Simultaneous Manufacturing/Structural Shape Optimization for Minimum Product Cost

التحسين الأمثل و المتزامن للتصنيع والبنيه الشكليه لأقل تكلفه للمنتج

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ملخص البحث

يعرض هذا البحث طريقة التحسين الأمثل للتصنيع و البنية الشكلية في آن واحد إذ تأخذ في الاعتبار كلا من أداء البنية و تكلفة الإنتاج. حيث تقوم على العلاقة المتبادلة بين الكتلة و تكلفة التشغيل و ذلك باستخدام التفريز الرأسي و التجليخ كطريقة تشغيل و تشطيب لأسطمبة افتراضية. والدالة المرجوة في هذا البحث هي تقليل التكلفة الكليه لتشمل تكلفة المادة و التشغيل. حيث سيتم رسم الشكل البنائي باستخدام B-Splines مع توليد بعض الفجوات و تكون إحداثيات النقط الممثلة لكل Splines متغيرة فى اتجاه Y و X. كما أن عوامل القطع كسرعة القطع و معدل التغذية و قطر العدة القاطعة تكون أيضا من المتغيرات. الشروط الموضوعة للمسألة التصميمية تشمل شروطا إنتاجيه و شكليه بنائية. و يتم انجاز هذه المسألة باستخدام برنامج MATLAB2011a و ANSYS 11 مع استخدام طريقة متتابعة البرمجة التربيعية (SQP) كطريقة حل مسألة التصميم الامثل. بافتراض أن هناك ثلاث حالات لتوليد الفجوات في المنتج اعتمادا على فكرة التحسين التوبولوجى إذ يتم المقارنة بين التكلفة المبدئية و النتائج النهائية لهذه الحالات كلها مع مقارنه النتائج اذا ما كانت دالة التصميم الأمثل هى حساب أقل وزن لدفعة المنتج و كذلك تم دراسة تأثير حجم الدفعة على شكل المنتج النهائى . وكانت نتيجة المقارنة بين الحالات الثلاثة أن الحالة التي تعتمد على توليد ثلاث فجوات هي أفضل في النتائج فقد كانت نسبة اختزال التكلفة حوالي 28% بعد عدد ثمان محاولات للدفعة بحجم خمسين قطعة بينما كان الاختزال في التكلفة حوالي 48% بعد عدد أربعة عشر محاولة لدفعة بحجم خمسة ألاف قطعة مع ظهور اختلاف فى الشكل النهائى للفجوات اعتمادا على حجم الدفعة المفروضة.

Abstract

This paper presents an integrated manufacturing/structural shape optimization method that considers not only structural performance but also machining cost. It explores the tradeoff between mass and machining cost with the application of the end-milling and grinding machining processes to machine and finish a virtual die. The objective function of the integrated optimization problem is the total cost (material & machining). The structural shape is constructed by using B-Splines and hole generation; the design variables are X- and Y-coordinates of the B-Splines control points. The design variables also include the cutting parameters i.e. the cutting speed, the feed rate and the tool diameter. The problem constraints are for both manufacturing and structural shape. The optimization problem will be achieved by interfacing between MATLAB2011a and ANSYS11 programs using Sequential Quadratic Programming (SQP) as a mathematical optimization solver. In this paper, there are three cases of hole generation in the product depending upon the idea of topology optimization. The comparison between the initial total cost and its optimal results for all cases is presented and the influence of the required batch size on the final shape is discussed. It is found that the reduction percentage in the total cost of the virtual die of the last case (i.e. three holes generation) is about 28 % by using SQP algorithm for batch size of 50 pieces after eight iterations and 48% for batch size of 5000

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pieces after fourteen iterations. The final optimized shape has also changed as a result of the product batch size demand.

KEY WORDS: Structural Shape Optimization, Manufacturing Optimization, Manufacturing Cost, B-Splines, SQP

1- Introduction

Developing a new product is carried out in a successive manner. In most cases, minimum cost is the goal in both design and manufacture step. This goal is realized in design step through minimizing the weight of the structure with constraints on strength and rigidity. It is thought that the minimum weight means minimum material and hence minimum cost. In Manufacturing optimization this goal is achieved through selecting the most economical manufacture process and optimizing it by minimizing the cutting tool path and/or minimizing the number of tool changes as an example. The point which is overlooked is that the minimum-weight-design does not necessarily lead to the global minimum product cost. It occurs frequently when the structure topology is optimized. The typical optimum topology structure has many grooves and holes of different sizes and is so complicated that its manufacturing is either impossible or very expensive [1].

