Journal of Manufacturing Engineering, September 2019, Vol. 14, Issue. 3, pp 111-116

AN EXPERIMENTAL STUDY ON INFLUENCE OF PROCESS PARAMETERS ON DROSS PROPERTIES IN LASER MACHINING OF AISI 304 MATERIAL

https://doi.org/10.37255/jme.v4i3pp111-116

***Aniket Jadhav and Shailendra Kumar**

Department of Mechanical Engineering, S. V. National Institute of Technology, Surat, Gujarat-395007, India

ABSTRACT

The present paper describes an experimental study on influence of process parameters on dross properties in laser machining of AISI 304 material. Process parameters namely laser power, cutting speed and gas pressure are considered in the present work. Design of experiments is done using response surface methodology and analysis of variance is performed in order to identify significance and influence of process parameters on dross height. It is found that laser power and gas pressure are most significant parameters followed by cutting speed. Dross height increases with increase in laser power and decreases with decrease in gas pressure. On the basis of experimental analysis, a second order mathematical model is developed to predict dross height. Model predictions and experimental results are found in reasonable agreement. Further, optimization of process parameters is also performed to minimize dross height.

Keywords: *Laser Machining, AISI 304, Process Parameters, Dross and Optimization.*

1. Introduction

AISI 304 is an austenitic stainless steel. It is a variant of the 300 series and with higher content of molybdenum, nitrogen, and nickel to ensure better resistance to corrosion and stress. Its composition provides better advantages and durability than other grades of stainless steel. AISI 304 steel has wide range of application like architectural, consumer, nuclear, ships, transportation industries, etc. [1]. Thick austenitic stainless steel is a difficult to cut sheet material and widely used in manufacturing industries due to exceptional mechanical properties. Cutting of these sheet materials by using conventional processes is difficult due to excessive tool wear, friction, vibration and poor surface quality [2, 3]. Laser machining of austenitic stainless steel is economical because laser beam can be mechanized, computer controlled and integrated into assembly lines [4]. Laser machining of stainless steel is widely used in fabrication industries. Fig. 1 shows laser cutting mechanism. It is a thermal energy based sheet cutting process where the absorbed thermal energy first heats the sheet material. Then it converts the approaching volume of sheet material into molten state that can be easily removed by gas pressure. Thermal energy for the process is mainly obtained from the intense laser light [5]. The non-contact nature of laser cutting means that there is no tool wear, no tool storage costs, no tool setup time and no plastic deformation of the cut surfaces [6]. During laser machining process, the kerf volume is changed into the molten state and blows out by an assistant gas. The jet of dross is generated which consists of metal droplets of different sizes. It adheres at the bottom edge of cut. Depending upon the process parameters, the dross height and thickness varies. Formation of dross affects the properties and surface finish of machined material [7]. Major process parameters of laser machining are laser power, cutting speed and gas pressure. In manufacturing industries, selection of paramount parameters is one of the important tasks to achieve minimum dross height formation while cutting steel materials.

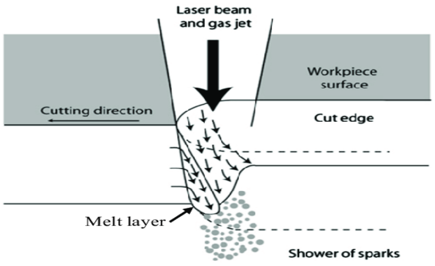

Fig. 1 Laser cutting schematic view [7]

