Molding gate optimization for weld line location away from structures loaded area

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Abstract. Weld lines, generated during injection molding, can significantly reduce the mechanical performance of structures. The choosing optimal gate location technique has been developed to set weld lines as far as possible from the region of maximum stresses. A flat product case was considered as an example of a typical aircraft structural element – a pin-joint lug molding from short-fiber reinforced thermoplastic composite material. The Golden-Section search method allowed to solve the optimization problem. Autodesk Moldflow in batch mode controlled by Matlab code through Synergy API was used to solve the direct molding task of determination of the weld line location from gate location dependence. An experiment of the lugs injection molding from several gate positions was carry out to verify the numerical weld line prediction. The solved problem allows choosing the gate position for ensuring the weld lines location away from structures loaded area.

1. Introduction
The gate location influences the mechanical characteristics of the injection-molded products. Gates are subject to requirements that ensure a balanced filling process and achieve a uniform distribution of pressure and temperature, which allows to significantly reduce deformation of the part [1,2]. When molding such products, when the flows are combined after the obstacles, weld lines are formed [3], which affect the strength of the product in this area. Control the weld line location by changing the gate location and wall thickness [4]. Chun [5] showed the effect of the thickness and location of the gate on the formation and position of the weld line. Dzulkpiapia and Azuddina [6] investigated the effect of melt injection temperature and pressure, as well as the technology of manufacturing the injection part on the quality of the weld line. Hopmann and Onken [7] experimentally assessed the strength of the weld lines created by obstacles of different geometric shape. The strength of weld lines decreases as filler content increases [8,9].

It is urgent to solve the problem of design automation of the gate, taking into account the requirements of stiffness and strength of manufactured products. There are several methods for optimizing the gate location: an empirical search method for analyzing general optimization methods [10], a random search method, a combined optimization scheme [11]. Yang [12] developed a method to optimize the gate location based on minimizing the filling pressure of the mold, the uneven filling and the temperature difference in the process of filling the mold.

Autodesk Simulation Moldflow [13,14] and Moldex3D [15], a comparison of which is presented in [16], are the main CAE products for solving the direct task of modeling injection molding. Their work
is based on the Hele-Shaw model, which implements an approach combining finite element methods (when calculating pressure, etc.) and finite differences (when calculating temperature distribution, etc.) [17].

Composites reinforced by short fibers find application in cases where the shape of the product is difficult to make from multi-layer composites, or in cases where loads are applied in such a way that these composites encounter a delamination problem. Lugs are a typical structural element containing stress concentrators and transmitting large concentrated loads of variable direction. Lugs are used to connect many major components of the aircraft, including for attaching engines to pylons, for connecting ailerons, flaps and spoilers to wings, and also for the actuator mechanisms on landing gear [18]. Many aircraft failures in the past were caused by damages at lug joints, therefore, ensuring the structural integrity of these joints is an important issue in the design of aerospace components [19]. Molding of lugs is associated with the flow around the axis of the lug, which leads to the formation of weld lines. The choice of the optimal location of gates allows to control the weld line location and ensure that it is located in the least loaded area of the lug. The purpose of this work is to automate the optimal location of gates at lugs molding to ensure maximum removal of the weld line from stress concentration areas.

2. Methodology

2.1. Formulation of the problem

Antoni and Gaisne showed in [20] that the maximum equivalent stress point locates \( \varphi_{\text{max, EQV}} \approx 81^\circ \) from the line of loading force application (figure 1a). The variable direction force transmission is the purpose of pin-joint application. Consider a lug loaded with changing between 0° and 60° direction force (from \( F_1 \) to \( F_2 \), \( \angle(F_1,F_2) = 60^\circ \)). The range of force and the loaded area location are shown in figure 1b.

Weld line that inevitably occurs during the flow around the holes of the lugs in their production by molding from short reinforced composite materials is the weak spot of the lug. The weld line location is determined by the gate location. We find the optimal gate location to set the weld line as far as possible from the area of maximum equivalent stress location.

Finding the gate location is the inverse of the molding problem. We solve the inverse problem through a sequence of direct tasks as an optimization problem. The quality criterion as a function of the gate location can be determined by the minimum of angles between weld line and points of maximum equivalent stress location (1):

\[
k = \min(\Delta \varphi_{\text{up}}, \Delta \varphi_{\text{down}}),
\]

where \( \Delta \varphi_{\text{up}} = \varphi_{\text{weld}} - \varphi_{\text{up}} \), \( \Delta \varphi_{\text{down}} = \varphi_{\text{weld}} - \varphi_{\text{down}} \) - the angle between the weld line and the boundary of the area of maximum stresses on up and down side of the lug (figure 1b), \( \varphi_{\text{up}} = 60^\circ + 81^\circ = 141^\circ \), \( \varphi_{\text{down}} = -81^\circ \), \( \varphi_{\text{weld}} = f(\varphi_{\text{gate}}) \) – the result of solving a direct molding problem.
The optimization task is set as a search for the maximum of \( k \) criterion with a restriction on the gate location coordinate \( \varphi_{\text{gate}} \in [\varphi_{\text{min}}, \varphi_{\text{max}}] \). This formulation of the maximin problem allows setting the weld line as far as possible from the loaded area of the lug. We’ve supposed \( \varphi_{\text{min}} = -20^\circ, \varphi_{\text{max}} = 80^\circ \) (figure 1b).

