and secondly taking into account the possibility of minimizing weldlines through the various process parameters in injecting real parts. The weldlines in parts produced under different conditions were quantified in order to optimize the injection conditions which can offer minimal weldline width.

Methodology

Methods of Weldlines Improvement

The formation of weldlines is a complex phenomenon, influenced by the filling pattern which in turn being impacted by various factors during the filling phase such as melt temperature, mold temperature, injection speed and the part geometry, as addressed by various studies [1, 2, 5]. The weldline positions can be very well calculated by CAE software, or identified by visual inspections. In the meanwhile, characterizing the size of weldlines requires a lot more investigation. In order to improve weldlines, one should look into two aspects:

- The method of characterizing weldlines, i.e. quantifying the geometry as well as other characteristics of the weldlines.
- The study of factors influencing the formation of weldlines, doing sensitivity analyses of the factors and trying to quantify the impact of each factor.

In efforts to characterize possible weldlines, two types of tools can be well used. A straight forwards method is to characterize the weldline geometry under microscopic view which is in suitable range with the weldlines. According to the formation of weldlines, important geometries can be the width, the depth and the length of the weldline relative to the part geometry.

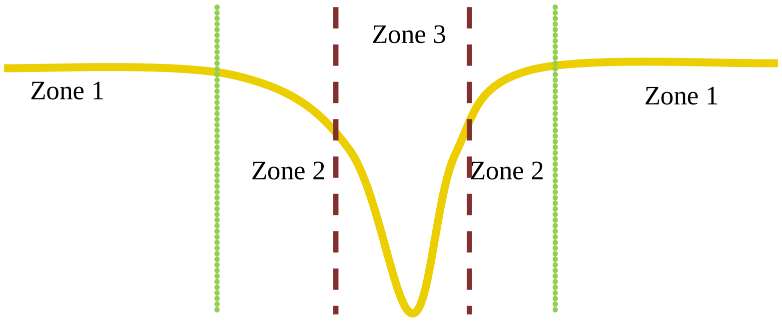
Nevertheless, investigating factors influencing the weldline formation shows that even if the hardware factors for one mold set, such as gate and venting systems, are not changed, one can influence the filling pattern by changing the soft factors such as the mold temperature, the melt temperature and the flow speed. Increasing the values of such factors often result in an improvement of the weldlines. One should take into account also that, the general process window as well as other product specification should be well respected during alternating such soft factors. The approach for this part of the research is to firstly establish a realistic process window, secondly to establish the test points for collecting data and to understand the impact of each factor in order to move to the next process window for optimization.

In this experimental study, the data were collected in a systematic way from the actual injection tests. Studying the real parts produced under various process conditions is the most suitable way to observe the effect of the soft factors under real productions.

In this phase of the study, characterizing the weldlines focus on measuring the width of the weldlines. In parallel, only the soft factors such as the melt temperature (T_{melt}), the mold temperature (T_{mold}) and the injection speed (V_{inj}) are considered.

Experiment Perspective

The cross section of weldlines can be seen similar to a V-shape where in most cases the outer edges are not always sharp. Under microscopic view, these areas are normally in the grey zone (Zone 2) with position depending on the lighting on the part surface. Only from a certain point of the V-edge (Zone3) that the contrast between the inner part of the V-shape and the part surface is well seen, as illustrated in Figure 1.



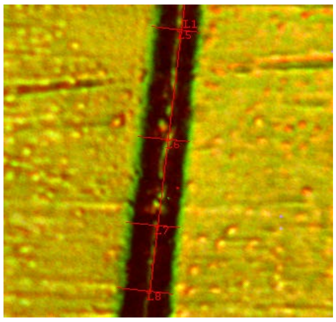


Figure 1. Weldline width definition

In this study, samples were produced in batches under various injection conditions and afterwards examined under microscope for weldlines characterizing and examining the influence of changing the process parameters on weldline improvement of specific models.

Normally in industrial practice, the lower range of the process window is selected for production parameters in order to minimize the energy cost for production as well as minimizing the possibility for plastic degradation due to high temperature and pressure. The parameters will be adjusted only when errors such as incomplete filling or weldlines occur. The actual experiment was therefore planned into two series of tests:

Test 1: The lower bound of the process window is selected. The data of the weldline widths will be collected and analyzed to observe the trend for adjusting the parameter to the other corner of the process window.

Test 2: Base on the new process window, a new set of parameters are tested to find the best solution for the weldline width problem.

For the current material PC EH1050, the estimated process window for temperature is between 60-120ºC, while the melt temperature is between 280-330ºC.