**Corresponding Author - E- mail: skbudhwar@gmail.com*

Some researchers have made efforts to improve cutting performance of laser machining for stainless steel material. Dross formation is an important performance parameter because it affects the aesthetic appearance and requires additional machining operations after laser machining [8, 9]. Salem et al. [10] experimentally studied fibre laser cutting for thick carbon steel sheets. They varied laser power, scanning speed and gas pressure. They concluded that heat affected zone width is affected significantly with the gas pressure due to the formation of the adhering dross at the bottom of cut edge. Ahn et al. [11] analyzed that higher amount of dross is observed on the bottom surface due to excessive melting of workpiece. Chen and Yo [12] developed a hybrid approach to optimize process parameters for cutting stainless steel using pulsed fibre laser. It was found that dross height increases with increase in laser power at high cutting speed. At low speed, laser power has little effect on dross formation. Teixidor et al. [13] characterized geometrically dross height based on energy balances in fibre laser cutting. Muhammad et al. [14] analyzed qualitatively the fibre laser cutting of stainless steel tube and the effect of introducing water flow in tubes on back wall dross formations. Kleine et al. [15] considered cutting speed and laser power as the significant terms in order to improve dross formation in fibre laser cutting of stainless steel material. Baxter et al. [16] described a system to introduce oxygen gas through the workpiece to oxidize dross formed during laser cutting process. Oxygen gas cools the dross as well as workpiece while at the same time oxidizes it. Tessier et al. [17] conducted experiments on a coolant system which is pumped through the inner portion of the specimen before and during laser cutting. The dross formed with the coolant, solidifies and is flushed out of the specimen along with the coolant. Tani et al. [18] have studied the mechanism of melt flow on the cut front. They found that the dross on both sides of cut depends on the melt film condition throughout the kerf. Schulz et al. [19] have investigated that dross formation is related to properties of the melt such as its thickness and velocity. Yilbas and Aleem [20] have concluded that the size of the fumes released has a linear relation with the amount of dross produced. Its formation depends on the laser cutting parameters. The dross height formation thickness increases with the increase of the laser output power. It reduces with increase in assisting gas pressure. Jarosza et al. [21] have reported that increasing occurrence of dross, molten metal and a rough surface at the bottom of workpiece are due to decrease in cutting speed. Additionally, presence of burnt metal was observed on the lower part of workpiece with the lowest speed. Madhukar et al. [22] observed that dross height varies with the laser power and cutting speed. Yan et al. [23] have investigated striation and dross free cutting on alumina sheet using fibre laser machining. Fig. 2 shows scanning electron microscope (SEM) image of cut surface profile taken to study morphology of dross height formation during laser machining.

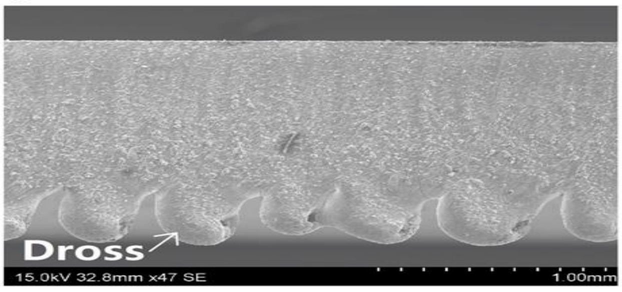

Fig. 2 SEM of cut surface profile [23]

Rahimia et al. [24] studied laser engraving qualitative characteristics of composite material based on experimental results. Designed experiments based on central composite rotatable design were investigated using a response surface methodology model. Desirability function was used to optimize the models. Bara et al. [25] investigated the influence of process parameters on drilling characteristics of 304 stainless steel of 1.5 mm thickness material using Nd:YAG laser drilling through desirability function optimization technique.

From the literature review, it can be concluded that many researchers have investigated influence of different process parameters on responses namely surface roughness, kerf width, kerf taper angle, kerf deviation, heat affected zone, striations, etc. in laser machining. Very few efforts have been made in studying the influence of process parameters on dross properties in laser machining of thick stainless steel. In the present paper, research work related to laser machining of thick AISI 304 stainless steel is described. The main objective of present work is to study the influence of process parameters on dross height. The paper is structured as follows: section 1 gives introduction, section 2 describes experimental work, section 3 presents results and discussion, section 4 discusses optimization of process parameters, and finally concluding remarks are given in section 5.

2. Experimental Work

The experiments are conducted on Bystronic fibre laser machine available at M/s Kakade Lasers, Pune, India. It has a 1.06 μm wavelength and maximum laser power output of 6000 W. The focal length of the lens used is 127 mm and the nozzle diameter 2 mm is kept constant throughout the experimentation. The nozzle stand-off distance maintained during the experiment is 1.5 mm. A 25 mm thick AISI 304 stainless steel plate is used as workpiece material. For experimentation, 17 workpiece samples of size 30 × 30 mm are cut. The chemical composition and mechanical properties of AISI 304 material are given in Tables 1 and 2, respectively.

