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Experimental analysis of ultrasonic heating of polypropylene during ultrasonic moulding process

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Abstract

The present study shows the results obtained in the experimental measurement of polypropylene heating when applying high power mechanical ultrasounds. The objective is to understand the behaviour of the polypropylene pellets during the ultrasonic moulding process (USM). For this study, a simplified geometry has been considered (a solid cylinder), and the evolution of the temperature has been recorded with a high velocity infrared camera. The results show that the heating ratio in the polymer is non-linear and highly inhomogeneous. For the analysis of the results, the cylinder has been divided into three different regions depending on the distance from the sonotrode, and the temperature evolution shows four different steps, according to the heating mechanisms involved. Both ultrasonic amplitude and applied pressure affect the temperature evolution of the whole polymer while the change in the applied force modifies the temperature distribution in the polymer and the heating mechanisms present.

Ultrasonic Moulding Process

UltraSonic Moulding (USM) is a new moulding process powered by ultrasonic energy and specifically designed for the production of mini and micro plastic parts [(1), (2)]. This process plasticizes the polymer pushing it to a vibrating ultrasonic sonotrode. The polymer is then transferred to the mould while it is being melt. The different elements and steps involved in the process are sketched in Figure 1.

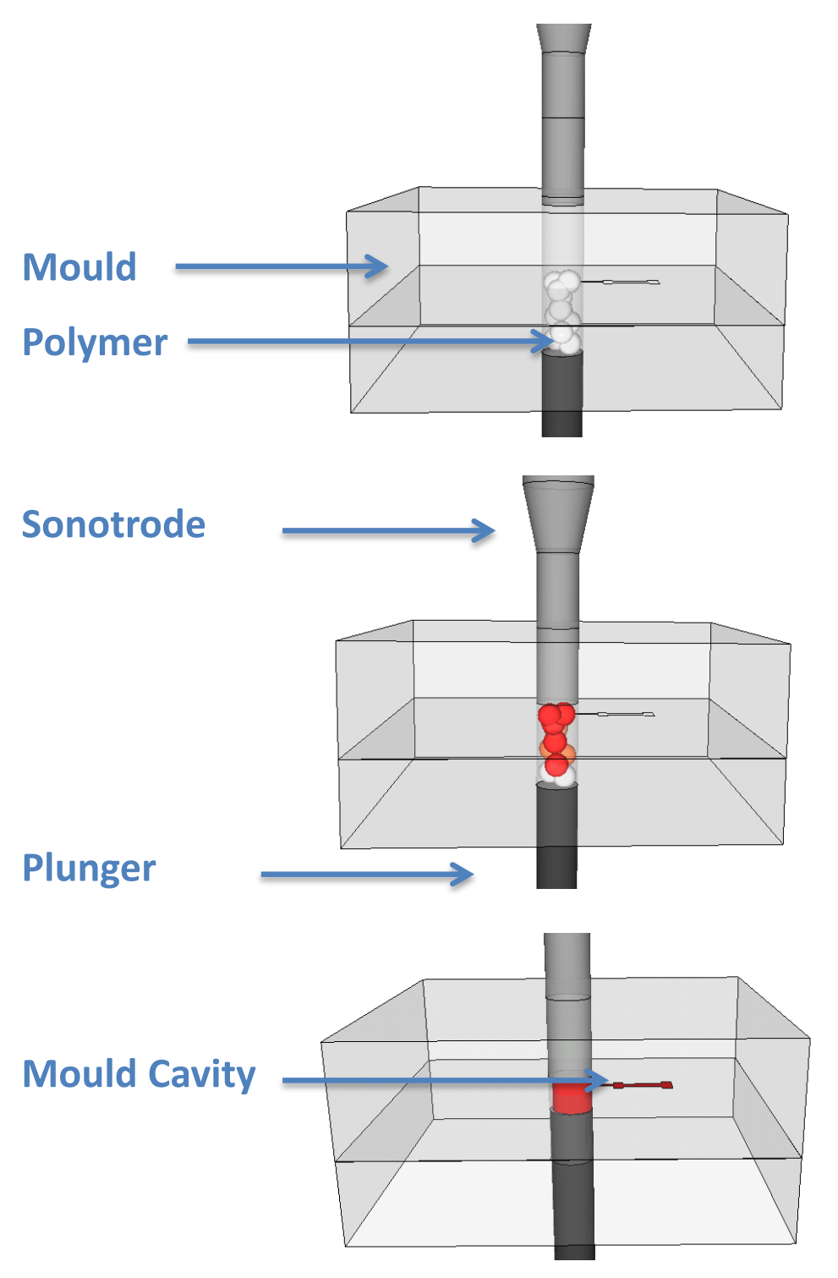
The commercial machine used for the USM process is the Sonorus 1G, manufactured by Ultrasion. The main components included in the machine are displayed in Figure 2.