End milling is widely used in most of the manufacturing industries due to its capability of producing complex geometric surfaces with reasonable accuracy and surface finish. So, it is selected to be the manufacturing process while grinding process is used for finishing operations.

Depending on the geometric feature, structural optimization problems are divided into three classes: size optimization, shape optimization, and topology optimization as shown in Fig. 1. While manufacturability plays a significant role in determining the cost of the engineering product, it has not been widely incorporated for structural shape optimization. A limited number of researches is presented in this area. The optimized shape is manufactured at a reasonable cost and the objective was the minimum compliance to optimize the topology from an initial structural layout [1]. The optimization considering structural performance and manufacturing cost are presented in [2-3]. Their cost models are based on empirical data and the design variables consist of component sizes and section properties.

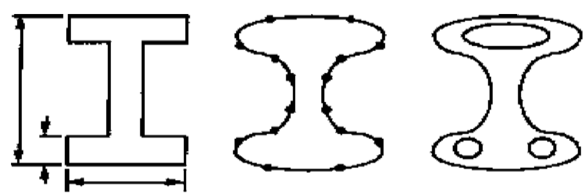


Fig.1 Types of geometry parameterization:
a) Sizing b) Shape c) Topology

A structural shape optimization considering mechanical performance and manufacturing cost is presented using the mass as a metric for structural performance and maximum stress [4-5]. Manufacturing and machining factors during the optimization process are considered by introducing manufacturing and machining constraints into the shape/topology optimization formulation. The objective function was the minimum compliance subjected to volume constraint [6]. A new approach which considers product/process guidelines input/output data in the optimization phase is introduced in [7]. The designer could focus on the engineering problem rather than on how to fit it. It is noteworthy that the literature contains no similar work on the optimization of the machining cost as an objective containing both material and machining costs under effective manufacturing and structural shape constraints using mathematical programming algorithms. So, this work aims to achieve a global minimum product cost from both design and manufacturing viewpoints.

2 -Design Problem Definition

The global minimum product cost can be realized through simultaneously optimizing the structure and the manufacturing of the product. This means that a nested optimization methodology is used. The outer optimization loop is for the shape optimization of the structure and the inner optimization loop is for the manufacturing optimization. In each iteration of the structural shape optimization loop, the minimum manufacturing cost is calculated through the inner optimization loop. The objective function of the outer optimization loop will be the total cost including the material and manufacturing cost. This simultaneous optimization methodology will be presented in the application of estimating the global minimum cost of the optimized machined die and the total material consumption in a certain batch size of the effective product.

3 - Manufacturing Cost and Machining Time Estimation for Die

It is important to estimate the machining time and cost of the selected manufacturing process that includes end milling and grinding in addition to the total material cost.

Material Cost includes the cost of the total material consuming in certain batch size in addition to the cost of the die material itself. The die logically has a fixed material cost while the material cost of the product batch is variable depending on the product shape. The Selected Die material is a Hot Work Die steel H13 [8] whereas the selected product material is AL 6061-T6 because of its wide availability.

Labor Cost depends upon of the total machining time. The direct labor cost is calculated as expressed in the following relation:

$$\textit{Direct Labor Cost} = (R_o + R_m)\, T_{total} \quad (1)$$

Where R_o is the operator's rate, R_m is the machine rate and T_{total} is the total manufacturing time spent in processing a job.

Tooling cost includes the cost of tool and changing tools. The optimization model in this study is based upon Taylor's tool life equation $V * T^n = C$ to calculate the tool cost. Where “n and C” are Taylor's tool life Constants. They depend upon the tool material. The value of “n” lies in range (0.1:0.2) [9] and “C” is equal to 33.98 m/min for HSS in end milling process [10].

Machining time is defined as the duration laps from feed engagement to feed disengagement. In this work, the Feature Based Estimating Approach [11] is used because it has many advantages. One advantage of the proposed system in this research is that this system can handle an infinite number of shapes with feature information. It is also easy to calculate the material removal rate and features volume removal whenever the cutting parameters are selected. Machining volume removal is directly related to the volume of manufacturing features. Machining volume for each feature can be obtained by mathematical calculation [12]. There is no need to select the optimum tool path during cutting. Another advantage is that this system estimates manufacturing cost accurately and rapidly [13]. The great advantage of using this method is that it enables us to involve the generated areas and splines lengths in each optimized iteration to verify the idea that the shape of generated surfaces depend on the batch size of product. Machining time is composed of the rough, finish and approach cutting time, and the tool approach time. Roughing cutting time is proportional to the machining volume removed for all types of features while finish cutting time is proportional to the area of the finish cut [14]. It is often necessary to know the machine power requirements for an anticipated feed, speed, and depth of cut for a particular material or class of materials. In the present work, the required cutting force is calculated in the constructed optimization program at each iteration to check that it is less than the maximum allowable cutting force of the machine depending upon the known machine motor power.

