“WHY CORROSION RESISTANT SCREWS CAN BIND IN THE EXTRUDER BARREL”

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INTRODUCTION

In the extrusion of fluoropolymers the extruder screw and die generally have to be made out of a highly corrosion resistant material. Common materials used for this purpose are Hastelloy, Monel, Inconel, and Duranickel. These materials not only have corrosion resistance that is much better than the typical 4140 steel that is used for most extruder screws, there are other properties that are quite different from 4140 steel as well. As a result of these other properties these corrosion resistant screws are much more susceptible to getting stuck in an extruder barrel than screws made of 4140 steel. Since screw binding usually results in considerable damage to the extruder with associated downtime and cost, not to mention aggravation, it is important for processors to be aware of the pitfalls of using screws made out of highly corrosion resistant materials.

THE MECHANICS OF SCREW BINDING

When a screw is installed in an extruder the typical radial clearance between the screw and the barrel is 0.001D, where D is the diameter of the extruder. This is the clearance at room temperature. When the machine is in operation the actual clearance between the screw and the barrel can be quite different. There are two main reasons for the change in clearance under actual processing conditions. One reason is temperature, the other is compressive load on the screw. When the processing temperature is much greater than room temperature, the clearance can change when a) the coefficient of thermal expansion (CTE) of the screw and barrel is different and b) the temperature of the screw is different from the barrel.

CHANGES IN CLEARANCE DUE TO TEMPERATURE

When the screw and barrel increase in temperature, both the screw and barrel will increase in diameter due to thermal expansion. If the CTE of the screw is greater than the barrel, the clearance between the screw and barrel will reduce with increasing temperature. Values of the CTE for several materials are shown in table1 together with data on thermal conductivity, and elastic modulus.

For a 25.40 mm (1.000”) barrel running at 333.3°C (600°F) above room temperature, the increase in I.D. is 9.652E-2 mm (0.0038”) when the CTE is 11.34/°C (6.3E-6/°F). For a 25.3492 mm (0.998”) Monel screw with a CTE of 13.86E-6/°C (7.7E-6/°F) running at 333.3°C (600°F) above room temperature, the increase in screw diameter will be 0.1168 mm (0.0046”). Thus, the difference between the thermal expansion of the screw and barrel diameter is about 0.02 mm (0.0008”) or 0.01 mm (0.0004”) based on the radius. If the radial clearance is 0.0254 mm (0.0010”), the clearance will reduce to 0.01524 mm (0.0006”) due to the differential thermal expansion. Thus, the clearance is reduced but still greater than zero provided both the screw and barrel are at the same temperature.

In an operating extruder, however, it is not very likely that the screw and barrel are going to be at the same temperature. The largest difference between the screw and barrel temperature is likely to occur in the feed throat. The feed throat of most extruders is water cooled and, therefore, close to room temperature in many cases. The screw temperature in the feed section, however, can be (and in many cases will be) much higher because the high temperatures in the compression and metering section will raise the feed section temperature due to thermal conduction.

If the feed throat is maintained at room temperature and the screw temperature in the feed section is 166.7°C (300°F) higher, then the screw diameter will increase from 25.3492 mm (0.998") to 25.4076 mm (1.0003") if the CTE=13.86E-6/°C (7.7E-6/°F). This corresponds to 0.0023 mm per mm (inch per inch) of screw diameter. The screw diameter now is larger than the diameter of the feed throat and the screw will bind! The question can be asked, is this temperature difference not equally likely to occur in a screw made out of 4140 steel? The answer is no and the reason has to do with the thermal conductivity of these materials. The thermal conductivity of corrosion resistant metals tends to be considerably lower than that of steel, by a factor of three to five, see table 1.