Some **advantages** over conventional microinjection moulding are:

- Short time of residence at high temperatures
- Lower temperature needed to inject material
- Lower injection pressure
- Energy savings
- Material savings

On the contrary, some **drawbacks** still to be addressed are:

- Possible presence of bubbles due to cavitation
- Extremely fast heating and difficult to control
- Little knowledge in the effect of the parameters.



(1) The polymer is placed in the plastification chamber

(2) The sonotrode vibrates and melts the polymer pellets pushed by a plunger

(3) The melted polymer flows into the mould cavity

Figure 1.- Steps involved in the Ultrasonic Moulding Process

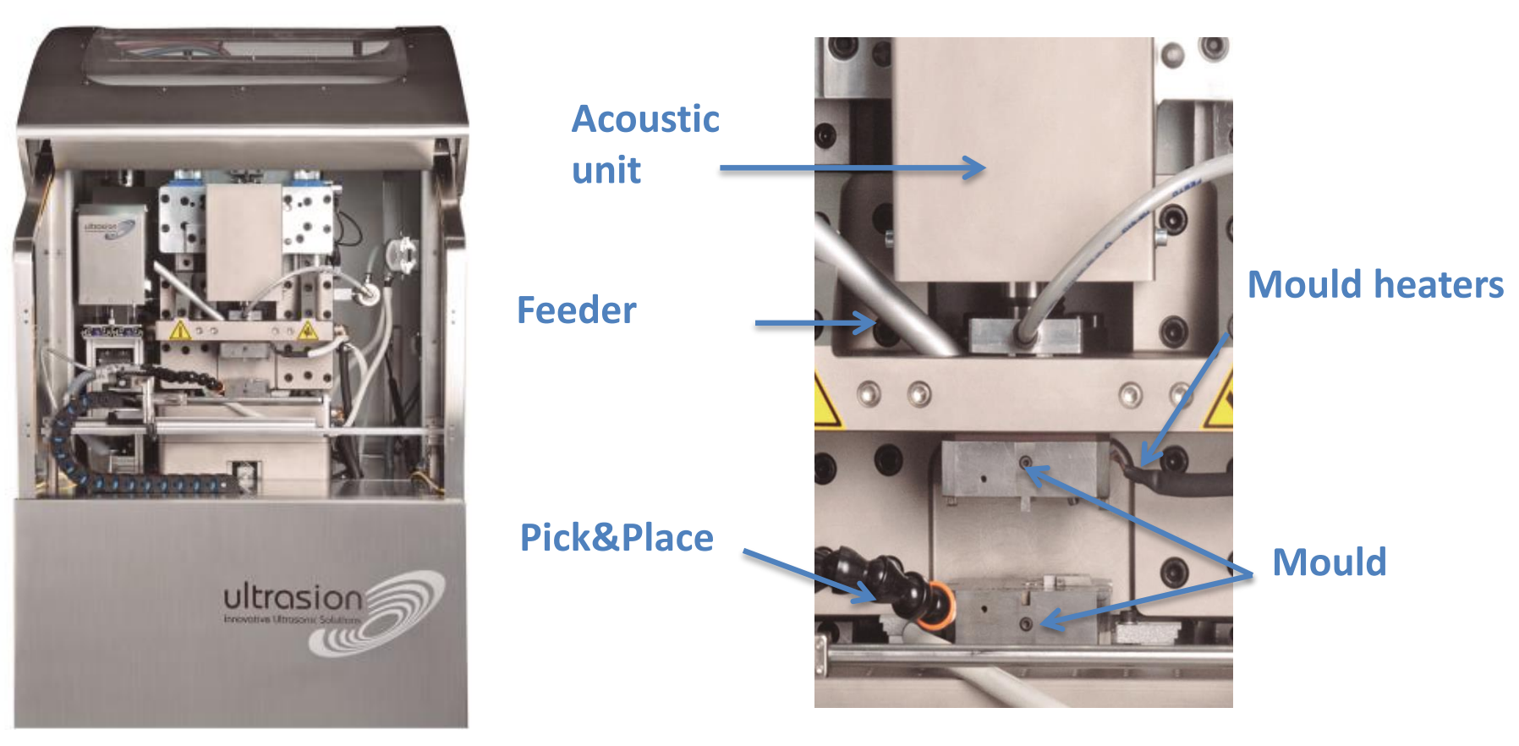


Figure 2.- Sonorus 1G machine and its main components

Experimental setup

A set of experiments have been performed with polypropylene cylinders to study the polymer heating under ultrasonic vibrations. The samples used are 8 mm diameter and 20 mm high cylinders of *Moplen HP556E* natural polypropylene. The samples are placed 5mm inside the lower partition of a mould without cavity (see Figure 3).