4 Structural Shape Optimization

Structural Shape design optimization problems are difficult to solve. Such problems need more computational time and requirements [16]. There is no single method or technique for solving all optimization problems efficiently. In this research, Mathematical Programming techniques such as Sequential Quadratic Programming (SQP) are used to find the minimum of a function of several variables under a prescribed set of constraints. The basic idea in the present work is to change the topology of the product by generating holes that may vary in size and shape, so a different number of holes may lead to different (locally) optimal solutions. The structural shape optimization is used to optimize the size and shape of the virtual die cavities. Some of exterior boundaries of die cavities and interior boundaries of inserted holes are represented by using the B-Spline formulation to pull on the different control points to modify the die profile in order to reach the objective. Hence, the degrees of freedom of the control points are the design variables. The optimization problem is formulated in "MatLab R2011a" platform. The optimization tool available in "MATLAB R2011a" that finds a minimum of constrained nonlinear multivariable objective is 'fmincon'. The Sequential Quadratic programming (SQP) algorithm will used as a solver for the optimization problem. The MaTLAB spline tool box is also used to construct the B-Splines that represent the boundaries and holes generation in this work.

Structure Shape Representation for Product

The boundaries shape can be described using polynomial functions and using design variables that control their shape. B-Splines have many advantages in this respect: they are smooth enough, although they allow for large variability of shapes which they describe. One of the most important advantages of this formulation is local control. Since each control vertex is associated with a basis function, it only influences a local portion of the curve and it has no effect on the remaining part of the curve. Because of the previous advantages of B-Spline shape representation, it will be used in this research to represent some exterior boundaries and the interior generated holes in the produced part. Fig. 2 shows how the B-Spline curve and surface are fitted by their control points and knots whereas Fig. 3 shows how the closed B-Spline curve can represent the hole. The control point positions that define the B-Splines in the structure are selected as design variables for achieving the best objective performance. A third degree B-Spline basis function is used. A shape optimization problem can be formulated and solved for optimal structural performance. The B-Spline control points (the shape design variables) have a variation in their coordinates position along x and y directions (2D).

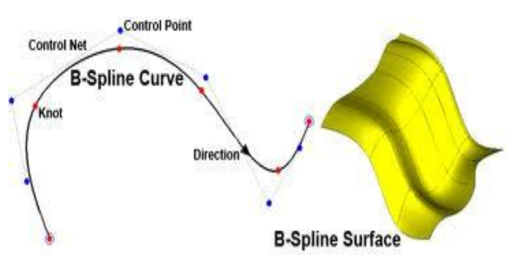


Fig. 2 The formation of the B-Spline curve and surface

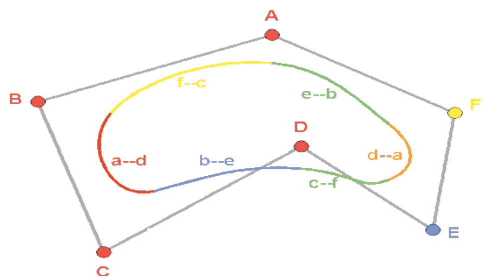


Fig. 3 Closed Cubic B-Spline curve (Control points order ABCDEFA)

Finite Element Modeling

Finite Elements is a well-known tool for structural analysis. It is applied to determine the deformation and stresses in a product structure subjected to loads and boundary conditions. The finite element method based on Lagrangian representation is used to model the product in the optimization problem because it is more accurate and flexible in sensitivity analysis calculation [19]. The integration between the MATLAB R2011a and ANSYS11 programs plays a vital role to evaluate our work. An effective MATLAB function is constructed to invoke an ANSYS environment and build a complete finite element model of geometric solid of the product part in ANSYS. The finite elements analysis in ANSYS is evaluated and free-meshing is implemented. The structural compliance is calculated in ANSYS then exported to MATLAB environment again.