The lower thermal conductivity of corrosion resistant materials will reduce the amount of heat that can be transferred from the screw shank to the reducer. As a result, the shank and feed section of the screw will be at higher temperature as compared to a high conductivity screw. Figure 1 shows the thermal expansion graphed against the temperature difference between the screw and barrel. The graphs shows several values of the coefficient of thermal expansion. From figure 1 it is clear that it takes only a temperature difference of about 167 to 222°C (300 to 400°F) to have the screw lock up in the barrel, considering that the coefficient of thermal expansion is in the range of 10E-6 to 17E-6/°C (6E-6 to 10E-6/°F). It is clear that if a polymer is processed at 371°C (700°F), it is quite possible that the screw temperature will be more than 167°C (300°F) above the barrel temperature.

When viscous heating is significant, the screw temperature will tend to be higher than the barrel temperature, at least with a neutral screw. Janssen et al. (1) found that in extruders without screw cooling the screw temperature gives a much better indication of the mean polymer temperature than does the barrel temperature. Finite element analysis of non-isothermal, non-Newtonian flow in extruders (2) also found that screw temperatures tend to be higher than barrel temperatures when viscous heating is significant. As a result, the screw temperature in the metering section of the screw may be significantly higher than the barrel temperature. Therefore, the temperature difference between screw and barrel in the feed section may be greater than what might be assumed based on the measured barrel temperatures.

Few publications are available that provide data on screw and plastic temperatures along an extruder. The publication by Marshall et al. (3) provides some interesting experimental data. They confirm that the screw temperature in the metering section is higher than the barrel temperature. Further, they measured screw temperatures in the feed section and found temperatures in the range of 115 to 127°C (240 to 260°F) with barrel temperatures of 190°C (375°F). When barrel temperatures are around 371°C (700°F), it can be expected that the feed section of the screw will be in the range of 204 to 260°C (400 to 500°F) if not higher.

FEA OF TEMPERATURE DISTRIBUTION IN EXTRUDER SCREWS

In order to confirm whether the model proposed in the previous section is correct, predictions of the temperature distribution in extruder screw processing FEP were made using finite element analysis. The program used is FEHT (4), a program developed at the University of Wisconsin - Madison.

Figure 2 shows the thermal boundary conditions that were used in the analysis; 697 nodes were used with 1280 triangular elements. The feed throat temperature is set at 15.6°C (60°F), the barrel temperatures are set at 288 (550), 371 (700), 371 (700), and 371°C (700°F), the screw shank is set at 93°C (200°F), the screw tip is at 371°C (700°F), and the heat flux at the screw centerline is zero in radial direction. The program does not take into account viscous dissipation or convection; the heat transfer is purely by conduction. The thermal conductivity of the FEP is taken as 0.246 J/ms°K (0.142BTUft/ft^{2}hr°F).

Figure 3 shows the predicted temperature distribution when the screw is made out of 4140 steel and figure 4 shows the temperature distribution in the Monel screw. Comparing figures 3 and 4 it is clear that with the Monel screw higher temperatures occur in the feed section of the screw. This must be due to the thermal conductivity since this is the only difference between the two cases. These predictions confirm that a lower thermal conductivity of the screw material can lead to higher temperatures in the feed section of the screw.

In the case of the Monel screw the screw temperatures in the feed section range from about 150 to 260°C (300 to 500°F).

CHANGE IN CLEARANCE DUE TO COMPRESSIVE LOAD

When an extruder screw develops pressure in the plastic melt to force it through a die, the pressure at the end of the screw will cause a compressive thrust load on the screw. As a result, the length of the screw will reduce, while at the same time the diameter of the screw will increase. The relative increase in the screw diameter can be expressed as:

$$\frac{\Delta D}{D} = \frac{\Delta L}{2L} = \frac{P}{2E}$$

Values of the elastic modulus for several materials is shown in table 1. If the pressure is 34.5 MPa (5000 psi) and the modulus 2.07E5 MPa (30E6 psi), the ΔD/D=8.3E-5. Thus, for a 25.4 mm (1") screw, the increase in diameter will be 0.0021 mm (0.000083"). This means that the increase in diameter due to compressive load is quite small compared to the effect of differential thermal expansion. As a result, the effect of radial expansion due to compressive load is likely to be only a minor factor in the chance of the screw locking up in the barrel.