A SC655 FLIR infrared camera with a frame rate of 200Hz has been used to obtain the temperature during the ultrasonic heating process (see Figure 5). An external trigger is applied to synchronize the ultrasonic cycle time with the infrared camera recording time.

Figure 3.- Mould setup

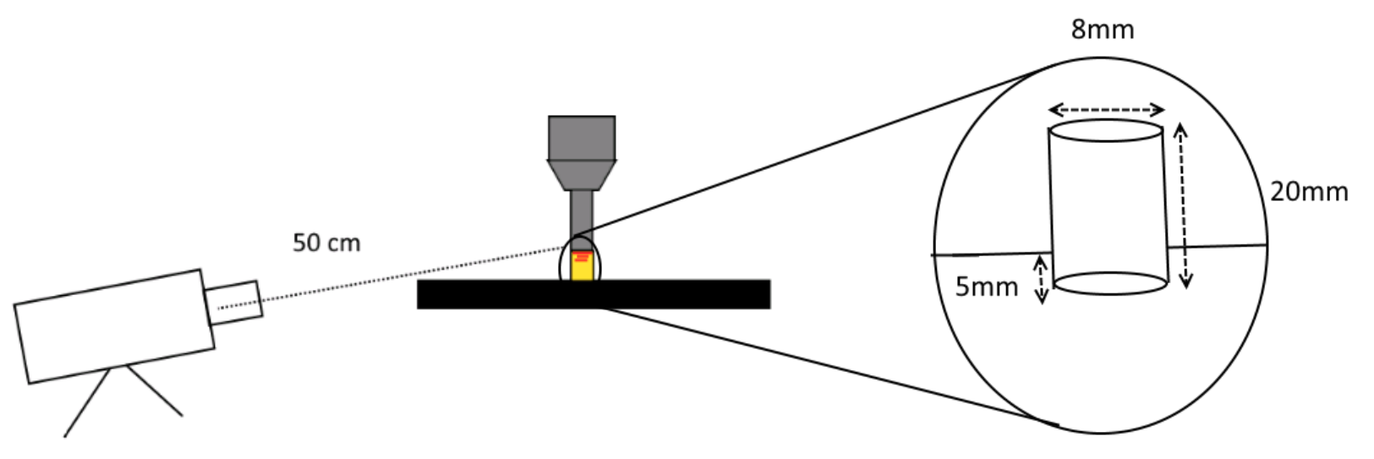


Figure 4.- Experimental measurement setup

After a preliminary test, a full factorial experiment with two factors (sonotrode amplitude and the plunger force applied to the cylinder) and two levels has been performed. An additional level with 500 N of force has been also been considered an it will be analyzed separately. For each experimental set, 10 runs have been done. The parameters used for each set are listed in Table 1.

Experimental runs	Amplitude (µm)	Plunger Force (N)
1-10	28	1000
11-20	28	2000
21-30	44	1000
31-40	44	2000
41-50	28	500
51-60	44	500

Table 1.- Experimental set

For each experiment, the temperature has been obtained and exported using *FLIR Thermacam Researcher®* software

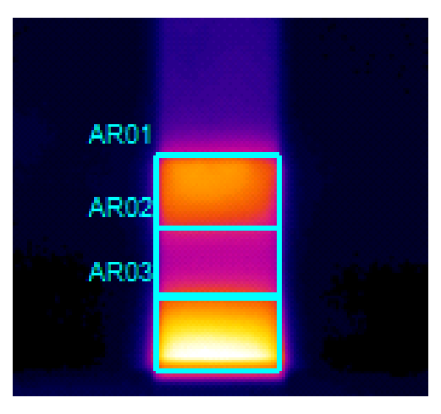
The camera temperature range has been chosen to be from -40ºC to 160ºC, since the heating of the polymer in solid state was the main objective of the experiment.

Figure 5.- SC655 FLIR camera

Results

Cylinder regions

For the analysis of the results, the cylinder has been divided in three regions.



AR0 – Whole cylinder
AR01 – Upper region
AR02 – Middle region
AR03 – Lower region

Temperature evolution

The average and maximum temperatures have been obtained for each area and for the whole cylinder during all the cycle.