5 Integrated Manufacturing/Structural Shape Optimization

Despite the recognition of majority of the total cost of a product potential, the use of structural optimization in practice has been limited by the lack of true concurrent structural performance and manufacturing cost optimization of structural components with the use of B-Spline curves for increased design freedom. This research tries to overcome that limitation by integrating both aspects in one optimization problem.

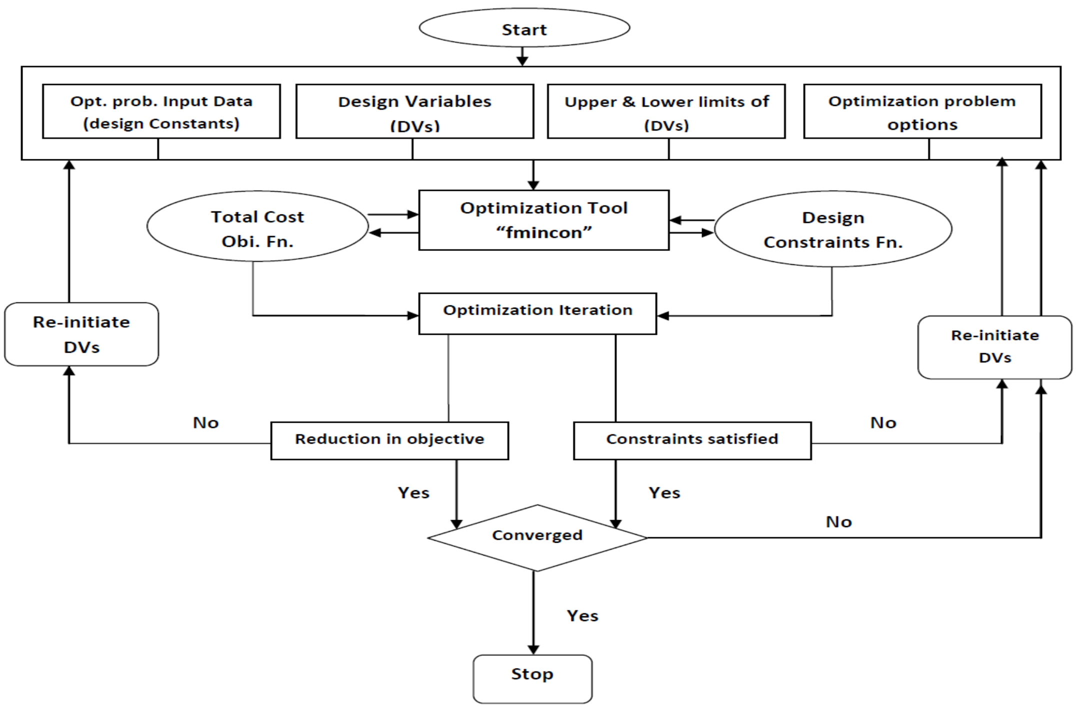
The proposed optimization problem

The proposed methodology in this work relies on the concept of topological sensitivity that captures the first order impact of inserting some holes within a domain on various quantities of interest. A structural shape optimization method that considers not only the structural performance, but also the manufacturing cost is presented. It explores the tradeoff between mass and manufacturing cost with the application of the end-milling and grinding manufacturing processes to produce the virtual die. This means that a nested optimization methodology is used. The outer optimization loop is for the shape optimization of the structure and the inner optimization loop is for the manufacturing optimization. In each iteration of the structural shape optimization loop, the minimum manufacturing cost is calculated through the inner optimization loop. Fig. 4 shows the flow chart of the proposed optimization process.

Optimization Problem Definition

The Optimization Model developed in this work is a nonlinear, multi-variable and multi-constrained model of a complex nature. The supposed product produced by the manufactured die is a plate containing some inserted holes to give a virtual topology of the product. Because of the importance of beams that play a significant role in many engineering applications, the die product is supposed to be used as a “MBB-beam”. The idea is to optimize the shape of a lower boundary edge and the generated holes in “MBB-beam” under the idea of topology optimization. The “MBB-beam” is supposed to have a dimension “ 20× 10×1 cm^3” and the die skin is increased over these dimensions with 1cm in each direction. The die has two halves; the lower has the pocketing that represents the die cavity surrounded by the generated boundaries of the beam, whereas the upper half contains the cores that represent the generated shaped holes produced to reduce the weight of the beam by reducing the product area. The cutting conditions in this work include the machine tool classifications and the cutting parameters selection for end milling and grinding processes to produce the surfaces of die halves. The optimization program that is constructed in this research invokes all constant cutting data (such as the physical properties of die and work-piece materials, type of machine that is used in machining process, machine and labor rate, etc) depending upon the cutter diameter selection at each iteration of optimization from database Excel file.