Table 1. Chemical composition of AISI 304

C	Cr	Ni	Mn	Si	P	S	Fe
0.08	18-20	8-10.5	2.0	1.0	0.045	0.030	Balance

Table 2. Mechanical properties of AISI 304

Properties	Values
Specific gravity, d (g/cm^3)	7.93
Tensile strength, σ (kgf/mm^2)	520
Yield strength, σb (kgf/mm^2)	205
Elongation, δ (%)	40
Vickers-hardness (HV)	200

Process parameters namely laser power (LP), cutting speed (CS) and gas pressure (GP) are considered in the present study. Levels of process parameters as listed in Table 3 are selected on the basis of literature review [1,4,6]. Some trial runs were taken to determine the range of process parameters suitable for the experimental conditions (i.e., laser power, cutting speed and gas pressure). Care was taken to avoid surface melting. After few trial runs, the range of process parameters was determined. Experimental design includes 2 levels and 5 centre points. Total 17 experiments are carried out according to design suggested by Design expert software V11. Response surface methodology (RSM) with Box-Behnken (BBD) design is used to design experiments. BBD was chosen because of the shorter range of process parameters (2 levels) instead of spherical central composite design (CCD). Another advantage of BBD is that it does not contain combination of factors at which all factors are simultaneously at their highest or lowest level, thus can avoid experiments under the extreme conditions [26]. Machined workpiece samples are shown in Fig. 3 and measurement of dross height is shown in Fig. 4.

Table 3. Laser cutting factors and their levels

		Levels	
Symbols	Parameters	Level 1	Level 2
A	Laser Power	5500	6000
B	Cutting speed	150	200
C	Gas pressure	8	12

Fig. 3 Machined workpiece samples of AISI 304 material

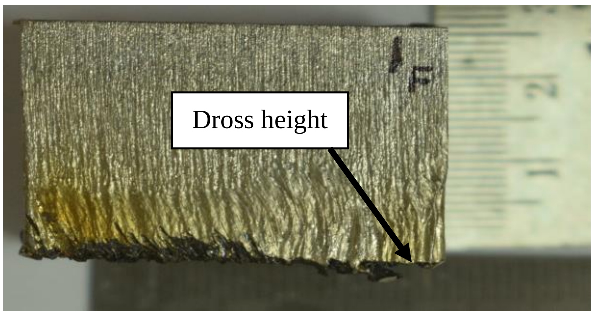

Fig. 4 Measurement of dross height

Table 4. Experimental Design and measured values of dross height

Standard	Run	LP (kW)	CS (mm/min)	GP (bar)	Dross height (mm)
1	10	-1	-1	0	2.4
2	16	1	-1	0	2.5
3	1	-1	1	0	2.5
4	4	1	1	0	2.25
5	13	-1	0	-1	2.6
6	2	1	0	-1	2.3
7	17	-1	0	1	2.45
8	11	1	0	1	2.55
9	7	0	-1	-1	3.35
10	8	0	1	-1	2.3
11	15	0	-1	1	3.5
12	9	0	1	1	2.35
13	6	0	0	0	3.2
14	5	0	0	0	2.2
15	3	0	0	0	2.55
16	12	0	0	0	2.75
17	14	0	0	0	3.3

After experimentation the dross height at the bottom of surface for all the samples is measured. Photographs of the cut surfaces are taken with the high resolution camera (Canon DCC, Model-242S821) and an average of three measurements for each run is recorded. Then dross height is measured using commercial software “Image J”. Experimental design and the measured values of dross height are given in Table 4.

3. Results and Discussion

Table 5 shows the ANOVA for dross height. The analysis is carried out at 95% confidence level. The significance of model can be verified by F-value of 61.56. Laser power and gas pressure are the most significant parameter followed by cutting speed. Interactions between them are also significant. Likewise, a quadratic term of cutting speed is a significant parameter.

Table 5. ANOVA for dross height

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	2.78	9	0.3089	61.56	< 0.0001	significant
A	0.0450	1	0.0450	8.97	0.0201	
B	2.26	1	2.26	449.96	< 0.0001	
C	0.0528	1	0.0528	10.52	0.0142	
AC	0.0400	1	0.0400	7.97	0.0256	
B^2	0.3758	1	0.3758	74.89	< 0.0001	
Residual	0.0351	7	0.0050			
Lack of Fit	0.0281	3	0.0094	5.36	0.0693	not significant
Pure Error	0.0070	4	0.0017			
Cor Total	2.82	16				

The predicted and adjusted R^2 value of 0.8363 and 0.9715 reveals reasonable agreement. It is found that predicted results are in good agreement with the experimental results as shown in the Fig. 4. It predicts dross height and is also useful to identify relative impact of the factors by comparing the factor coefficients.