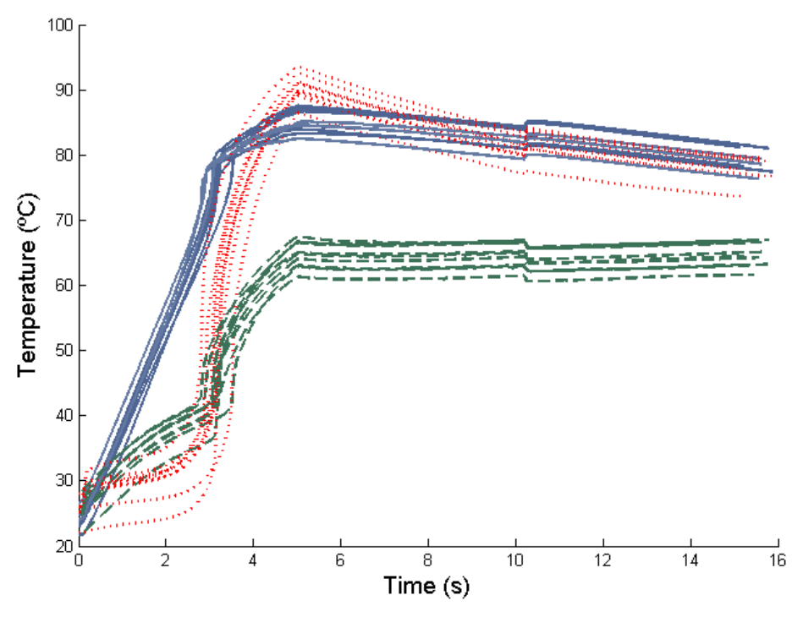


Figure 6.- Average temperatures obtained in experimental runs 1-10 for lower region (blue), middle region (green) and upper region (red)

The average heating rate has been calculated for each region. All the regions have a similar heating rate behavior