Fig.4. Flow chart of integrated optimization problem using MATLAB optimization tool box



The selected end-mill for rough cut is un-coated "HSS" 2-flute single end 30° RH Spiral Ball nose End Mills", whereas the finishing end-mill has the same characteristics but with 4-flute. The Axial depth of cut (l) will be constant in this work and take it equal to $0.2Dc$ (Dc is the cutter dia.) [11]. The radial depth of cut ($Rdoc$) will also be equal to $0.5\ Dc$. The feed per tooth (f_t) for rough cut range is 0.10 : 0.18 mm/tooth and the cutting speed (V_f) range lies (18:30 m/min) [15]. The cutter diameter, rough cutting feed and speed are the design variables in the nested optimization problem in this work. For mill finish cut, the feed is very small; it is supposed to be equal to ($0.1f_t$), whereas the cutting speed will be ($1.5V_f$).Grinding wheel speed is ranged between (1200-1800 m/min). Work speeds are in the range (20:40 m/min); and depths of cut of 0.015 mm for roughing, and around 0.005 mm for finish grinding. Specific metal removal rate ($SMRR$) that represents the rate of material removal per unit of wheel contact width is taken 300 mm^3/mm width/min.

The optimization problem formulation

The purpose of the *objective function* is to minimize the total manufacturing cost for milling and grinding (TCost). The *Design* *variables (DVs)* in the proposed manufacturing/shape optimization problem will be the control points coordinates (along x, y directions) of each B-Spline, the end-milling cutting speed *(V)* and feed (f_t), the end mill diameter (*Dc*). The cutting speed and feed along end milling finish and grinding super finish operations are dependent variables; they presented as a percentage of cutting speed and feed/tooth of milling rough cut. The objective function and constraints are non-linear functions of the design variables:

Min TCost = Material cost + Labor cost + Tooling cost

Subjected to $g_i(x) \leq 0$

i:the number of constraints

The design inequality constraints in this investigation will constrain the positions of control points of B-Splines with respect to each other; the computed structure compliance will constrain the volume of the product. It must be less than a certain value (unit length/N) and the manufacturing constraints will include the maximum cutting power available, the maximum feed rate of the product machine, the maximum spindle speed available, the maximum allowable cutting force and the required surface roughness for rough and finish cut of the production processes.

6 Results and Discussion

Case(1): One circular hole insertion

Fig. 5 presents the initial shape of the product that will be produced by the virtual machined die. The product is supposed to be a plate. This plat acts as MBB beam. A hole with 1cm radius is generated in the design domain. The design parameters of this structure are illustrated in Table 1 whereas Table 2 contains the initial and final optimization data of objective function, Manufacturing DVs, and State Variable (SV) for the optimization method for both batch size (i.e. 50 &5000). The optimization algorithm SQP is converged for batch50 after 7 iterations while it converged after 9 iterations for batch 5000. Fig. 7a and b represent the initial and final shapes of product for both batches (i.e. 50 & 5000) which are plotted using MATLAB platform. As we see from Fig. 7a and b, the final optimized shapes are affected by the batch size. The shape of interior and exterior boundaries in final product varies, depending upon batch size. It can also be clearly noticed that there is a variation in reduction percentage in the components of the objective function (such as material cost, labor cost, tooling cost in end milling and grinding cost).

Case2: Two holes insertion

Depending upon the idea of topology optimization, the product design domain may contain many holes to reduce the material consuming; a two holes insertion case is introduced. All initial conditions that are used in the previous case of one circular hole insertion are the same except an excess insertion of one more circular hole with radius 1 cm; see table 1. The optimization problem is converged after 11 iterations for batch50 while it converged after 10 iterations for batch5000. As it is noticeable from Fig. 7c and d, it can be seen that the optimizied shape that is produced by SQP for batch50 is different from that produced for batch 5000 and by observing table 2 for one and two hole generation, the reduction in total cost slightly appears specially for batch5000 despite the increasing number of holes.