2.2. Solution method
To solve the optimization problem Golden-Section search method [21] was implemented as Matlab code (figure 2a). Criterion function \( k \) calculated by equation (1) which requires the calculation of direct molding problem \( \varphi_{\text{weld}} = f(\varphi_{\text{gate}}) \). The for cycle consist of 30 iterations or brakes if dividing the optimization segment leads to \( \varphi_1 \) and \( \varphi_2 \) corresponds to one mesh node.

**Figure 2.** Solution flowchart: (a) Golden-section search, (b) direct task solution at Matlab using Moldflow through API.
To calculate molding Autodesk Moldflow 2019 was used in batch mode. The calculation was controlled due to Synergy Application Programming Interface (API) .vbs scripts, automatically generated by Matlab code at each iteration (figure 2b). The mesh and process settings generate only at the first iteration. Gate creation (at first iteration) and gate moving (at next iterations) carry out after mesh generation therefore we attached to the gate node number which is found by separately Matlab function based on UDM mesh analysis and determining the closest node to the given gate coordinates. Moldflow weld line calculation results are exported to a .xml file. Weld line is considered as a line, in which the angle of meld front convergence does not exceed 135°, where 0° corresponds to converge head-on. Based on an analysis of the imported through .xml weld line coordinates, the Matlab function determines the mean weld line angle $\phi_{weld}$.

3. Experimental part
The injection of the 3 mm thickness lugs from several gate positions (figure 3) is conducted for the verification of the direct problem of determining the dependence of the weld lines position with respect to the gate position. The molten material is polyamide 6, 30% carbon fiber reinforced, was injected in a Negri Bossi VE 210-1700. The melt temperature was 260 °C, mold temperature was 170 °C, the filling was performed at a flow rate of 19.8 cm$^3$·s$^{-1}$. The filling front is presented in figure 4.

![Figure 3. Lugs mold from several gate positions.](image1)

![Figure 4. Filling front, $\phi_{gate}$: (a) 105°, (b) –66° and 0°, (c) 115°, (d) 90°.](image2)

Determination of the weld lines was simulated in Autodesk Moldflow with a mesh conformed by 756 681 tetra elements (figure 5). The average element edge size is 1.5 mm, which corresponds to 9° and 18° of the outer and inner arc lengths. Experimental and numerical model fill time comparisons are presented in figure 6. The difference in the numerical and experimental front filling (gate location at 0° in figure 6b) is due to the simulated and produced gate width, 2 mm and 2.3 mm respectively which represents a 15% gate widening.

For assessing the weld line position were investigated not fulfilled injections. The gate position at 105°, –66° and 0° was investigated for 10 samples (table 1), and the gate position at 115° and 90° for 2 samples (table 2). $\phi_{gw}$ in tables 1 and 2 means the angle between gate and weld line.
Experimental verification has shown that the weld line numeric prediction error isn’t large than mesh element scale. The difference between the experimental and numerical values in the cases 105°, –66°, 0° and 115° was less than 7°, in the case 90° the difference was 10.2°, hence, the differences are lower than the arc’s length which confirms that the used calculation method provides high numerical accuracy.

**Figure 5.** Weld line prediction.  
**Figure 6.** Experimental and numerical model fill time comparison, \( \varphi_{\text{gate}} \): (a) 105°, (b) -66° and 0°, (c) 115°, (d) 90°.

**Table 1.** Weld line in experiments and numerical model comparison in 105°, –66° and 0° gate position cases.

| 105° gate case | –66° gate case | 0° gate case |
|----------------|----------------|--------------|
| **Lug** | \( \varphi_{\text{gate}} \) | \( \varphi_{\text{weld}} \) | \( \varphi_{\text{gw}} \) | **Lug** | \( \varphi_{\text{gate}} \) | \( \varphi_{\text{weld}} \) | \( \varphi_{\text{gw}} \) | **Lug** | \( \varphi_{\text{gate}} \) | \( \varphi_{\text{weld}} \) | \( \varphi_{\text{gw}} \) |
| 1 | 104.5 | –89.3 | 193.8 | 1 | –66.0 | 137.9 | 203.8 | 1 | –5.2 | 176.9 | 182.1 |
| 2 | 104.5 | –88.6 | 193.1 | 2 | –67.6 | 137.3 | 204.9 | 2 | -4.6 | 175.4 | 180.0 |
| 3 | 104.3 | –88.4 | 192.7 | 3 | –67.6 | 139.7 | 207.3 | 3 | -4.6 | 174.9 | 179.5 |
| 4 | 103.6 | –85.5 | 189.1 | 4 | –66.4 | 140.6 | 207.0 | 4 | -4.9 | 178.0 | 183.0 |
| 5 | 105.5 | –88.4 | 193.9 | 5 | –65.2 | 137.8 | 203.0 | 5 | -4.5 | 174.9 | 179.4 |
| 6 | 105.2 | –87.3 | 192.5 | 6 | –66.3 | 140.9 | 207.2 | 6 | -4.4 | 176.3 | 180.7 |
| 7 | 105.0 | –89.2 | 194.2 | 7 | –66.1 | 138.1 | 204.2 | 7 | -4.1 | 176.6 | 180.7 |
| 8 | 105.4 | –88.1 | 193.5 | 8 | –66.0 | 140.8 | 206.8 | 8 | -3.1 | 176.6 | 179.7 |
| 9 | 105.1 | –88.6 | 193.7 | 9 | –67.1 | 142.2 | 209.3 | 9 | -3.4 | 176.0 | 179.4 |
| 10 | 104.9 | –86.7 | 191.7 | 10 | –66.2 | 141.2 | 207.4 | 10 | -4.3 | 176.2 | 180.5 |