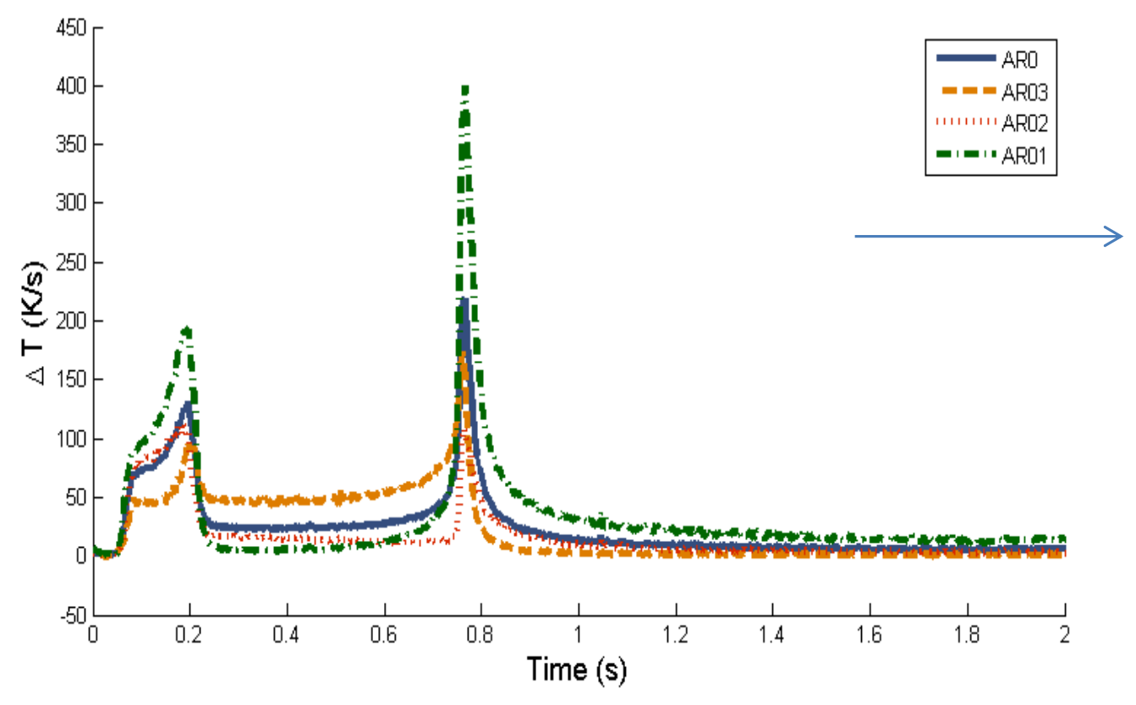
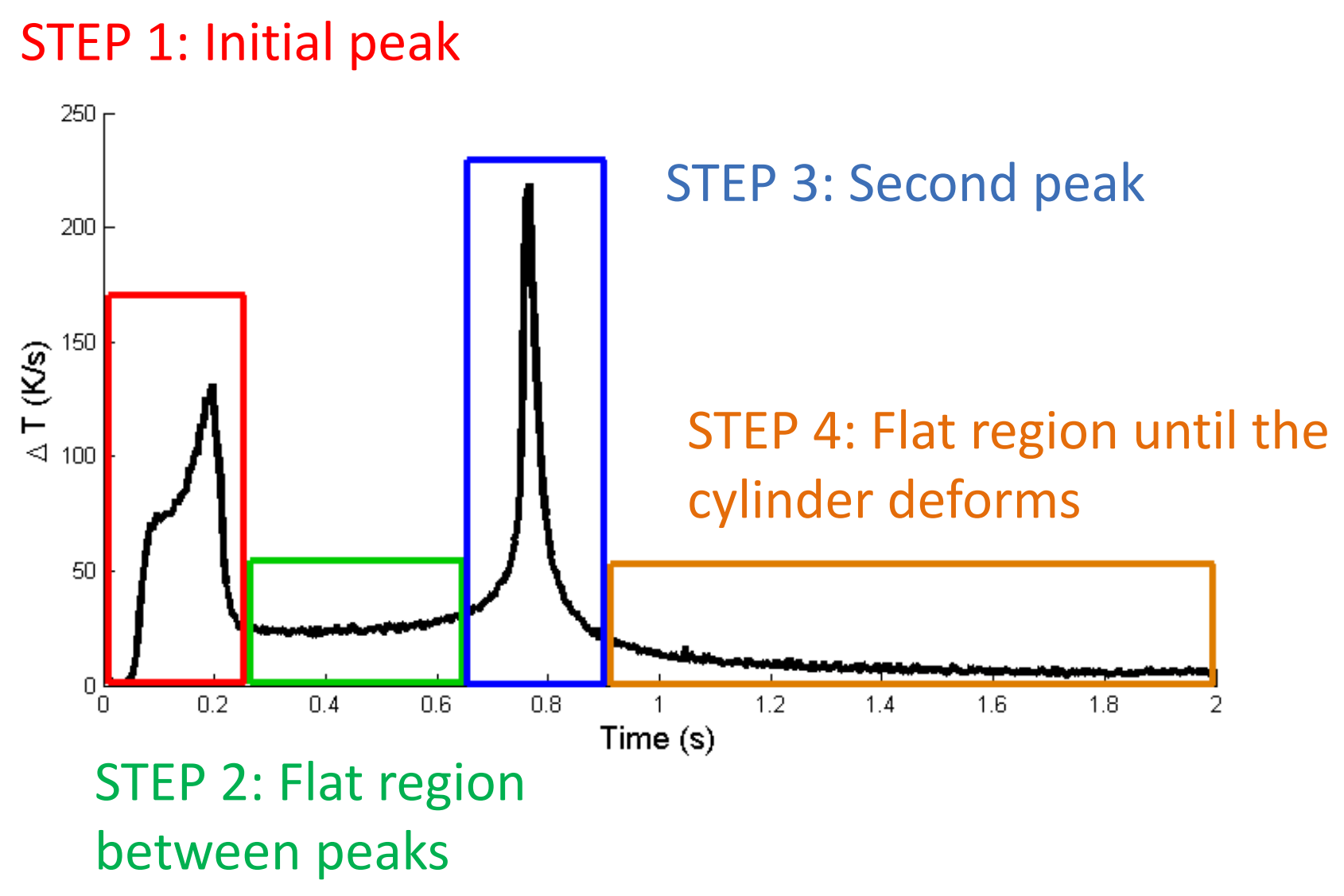


Figure 7.- Average heating rate for each cylinder region

Step classification

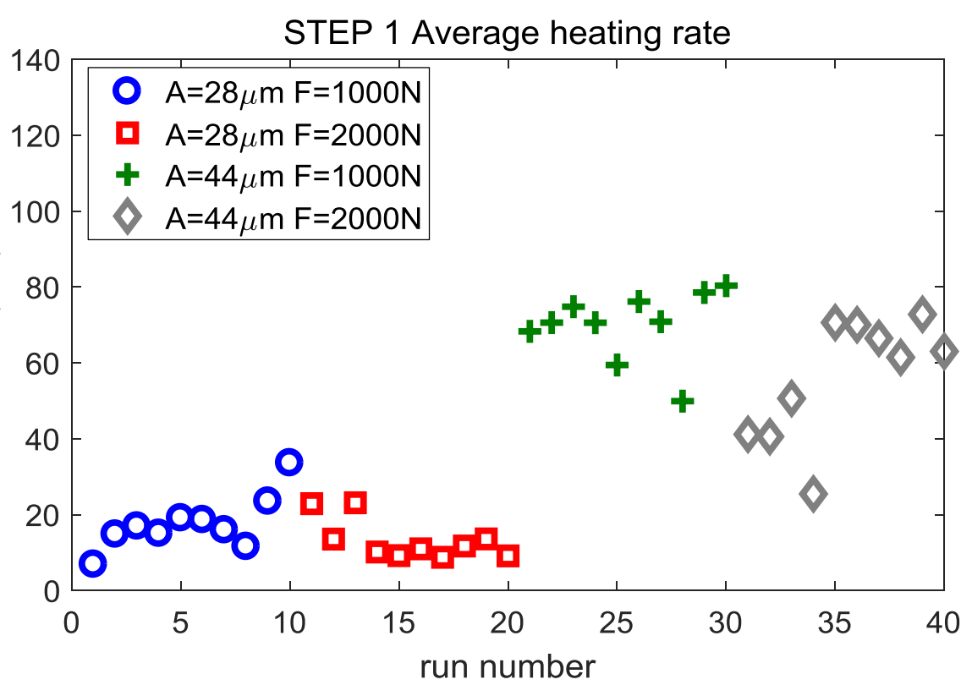
From the analysis of the temperature derivative results, the process has been divided in four steps:

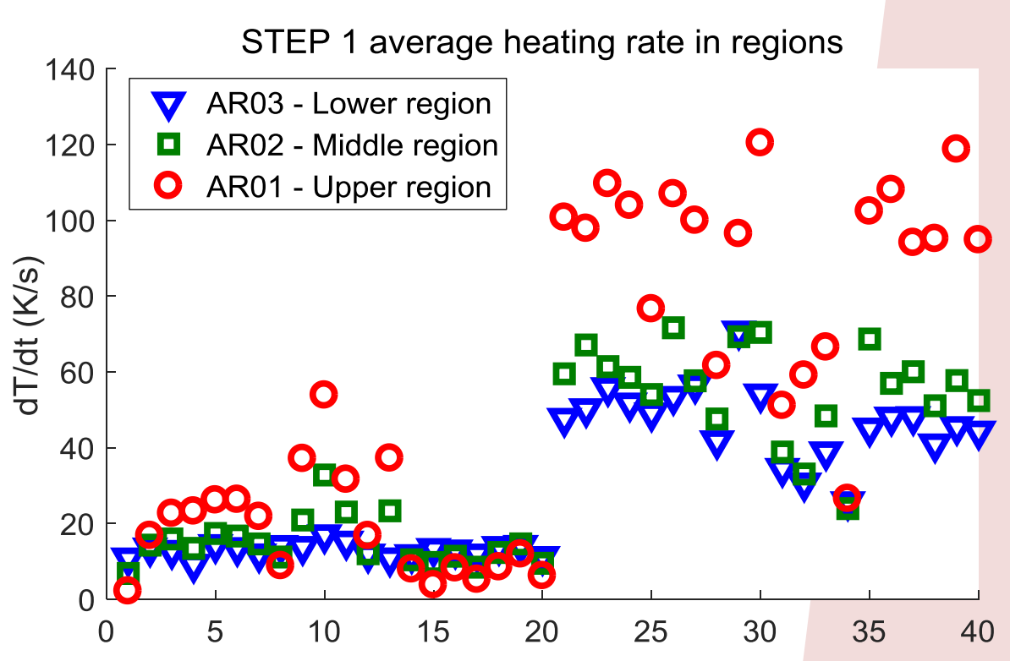


The evolution of the temperature change rate in the three considered regions shows four steps: in **STEP 1**, the sonotrode gets in contact with the polymer specimen, impacting it. As a result, the temperature rate increases abruptly defining an initial peak value. When the sonotrode is in complete contact with the specimen (**STEP 2**) , the upper region is heated due to the viscoelastic effect, while the lower part of the cylinder is heated due to the friction with the mold. In this second step of the process, the heating rate keeps constant, until some region of the polymer reaches the softening temperature of the material (around 90ºC). At this point, the material is not able to follow the sonotrode vibration and its upper region heats very quick due to a *hammering* effect (**STEP 3**). The heating rate defines a second peak, much higher and abrupt than the previous one. Finally, the polymer starts its deformation and its temperature increases until it melts (**STEP 4**). The material is now much softer and gets coupled again with the sonotrode. Viscoelastic heating is the predominant heating mechanism during this fourth and last step.