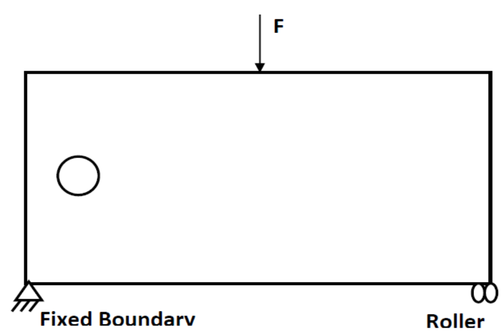


Fig. 5 Formulation of initial design shape of optimization prob., Case1 (one circular hole)

Table 1 Design parameters for the optimization problem.

Design parameter	*Value*
Product (plate) Dimension Length Width Thickness Generated hole radius	 20 cm 10 cm 1 cm 1cm
Batch Size	50 or 5000
Load (F)	1 N [20]
Young's Modulus (E)	1 N/m^2 [20]
Poisson Ratio (v)	0.3

Case3: Three holes insertion

One more circular hole is generated. Figures 7e and f represent the shape of the product in the initial and final optimized situation. The problem was converged after 8 iterations for batch50 and after 14 iterations for batch5000. By observing the results and shapes, the same trend is found; the shape of product is changed depending up on the batch size and the reduction in total cost is resulted due to the optimization of cutting conditions as the cutting speed is optimized to 18 m/min instead of 25 m/min, the feed will be 0.148 instead of 0.11 mm/flute and the optimized cutter diameter will be 7.93mm (5/16"). The increase in grinding cost is also noticed due to the increase in tool path length. Fig. 8 represents the initial and final optimized product and the two halves of virtual produced die for both batches in all three cases. The drawing is evaluated by Solid Works 2010.

By comparing the results of minimum total cost as the objective function in the three cases of the hole insertion, it is found that the total machining cost is increased by inserting excess holes despite the reduction in total material cost. This was observed in both batches.

A comparison between the total cost results from the global cost and the weight objective functions.

The minimum weight of the product in all cases is optimized and the substitution by the optimized design variables that result from the optimization problem in the global cost function is occurred. Table 3 represents the reduction percent in total cost results that are calculated by optimizing both the global cost and the weight of product batch. The reduction in total cost increases by using the global cost objective function in both batches while the reduction in calculated total cost by using the optimized weight is decreased. This happened due to the effect of simultaneous manufacturing/structure shape optimization.

Conclusion

A global minimum product cost from both design and manufacturing is achieved through simultaneously optimizing the structure shape and the manufacturing of the product using Sequential Quadratic Programming (SQP) optimization method. The total machining time is the major predominant on the optimization problem and the demand batch size has a great influence on the topological optimized shape. This work guides the topology technique into direction that is useful not only from theoretical viewpoint but also from practical viewpoint and opens the doors to produce a new kind of software that integrates the design and the machining in an innovated manner.

Table 2 The initial and final optimization data for all cases of holes generation for Batches 50 and 5000

	One Hole				*Two holes*				*Three Holes*			
	Batch 50		*Batch 5000*		*Batch 50*		*Batch 5000*		*Batch 50*		*Batch 5000*	
	Initial	*Opt.*	*Initial*	*Opt.*	*Initial*	*Opt.*	*Initial*	*Opt.*	*Initial*	*Opt.*	*Initial*	*Opt.*
Total Cost($)	3827.6	2737.03	29584.48	18323.75	3846	2747.37	29239.39	17430.9	3864.39	2757.58	28894.31	14942.76
Reduction (%)		28.49%		38.06%		28.57%		40.39 %		28.64%		48.28 %
Material. Cost	260.17	221.33	26017.05	15745.28	256.5	220.16	25649.89	14810.06	252.83	219.01	25282.74	12272.74
Reduction (%)		14.93%		39.48%		14.17%		42.26 %		13.38%		51.46%
Milling Cost	1462.71	411.87	1462.71	401.65	1465.88	412.26	1465.88	402.01	1469.05	412.65	1469.05	399.31
Reduction (%)		71.84%		72.54%		71.88%		72.58 %		71.91%		72.82%
Tool Dia. (mm)	6.35	7.93	6.35	7.93	6.35	7.93	6.35	7.93	6.35	7.93	6.35	7.93
(inches)	(1/4")	(5/16")	(1/4")	(5/16")	(1/4")	(5/16")	(1/4")	(5/16")	(1/4")	(5/16")	(1/4")	(5/16")
Cut. Speed (m/min)	25	18	25	18	25	18	25	18	25	18	25	18
Feed/flute (mm/flute)	0.11	0.148	0.11	0.148	0.11	0.148	0.11	0.148	0.11	0.148	0.11	0.148
Grinding Cost	2123.62	2114.95	2123.62	2218.82	2123.62	2114.95	2123.62	2218.82	2142.52	2125.92	2142.52	2270.71
Reduction (%)		0.41%		-4.48%		0.41 %		-4.48 %		0.77%		-5.98%
Compliance (cm/N)	26.57	42.47	26.57	105.17	26.57	42.47	26.57	105.17	26.83	42.67	26.83	119.4

Note: sign (-) means increasing in cost.