An explanation of location of the two tests on the window of the process parameters defined by plastic melt temperature and mold temperature is seen in Figure 2.

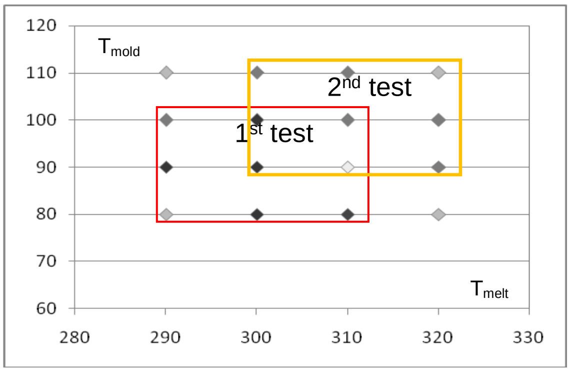


Figure 2. Location of the tests in process window of T_{melt} vs. T_{mold}

Result and Discussion

Test 1: Lower Range of Process Window

In Test 1, 7 different conditions as shown in Table 1 were tested. The parameters of the test were chosen so that the offered conditions were just enough to completely fill the cavity. This test therefore explored the lower part of the process window.

Table 1. Various Molding Conditions for Test Shot 1

	P00	**P10**	**P20**	**P30**	**P40**	**P50**	**P60**
$\mathbf{T_{melt}}$	300	300	300	290	310	300	300
$\mathbf{T_{mold}}$	90	100	80	90	90	90	90
$\mathbf{V_{inj}}$	30%	30%	30%	30%	30%	20%	40%

The samples collected for each condition were measured using microscope to obtain the width of the weldlines. The results obtained for each condition were summarized in Figure 3.

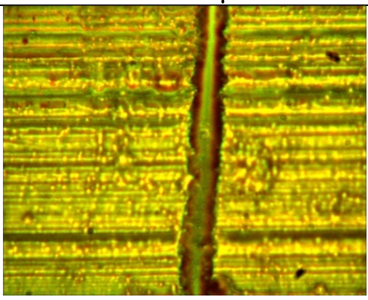
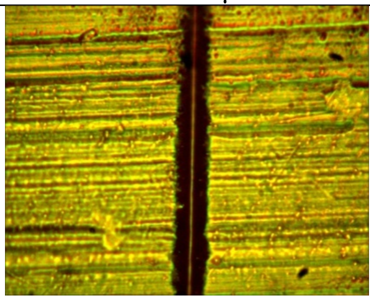
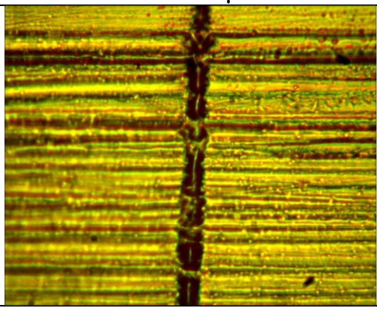
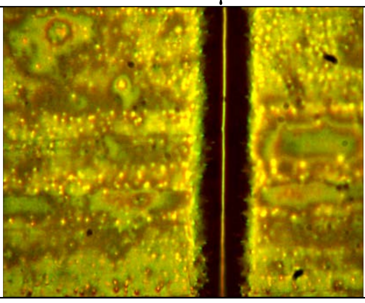
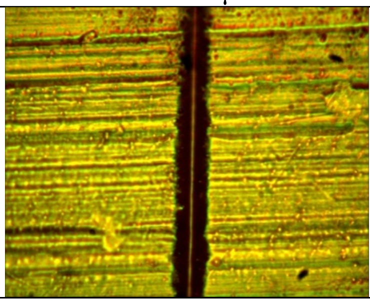
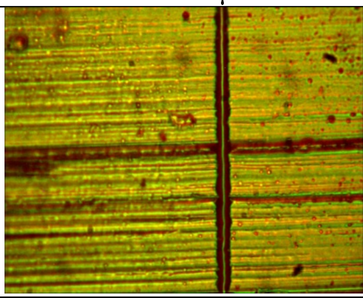
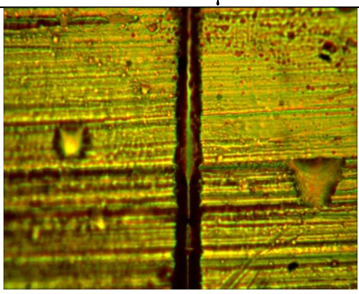
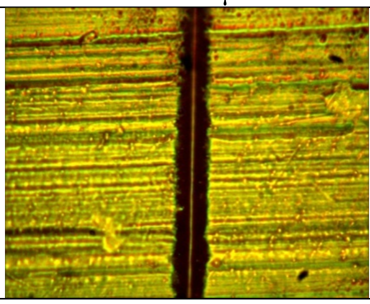
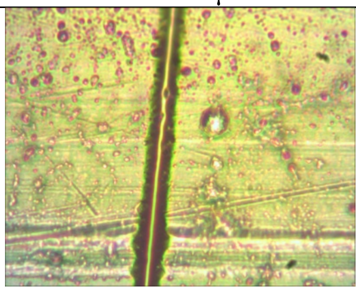
Samples in Variations of Mold Temperature (°C)		
P20	P00	P10
Tmold = 80°C	Tmold = 90 °C	Tmold = 100 °C
W = 4.25 μms	W = 4.04 μms	W = 3.13 μms
		