Analysis of results

STEP 1

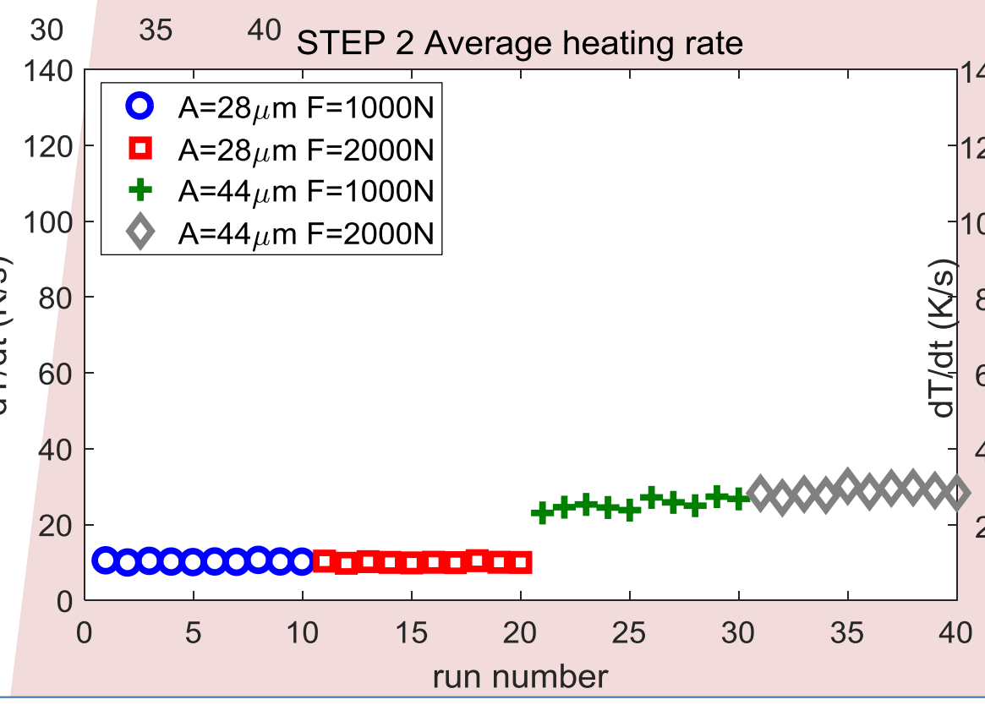


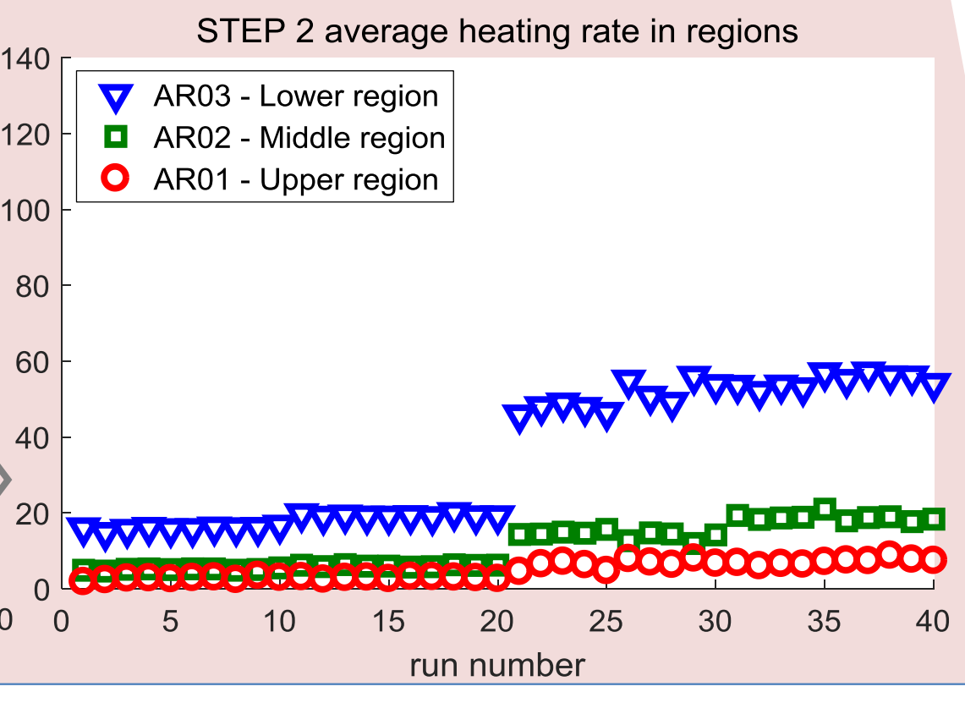


The average heating rate changes with the amplitude but not with the force, and the heating is more important in the upper region.
On the other hand, the dispersion in the results is very high, specially at high amplitudes. That can be due little differences in the initial cylinder position