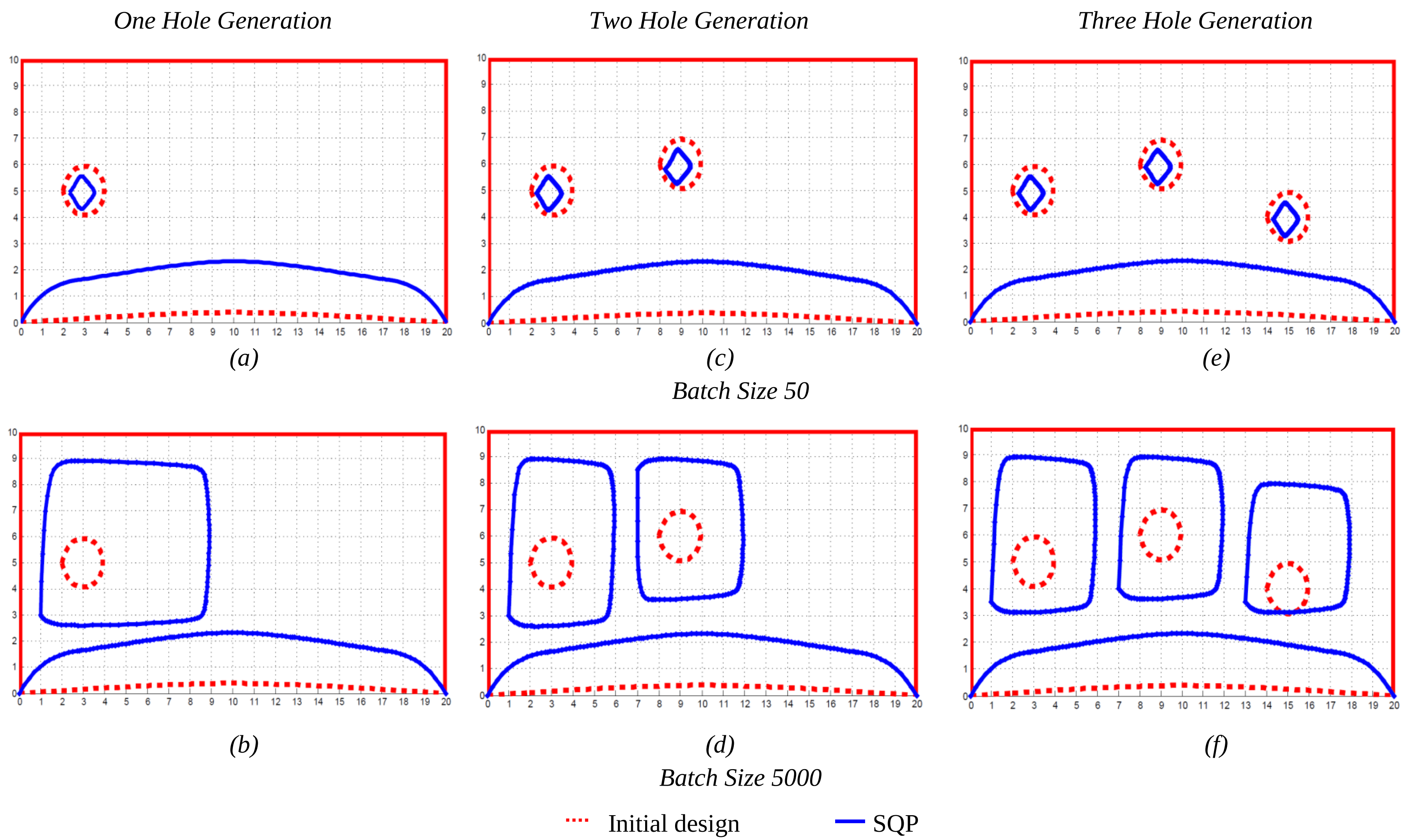


Fig. 7 Initial & optimized shape of product in three cases of hole insertion using SQP