Samples in Variations of Melt Temperature (°C)		
P30	P00	P40
Tmelt = 290°C	Tmelt = 300 °C	Tmelt = 310 °C
W = 6.54 μms	W = 4.04 μms	W = 2.04 μms
		
Samples in Variations of Injection Speed (%)		
P50	P00	P60
V_{inj} = 20%	V_{inj} = 30%	V_{inj} = 40%
W = 3.45 μms	W = 4.04 μms	W = 3.62 μms
		

Figure 3. Characterizing weldline on various condition under microscope for Test 1

Discussions

Provided that the weldline widths were measured and averaged over a length of about 12-20 μms, provided the parts measured were produced under varying conditions regarding Mold Temperature (T_{mold}), Melt Temperature (T_{melt}) and Injection Velocity (V_{inj}), the experiment data shows that:

- Increasing Melt Temperature has the most obvious and significant improvement of weldline. Increasing in Melt Temperature shows very nice improvement of weldline. Under the current condition, increasing Melt Temperature over 310^oC helps the weldline to be almost invisible to the naked eyes. This can be explained by the reduction of resin viscosity at high temperature that helps a better flow pattern and reducing cold welds at the positions where flow fronts meet.
- Increasing Mold Temperature has also obvious improvement of weldline, but not as highly significant as the Melt Temperature. Therefore, it can also be considered as a factor to be used to control weldlines. It was the higher temperature of the mold that also reduce the cold welds and thus lowering the weldline widths.
- Increase in Injection Velocity does not seem to have relevant improvement of weldline.
- Varying injection parameters such as Mold Temperature, Melt Temperature can be used to improve weldline, but should be used in consideration with process windows based on other specifications such as warping, sizing, cycle time, etc.
- For the current data, process condition P40 (T_{melt} 310, T_{mold} 90, V_{inj} 30%) has result in best weldline condition.
- Visual observations using naked eyes show that: The variations of the weldline width are normally not well observed if there is a case of visible weldline or invisible weldline. The visible weldlines are of width normally above 3μms to the medium trained eyes, i.e. the operator has about 1 week to get used to the observations. There is a grey zone when weldlines are both considered visible to some operator and invisible to the others, when weld line width is between 1.5-3 μms.

Test 2: Upper Range of Process Window

After the lower process window was explored in Test 1 and correlations were identified, it was shown that by changing the chosen process parameters to the upper bound seemed to promise an optimized condition for weldlines. Test 2 aimed at more thoroughly exploring the upper process windows to specify more carefully the correlations between the parameters and the weldlines values in order to find an optimized condition for a specific model.

Table 2. Weldline Width in μm under Molding Conditions for Test Shot 2

Test group #	Condition	Tmelt (°C)	Tmold (°C)	Vinj		
				20%	30%	40%
1	P1x	300	90	1,677	1,910	1,520
2	P2x	310	90	1,306	1,094	1,096
3	P3x	320	90	1,080	0,934	0,915
4	P4x	300	100	1,322	1,231	1,238
5	P5x	310	100	0,972	1,008	0,952
6	P6x	320	100	0,773	0,732	0,705
7	P7x	300	110	1,692	1,646	1,133
8	P8x	310	110	0,825	0,748	0,794
9	P9x	320	110	0,545	0,624	0,684

In detail, Test Shot 2 is to find an optimal point in the process window regarding the weldline width by exploring the upper values of the parameters such as the Melt Temperature, the Mold Temperature and the Injection Velocity.
The response surface was plotted for Test 2 as seen in Figure 4. The result obtained showed that the average weldline width can reach the maximum value of almost 2 μms and the minimum value of 0.5 μms. Though they can rather be well-detected under microscope views, the weldlines of width below 1 μm are almost invisible to the naked eyes with observation time under 30 seconds. They are even dominated by the actual surface scratches.
The average weldline width obtains the highest values under conditions of P1x and P7x, where the factor plays the important role in such values can be detected as the low Melt Temperature T_{melt}. The conditions resulted in average weldline widths of less than 1 μm are Conditions P2x, P3x, P5x, P6x and P8x, P9x.