**Mean** | 104.8 | –88.0 | 192.8 | **Mean** | –66.4 | 139.6 | 206.1 | **Mean** | -4.3 | 176.2 | 180.5 |

\( \sigma_{\text{sample}} \) | 0.6 | 1.2 | 1.5 | \( \sigma_{\text{sample}} \) | 0.8 | 1.7 | 2.0 | \( \sigma_{\text{sample}} \) | 0.6 | 1.0 | 1.2 |

**Model** | 105.3 | -90.8 | 196.1 | **Model** | –66.2 | 135.5 | 201.7 | **Model** | 0 | 180 | 180 |
Table 2. Weld line in experiments and numerical model comparison in 115° and 90° gate position cases.

|          | 115° gate case | 90° gate case |
|----------|----------------|---------------|
| Lug      |                |               |
| 1        | 116.4          | 91.4          |
| 2        | 115.7          | 89.7          |
| Mean     | 116.0          | 90.5          |
| σ<sub>sample</sub> | 0.5          | 1.2          |
| Model    | 114.3          | 90            |

4. Results and discussion

Lug with length 67 mm, thickness 3 mm, outer diameter 24 mm, hole diameter 12 mm was considered. The generated mesh consists of 36413 nodes and 196797 tetra elements with average edge size 0.8 mm (figure 7). Lug mold from PA6 reinforced with 30% short carbon fibers Akro-Plastic GmbH Akromid B3 ICF 30 black thermoplastic composite material. Mold temperature is 100 °C. Melt temperature is 240 °C. Flow rate is 30 cm<sup>3</sup>·s<sup>-1</sup>.

![Figure 7. Mesh for molding calculation.](image)

The result of weld line calculating for initial iterations is shown in figure 8. If the gate is located near the lug nose, the weld line is located near the opposite side of the hole, while when the gate is located on the lug side, the weld line is shifted to the lug base.

![Figure 8. Weld lines at initial gate locations: (a) φ<sub>min</sub> = -20°, (b) φ<sub>max</sub> = 80°.](image)
The optimization problem converges for seven iterations of the Golden-section search method (figure 9), after which the $\varphi_1$ and $\varphi_2$ borders began to correspond to the same mesh node for gate location. The solution of the inverse problem required ten solutions of the direct problem – four solutions for the first iteration and six solutions for the next six iterations.

Optimum gate angle is $\varphi_{\text{gate}}^{\text{opt}} = 57^\circ$. It corresponds to the mean weld angle $\varphi_{\text{weld}}^{\text{opt}} = -147^\circ$ (deviation from the analytic value $\varphi_{\text{weld}}^{\text{exact}} = -150^\circ$ determined by the mesh) and criterion value $k = 66.3^\circ$. Weld line with optimal gate location is shown in figure 10.

![Figure 9. Convergence plot.](image)

![Figure 10. Weld line after gate optimization.](image)

5. Conclusion
A technique has been developed for choosing the optimal location of material entry points when molding flat products in such a way that the weld lines in the structures are located far from the loaded areas. The Golden-Section search method allowed leading the inverse problem to the sequential solution of ten direct problems solvable using Autodesk Moldflow in batch mode controlled by Matlab code through Synergy API.

The experiment of the lugs injection molding from several gate positions is conducted for the verification of the dependence of the weld lines position with respect to the gate position. Comparison with experiment shows that the simulation results highly accurate represent filling front and weld line position – weld line prediction error does not exceed element mesh scale. Considering the gate position...
in the manufacturing of lugs will increase their strength and can be used in the design of aerospace components.

The used Golden-Section search method has shown itself well in the one-dimensional problem of optimizing the gate location along the boundary of a flat products. Investigation of the gate optimization problem for the spatial structures molding as well the multi gates cases are the topics for future studies. Their solution may require other optimization methods, including the use of a genetic algorithm, while the verified approach for solving the direct problem of molding simulation in batch mode can be used in optimization problems regardless of the number of gates and the shape of structure.

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