CONCLUSION AND RECOMMENDATIONS

The analysis above confirms that corrosion resistant screws do indeed have a greater chance of locking up in an extruder than screws made out of regular 4140 steel. The main culprit appears to be the low thermal conductivity of highly corrosion resistant metals, causing a large temperature difference between the feed throat and the feed section of the screw. The higher screw temperature will cause the screw to expand much more than the feed throat and the barrel, causing the screw to bind. Finite element analysis results confirm that a lower thermal conductivity of the screw leads to higher temperatures in the feed section of the screw.

The reason that screw binding problems often occur with highly corrosion resistant materials is that these screws are typically used for fluoropolymers that are processed at high temperatures, around 370°C or 700°F. In this case there are several factors that make screw binding more likely. One, at the high process temperatures there will be a higher temperature difference between the screw and barrel in the feed section. Two, the highly corrosion resistant material of the screw has a much lower thermal conductivity than 4140 steel and, therefore, will tend to have an even higher temperature difference between screw and barrel in the feed section. Three, the highly corrosion resistant material of the screw will have a higher coefficient of thermal expansion than 4140 steel and thus expand more.

There are a number of measures that can be taken to reduce the chance of screw binding, they are:

* screw cooling of the feed section
* increased temperatures on the feed throat
* reduced temperatures in the transition section
* reduced temperatures in the metering section
* increased clearance in the feed throat region

In most cases, the best way to avoid binding problems is to reduce the screw diameter in the feed section by at least 0.002 mm per mm (0.002" per inch) of screw diameter. Since most plastics are fed in pellet form, increasing the flight clearance in the early part of the feed section is most likely not going to have an effect of the performance of the extruder. On the other hand, an increased flight clearance in the feed section will substantially reduce the chance of the screw locking up in the extruder barrel or feed throat.

REFERENCES

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2. C. Rauwendaal and J Anderson, "Finite Element Analysis of Flow in Extruders," 52nd SPE ANTEC, 298-305, San Francisco, CA (1994)
3. D.I. Marshall, I. Klein, and R.H. Uhl, "Measurement of Screw and Plastic Temperature Profiles in Extruders," SPE Journal, V.20, No.4, April, 329 (1964)
4. FEHT - Finite Element Analysis, v6.98, copyright 1996-97, S.A. Klein, W.A. Beckman, and G.E. Myers, University of Wisconsin - Madison

Material	Coefficient of Thermal Expansion, /°C [/°F]	Thermal conductivity J/ms°K [BTUft/ft^{2}hr°F]	Elastic modulus MPa [psi]
Hastelloy C276	11.16E-6 [6.2E-6]	11.25 [6.5]	2.00E5 [29E6]
Inconel 718	12.96E-6 [7.2E-6]	11.42 [6.6]	2.00E5 [29E6]
Inconel 625	12.78E-6 [7.1E-6]	9.86 [5.7]	2.07E5 [30E6]
Monel 400	13.86E-6 [7.7E-6]	21.80 [12.6]	1.79E5 [26E6]
Monel 500	13.68E-6 [7.6E-6]	17.47 [10.1]	1.79E5 [26E6]
4140 steel	11.34E-6 [6.3E-6]	42.56 [24.6]	2.00E5 [29E6]
4340 steel	11.34E-6 [6.3E-6]	42.21 [24.4]	2.00E5 [29E6]
17-4 stainless	10.44E-6 [5.8E-6]	17.82 [10.3]	2.00E5 [29E6]
316 stainless	18.54E-6 [10.3E-6]	16.09 [9.3]	2.00E5 [29E6]
304 stainless	18.72E-6 [10.4E-6]	16.26 [9.4]	2.00E5 [29E6]