Influences of laser power and gas pressure are depicted in Fig. 5. It is observed that increasing laser power causes increase in dross height. This is because increasing laser power provides higher rate of high temperature oxidation reactions. It causes increase in liquid layer thickness which enhances the droplet diameter of molten workpiece. The droplet formed adheres to the workpiece and solidifies in the formation of dross. It is also observed that dross height decreases with decrease in gas pressure. It is due to the sufficient gas pressure is produced to remove molten material from the workpiece.

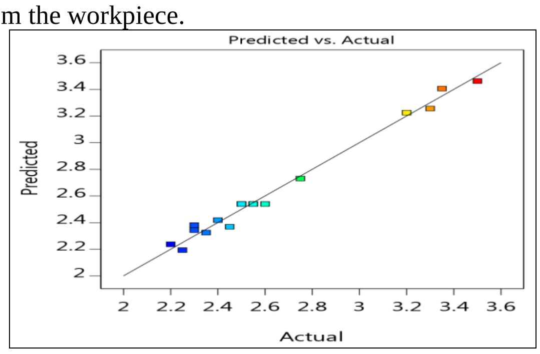

Fig. 4 Predicted vs. Actual values of dross

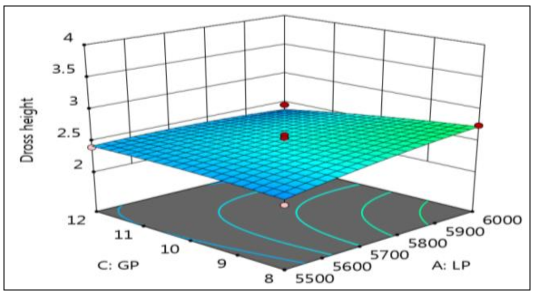

Fig. 5 Effect of LP and GP on dross formation

The perturbation plot representing the influence of process parameters on dross height are shown in Fig. 6. Effect of dross height has been plotted keeping other parameters at their middle values, i.e. at level zero. It is found that dross height increases with an increase in cutting speed. The reason behind this is by increasing cutting speed results in more melting of material along its edges. Due to this dross does not get removed and it settles at the lower part of the workpiece. It results in increase height of dross formation.

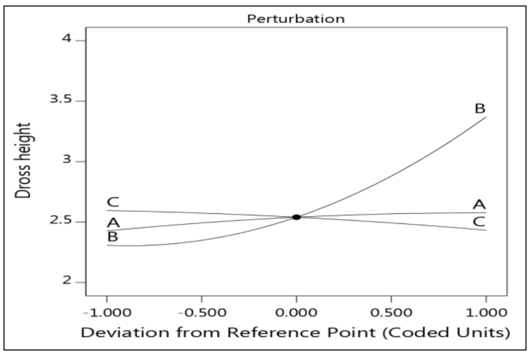

Fig. 6 Perturbation plot for dross height

The regression model is developed with respect to significant terms. The final regression equation for dross height in terms of coded factors is as given in Eq. (1)

$$\text{Dross height} = 2.54 + 0.075A + 0.53125B - 0.08125C - 6.19173e\text{-}16AB - 0.1AC - 0.0375BC - 0.03875\,A^2 + 0.29875B^2 - 0.02625C \quad (1)$$

4. Optimization of Process Parameters

In the present study, a set of process parameters is optimized to minimize dross height. The optimization is performed on the basis of desirability function. It is the method which simultaneously optimizes a series of response. The optimization for each response variable is defined in terms of minimum, maximum, in range or target. The values of the response variables are transformed to a free scale value between 0 and 1, and increases as the corresponding response value becomes more desirable [27]. Table 6 shows criteria for optimization and its optimized values.

Table 6. Criteria for Optimization

Factor	Goal	Lower Limit	Upper Limit	Optimized value
Laser power	In range	5500	6000	5984.771
Cutting speed	In range	150	200	160.324
Gas pressure	In range	8	12	11.951
Dross height	minimize	2.2	3.5	2.193

Bar graph for desirability of all factors and dross height is shown Fig. 7. This graph shows how well each factor satisfies the criteria and desirability of response. Desirability value of all factors is 1. Desirability value of dross height is also 1which is accepted.