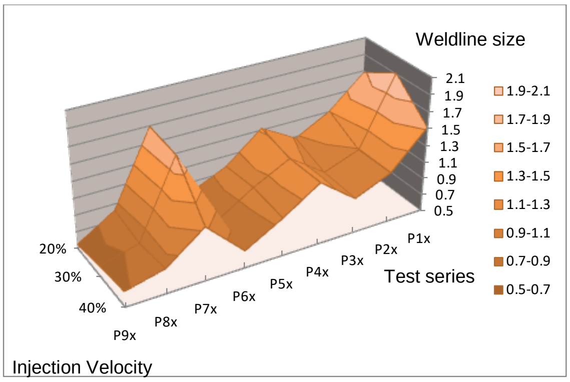


Figure 4. Response surface plot for Test 2

In general, it can be observed that:

- Increasing the Melt Temperature has the most crucial effect. This also agrees with the conclusion of Test 1. Sensitivity analyses on Melt Temperature showed that when keeping T_{mold} constant, at all Mold Temperatures, increase of Melt Temperature by 10°C to 20°C can help obtain the effect of weldline reduction of 20% to 40%, where the most significant improvement is formally seen when changing the Melt Temperature from 300°C to 310°C. The non-linearity of the improvement as compared to Test 1 can be explained by the non-linearity of the resin characteristic in response to the resin temperature.
- Increasing the Mold Temperature also has a good effect. A minor effect is attached to the Injection Velocity. Keeping the Melt Temperature constant, the average effect of changing the Mold Temperature T_{mold} can be examined. At Melt Temperature of above 310°C, there is an obvious reduction of weldline width while changing the Mold Temperature. An average improvement of 15% to 40% can be obtained if the Mold Temperature is increased from 90°C to 100°C or 110°C. The effect of changing the Mold Temperature is somehow similar between changing from 90°C to 100°C and 100°C to 110°C. A similar phenomenon is expected to be seen for T_{melt} of 300°C. However, the values obtained from P7x do not correspond to the whole system and should be checked.
- Keeping the Melt Temperature and the Mold Temperature constant, the average effect of changing the Injection Velocity can be examined. It can be seen that the effect of Injection Velocity exists yet quite minor as compared to the effect of Melt

Temperature and Mold Temperature. On average, increasing the Injection Velocity from 20% to 30% and 40% could well help to obtain a reduction of 3% up to more than 10% of the weldline width. The effect can be enhanced with good combination of Melt Temperature and Mold Temperature. Using lower Melt Temperature, the effect of increasing the Injection Velocity is more obvious, while using higher Melt Temperature of 310°C or 320°C, increasing the Injection Velocity to more than 30% is not recommended. On the contrary, a good improvement in weldline width can be seen in all cases of increasing the Injection Velocity to more than 30%. An improvement of more than 10% can be obtained.

According to the obtained results, one can see that the weldline problem can be very well reduced by changing the injection parameters, where the most important factors are the Melt Temperature and the Mold Temperature. The general explanation of the phenomenon is that the increase in those temperatures helps a better flow pattern and reduced cold welds.
From 27 optimization points obtained in Test 2, weldline width factor can be optimized to the minimum value of around 0.5 μms, reached by setting the condition to P91. A similar group of values for P92, P93 and P6x. However, setting the production under such conditions of very high Melt Temperature of 320°C should be carefully considered due to possible resin degradation. A trade-off can be found for P8x where the Melt Temperature is set to 310°C and the Mold Temperature is at 110°C where a weldline width of 0.8 μms was obtained. According to the visual and microscopic observations of the approved parts, the average weldline width of the approved parts ranged between 0.8-1.2 μms.

Conclusions

The current research has studied the causes of weldlines as well as methods to control weldline. The technical achievement includes more understanding about the part approval process, the process windows and the methods to improve weldlines on parts with no aesthetic cover of paint. Two series of tests have focus on factor analyses and optimization of weldline by changing the factors within the process windows. While Test 1 was an initial test that showed the response trends for changing process parameters, as well and the possibility for weldline improvement, Test 2 merely focused on DOE for optimal molding condition where minimal weldline width was considered as the target.

Acknowledgement

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