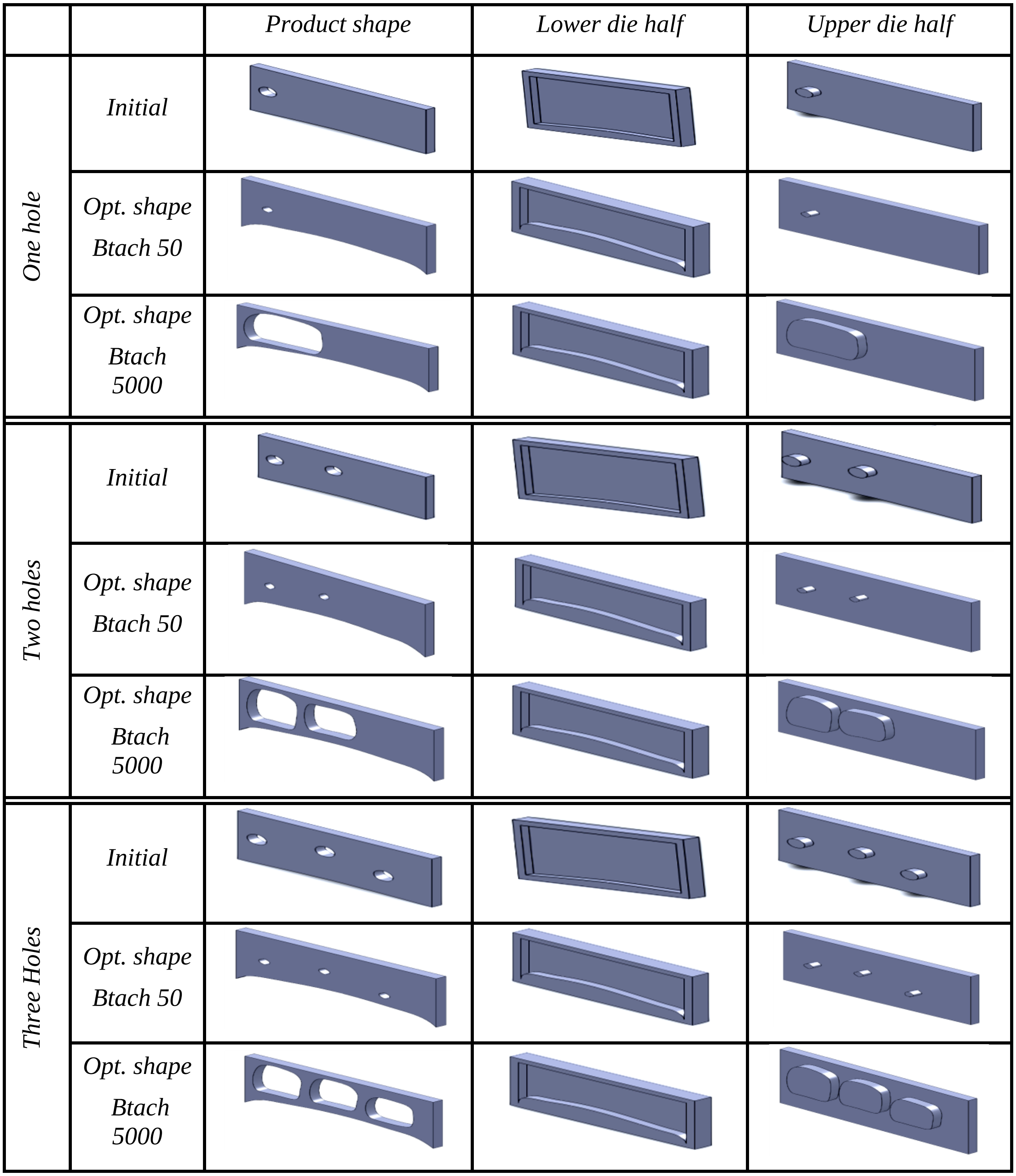


Fig. 8 Initial and Final optimized shape of the product and the two halves of virtual produced die for both batches in all three cases.

Table 3 The reduction percentage in total cost for both objective functions (minimum global cost & minimum weight)

	Reduction in total Cost (%)			
	Batch 50		Batch 5000	
No. of holes	Global Cost Objective	Weight Objective	Global Cost Objective	Weight Objective
One	28.49	1.59	38.06	35.08
Two	28.57	0.92	40.39	36.82
Three	28.64	0.65	48.28	44.66

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