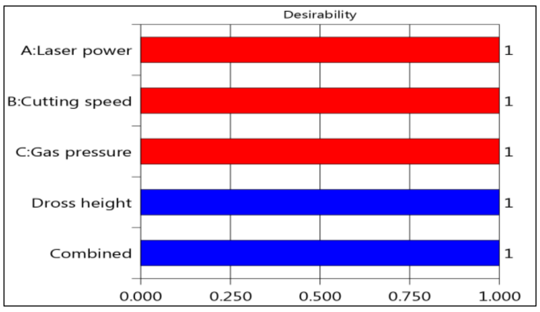

Fig. 7 Bar graph of desirability

Desirability variations with respect to LP and GP are shown in Fig. 8, when CS is at optimum level. Predicted value of desirability is approximately 1 which shows that process is most efficient at these operating conditions.

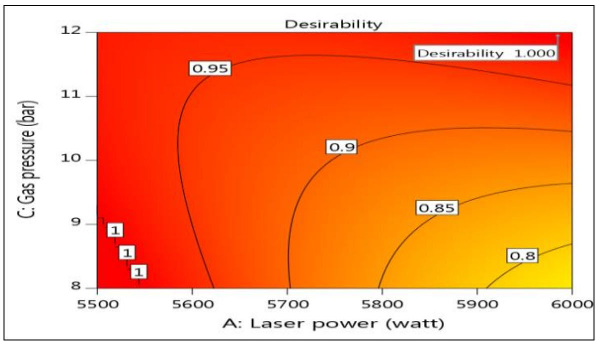

Fig. 8 Desirability value with optimum levels

4.1 Confirmation of Experiments

Confirmation of experiments is carried out by setting the parameters at their optimal values as 5750 W (LP), 175mm/min (CS) and 10 bar (GP). The results of confirmation tests are summarized in Table 7.

Table 7. Results of confirmation tests

Sample	Average Dross height
1	2.4565
2	2.5998
3	2.5676
4	2.2676
5	2.6341
6	2.3385

5. Conclusion

An experimental study on laser machining of AISI 304 is performed in the present work. The following conclusions are drawn from the present work.

i. Laser power and gas pressure are the most significant factors followed by cutting speed to minimize dross height.
ii. Dross height increases with increase in cutting speed and laser power, whereas it decreases with decrease in gas pressure.

Mathematical model is also developed to predict dross height. It is found that model predictions are in good agreement with the experimental results. Further, optimization of process parameters is performed to minimize dross height. The optimized value for the dross height of 2.191 mm is obtained at 5966 W laser power, 177 mm/min cutting speed and 11.90 bar gas pressure.

References

1. *Parthibana A, Chandrasekaran M, Muthuraman V and Sathish S (2018), “Optimization of CO_2 Laser Cutting of Stainless Steel Sheet for Curved Profile”, Materials Today: Proceedings, Vol. 5, 14531–14538.*

2. *Krajcarz D (2014), “Comparison Metal Water Jet Cutting with Laser and Plasma Cutting”, Procedia Engineering, Vol. 69, 838 – 843.*

3. *Akkurt A (2009), “Surface properties of the cut face obtained by different cutting methods from AISI 304 stainless steel materials”, Indian Journal of Engineering and Materials Sciences, Vol. 16, 373-384.*

4. *Ion J C (2005), “Laser Processing on Engineering Materials (Principles Procedure and Industrial Application)”, Elsevier Butterworth-Heinemann, Burlington.*

5. *Ghany K A and Newishy M (2005), “Cutting of 1.2 mm thick austenitic stainless steel sheet using pulsed and CW Nd-YAG laser”, Journal of Material Processing Technology, Vol. 168, 438–447.*

6. *Sharma Amit and Yadava Vinod (2018), “Experimental analysis of Nd-YAG laser cutting of sheet materials – A Review”, Optics and Laser Technology, Vol. 98, 264–280.*

7. *Juptner W P (2002), “LIA handbook of laser materials processing”, Optics Lasers Eng., Vol. 38, 608–610.*

8. *Rajaram N, Sheikh Ahmad J and Cheraghi S (2003), “CO_2 laser cut quality of 4130 steel”, International Journal of Machine Tools Manufacturing, Vol. 43, 351–358.*

