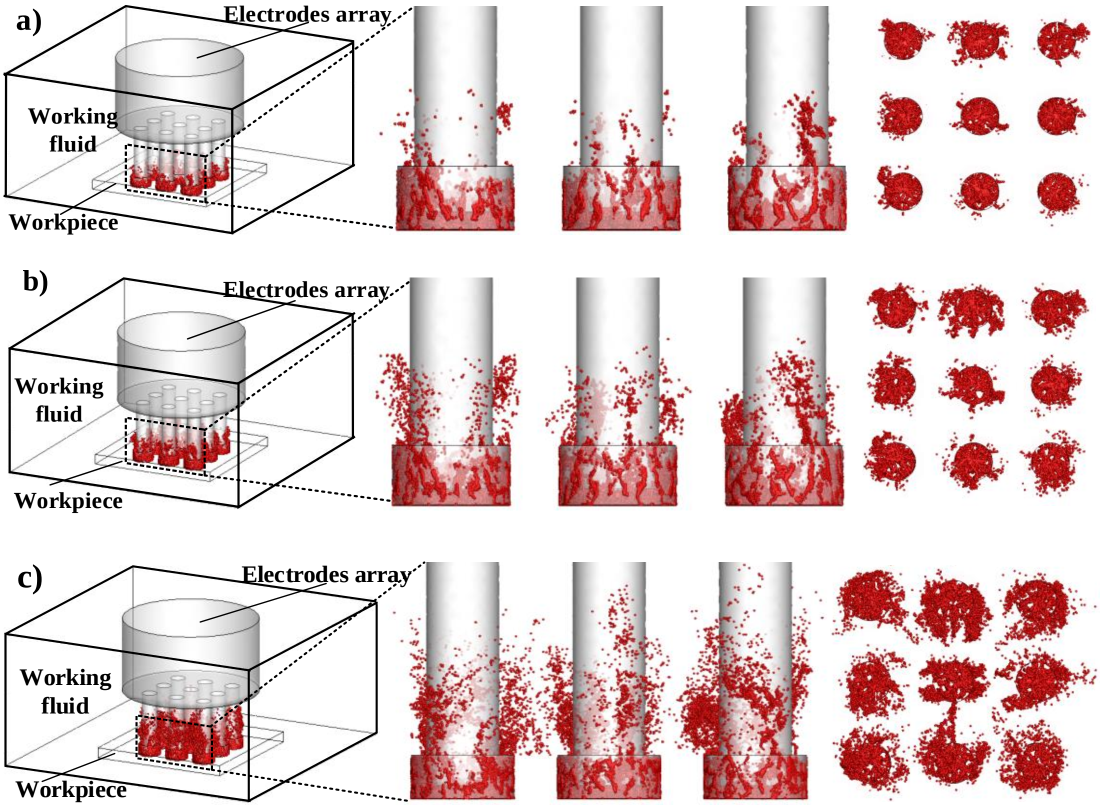

Fig. 5. Debris particles distribution with different ultrasonic frequencies: (a) 20 KHz, (b) 40 KHz, (c) 60 KHz.

It is shown in the Fig. 5 that under the condition of constant ultrasonic amplitude and depth-to-diameter ratio, a few debris particles are exhausted out of the hole with the ultrasonic frequency of 20 KHz, a great number of debris particles are exhausted out of the hole with the ultrasonic frequency of 40 KHz, and a massive quantity of debris particles are exhausted out of the hole with the ultrasonic frequency of 60 KHz. Therefore, it can be concluded that the increase of ultrasonic frequency is conducive to the exhaustion and distribution of debris particles. As shown in Table 5, the number of debris particles exhausted to outside of the hole with the different ultrasonic frequency is given.

Table 5. The number of debris particles with different ultrasonic frequencies.

Ultrasonic frequency（KHz）	Total of debris particles	Number of debris particles outside of hole	Proportion of debris particles outside of holes (%)
20	101060	536	0.53
40	101060	1389	1.37
60	101060	11682	11.56

It is shown in the table 5 that the proportions of debris particles outside of hole are 0.53%, 1.37% and 11.56% with the ultrasonic frequency of 20 KHz, 40 KHz and 60 KHz, respectively. As shown in Table 5, the higher the ultrasonic frequency, the more the debris particles exhausted from the discharge gap under the condition of constant ultrasonic amplitude and depth-to-diameter ratio because the higher the ultrasonic frequency, the stronger the ultrasonic vibration intensity in the same time. The high ultrasonic frequency intensity contributes to enhance the cavitation and pumping effect of the ultrasonic vibration. Therefore, the high ultrasonic frequency is help to exhaustion of debris particles out of the discharge gap.

5. Conclusions

Three-dimensional flow field simulation model of ultrasonic assisted EDM of micro-holes array was established by FLUENT software. The effect of ultrasonic vibration and the depth-to-diameter ratio on debris particles distribution in ultrasonic assisted EDM of micro-holes array were analyzed by numerical simulation.

The results show that reducing the depth-diameter ratio and increasing the ultrasonic amplitude and frequency are beneficial to enhance the exhaustion of debris particles out of the discharge gap and decrease the concentration of debris particles in the discharge gap. In addition, the experiment of ultrasonic assisted EDM of micro-holes array with electrodes arrays was carried out.

References

[1] V. K. Pal, S. K. Choudhury, The International Journal of Advanced Manufacturing Technology **85**(9-12), 2061 (2016).
[2] D. J. McFarland, J. R. Wolpaw, Current opinion in Biomedical Engineering **4**, 194 (2017).
[3] N. Tiwari, D. R. Edla, S. Dodia, Biologically inspired cognitive architectures, (2018).
[4] B. Rubehn, C. Bosman, R. Oostenveld, Journal of neural engineering **6**(3), 036003 (2009).
[5] X. Z. Fu, Q. H. Zhang, J. H. Zhang, Y. J. Zhu, Chinese Journal of Mechanical Engineering **47**(9),164 (2011).
[6] R. J. Ji, Y. H. Yong, Y. Z. Zhang, B. P. Cai, J. M. Ma, X. P. Li, The International Journal of Advanced Manufacturing Technology **59**(1-4), 127 (2012).

[7] R. J. Ji, Y. H. Yong, Y. Z. Zhang, B. P. Cai, J. M. Ma, International Journal of Advanced Manufacturing Technology **51**(1-4), 195 (2010).
[8] R. J. Ji, Y. H. Yong, F. Wang, International Journal of Refractory Metals and Hard Materials **29**(1), 117 (2011).
[9] W. J. Chang, Y. L. Chen, J. H, Jian, X. G. Gu, M. Fang. Journal of Basic Science and Engineering **S1**, 151 (2015).
[10] C. Zou, X. J. ZHU, X. L. Cui, J. Li, Science Technology and Engineering **18**(01), 222 (2018).
[11] S. Cetin, A. Okada, Y. Uno, Machine Elements and Manufacturing **47**(2), 553 (2004).
[12] W. L. Zeng, Z. L. Wang, M. G. Weng, Digest Journal of Nanomaterials and Biostructures **7**(2), 755 (2012).
[13] A. W. J. Hsue, T. J. Hab, T. M. Lin, Procedia CIRP **68**, 783 (2018).
[14] G. Z. Zhu, J. C. Bai, Y. F. Guo, Y. Cao, Y. Y. Huang, Proceedings of the Institution of Mechanical Engineers Part B Journal of Engineering Manufacture **228**(11), 1381 (2014).
[15] Z. L. Chu, W. S. Zhao, L. Gu, Journal of Mechanical Engineering **49**(11), 185 (2013).