Table 1, Thermal properties and elastic modulus for several materials

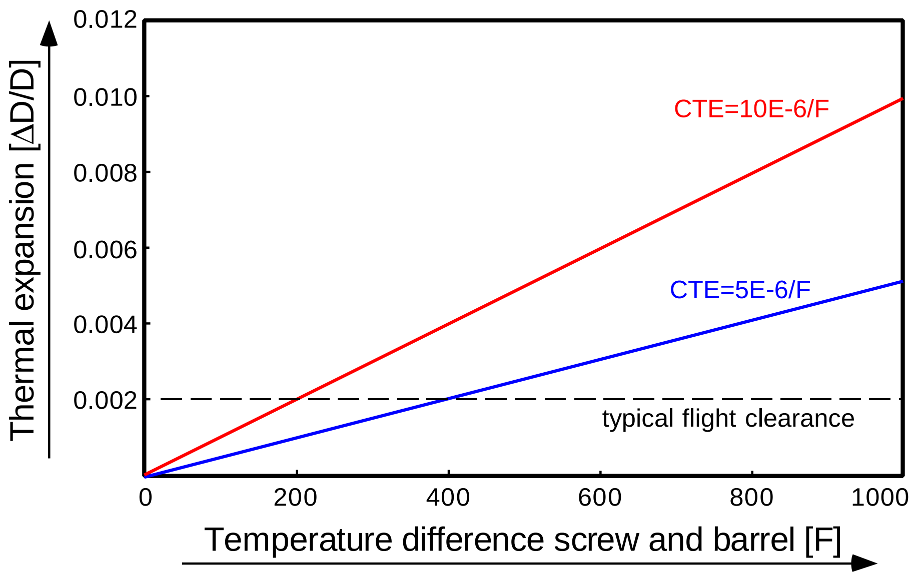

Figure 1, Thermal expansion vs. temperature difference

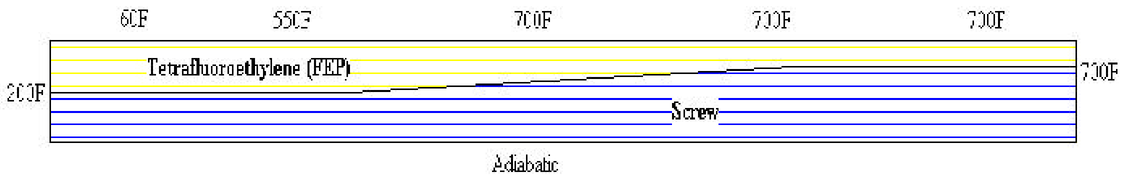

Figure 2, Schematic of thermal boundary conditions for FEA

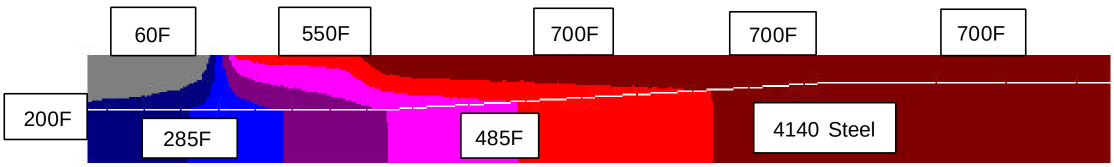

Figure 3, Predicted temperature distribution in 4140 screw

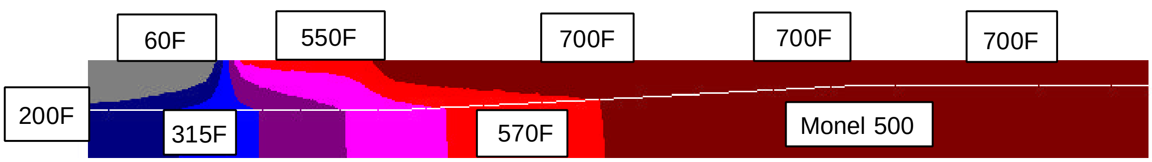

Figure 4, Predicted temperature distribution in Monel screw