9. *Ghany K A, Rafea H A and Newishy M (2005), “Using a Nd:YAG laser and six axes robot to cut zinc-coated steel”, International Journal of Advanced Manufacturing Technology, Vol. 28, 1111–1117.*

10. *Salem H G, Mansour M S, Badr Y and Abbas W A (2008) “CW Nd-YAG laser cutting of ultra low carbon steel thin sheets using O_2 assist gas”, Journal of Material Processing Technology, Vol. 196, 64–72.*

11. *Ahn D G, Byun K W and Kang M C (2010), “Thermal characteristics in the cutting of Inconel 718 superalloy using CW Nd-YAG laser”, Journal of Material Science Technology, Vol. 26, 362–366.*

12. *Chen K and Yao Y L (2000), “Process optimization in pulsed laser micromachining with applications in medical device manufacturing”, International Journal of Advanced Manufacturing Technology, Vol. 16, 243–249.*

13. *Teixidor D, Ciurana J and Rodríguez C (2014), “Dross formation and process parameters analysis of fibre laser cutting of stainless steel thin sheets”, International Journal of Advanced Manufacturing Technology, Vol. 71, 1611-1621.*

14. *Muhammad N, Whitehead D, Boor A and Li L (2010), “Comparison of dry and wet fibre laser profile cutting of thin 316L stainless steel tubes for medical device applications”, Journal of Materials Processing Technology, Vol. 210, 2261-2267.*

15. *Kleine K, Whitney B and Watkins K (2002), Use of Fiber Lasers for Micro Cutting Applications in the Medical Device, ICALEO, Scottsdale, USA, 1-10 .*

16. *Baxter W and Mackiewicz D (2014), United States Patent No. 0312005 A1.*

17. *Tessier and Brown W (1991), United States Patent No. US5073694.*

18. *Tani G, Tomesani L, Campana G and Fortunato A (2004), “Quality factors assessed by analytical modeling in laser cutting”, Thin Solid Films, Vol. 11, 486–491.*

19. *Schulz W, Kostrykin V, NieBen M, Michel J, Petring D and Kreutz E. W (1999), “Dynamics of ripple formation and melt flow in laser beam cutting”, Journal of Physics-Applied Physics, Vol. 32, 1219–1228.*

20. *Yilbas B S and Aleem B J A (2006), “Dross formation during laser cutting process”. Journal of Physics D Applied Physics, Vol. 39, 1451–1461.*

21. *Jarosza K, Loschnera P and Niesłonya P (2016), “Effect of cutting speed on surface quality and heat-affected zone in laser cutting of 316L stainless steel”, Procedia Engineering, Vol. 149, 155 – 162.*

22. *Madhukar Y K, Mullick S and Nath A K (2016), “An investigation on co-axial water-jet assisted fiber laser cutting of metal sheets”, Optics and Lasers in Engineering, Vol. 77, 203–218.*

23. *Yan Y, Li L, Sezer K, Whitehead D, Ji L, Bao Y and Jiang Y (2012), “Nano-second pulsed DPSS Nd:YAG laser striation free cutting of alumina sheets”, International Journal of Machine Tools and Manufacture, Vol. 53, 15–26.*

24. *Rahimia M H, Shayganmanesha M, Noorossanab R and Pazhuheianb F (2019), “Modelling and optimization of laser engraving qualitative characteristics of Al-SiC composite using response surface methodology and artificial neural networks Mohammad”, Optics and Laser Technology , Vol. 112, 65–76.*

25. *Bara A, Sahoo S K, Naik S S, Sahu A K and Mahapatra S S (2018), “Multi Response Optimization of Nd:YAG Laser Micro Drilling Characteristics of 304 Stainless Steel using Desirability Function Approach”, Materials Today: Proceedings, Vol. 5, 18975–18982.*

26. *Ferreira S L C, Bruns R E, Ferreira H S, Matos G D, David J M, Brandao G C, Silva, da EGP, Portugal LA, Reis dos PS, Souza AS, Santos and dos WNL (2007), “Box-Behnken design: an alternative for the optimization of analytical methods”, Anal Chim Acta, Vol. 597, 179–86.*

27. *Myers R H, Montgomery D C and Anderson Cook C M (2016), “Response Surface Methodology: Process and Product Optimization Using Designed Experiments”, John Wiley & Sons.*