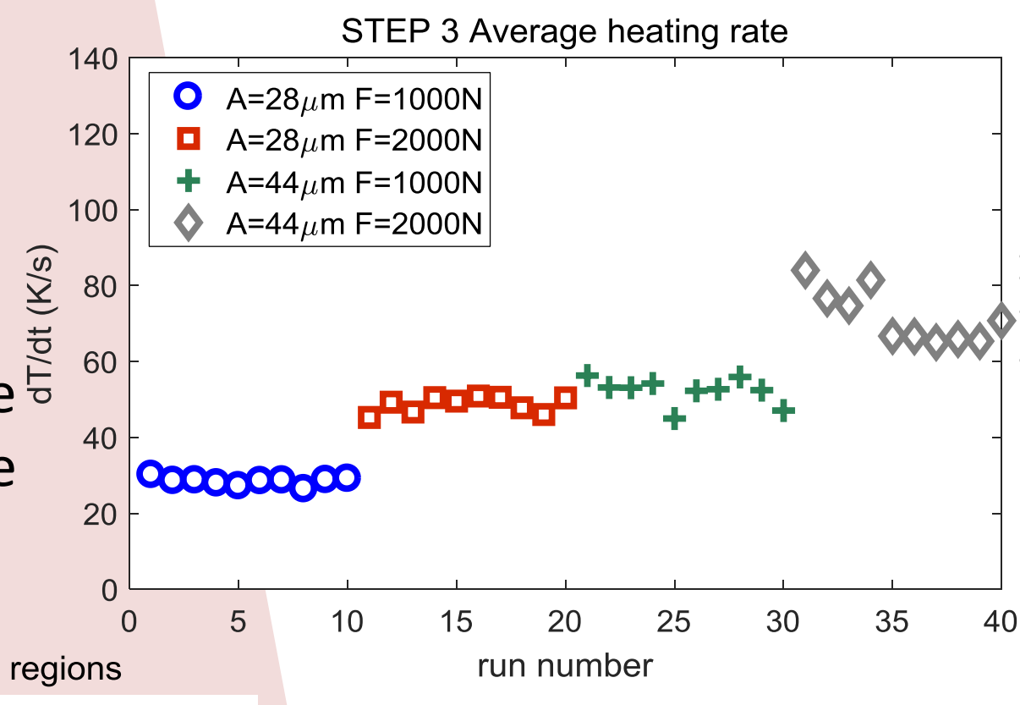
STEP 2

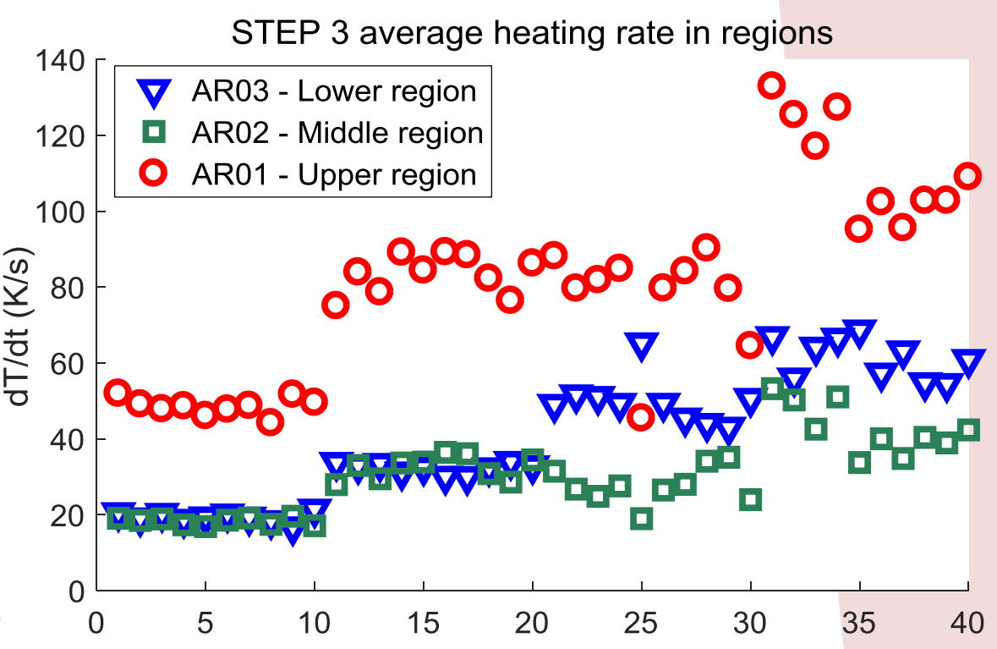
It can be observed that, again, amplitude is the most relevant parameter for the overall heating of the cylinder.
In this step, the lower region has a higher heating rate than the upper region, so it can be concluded that the friction heating is higher than the viscoelastic heating





STEP 3

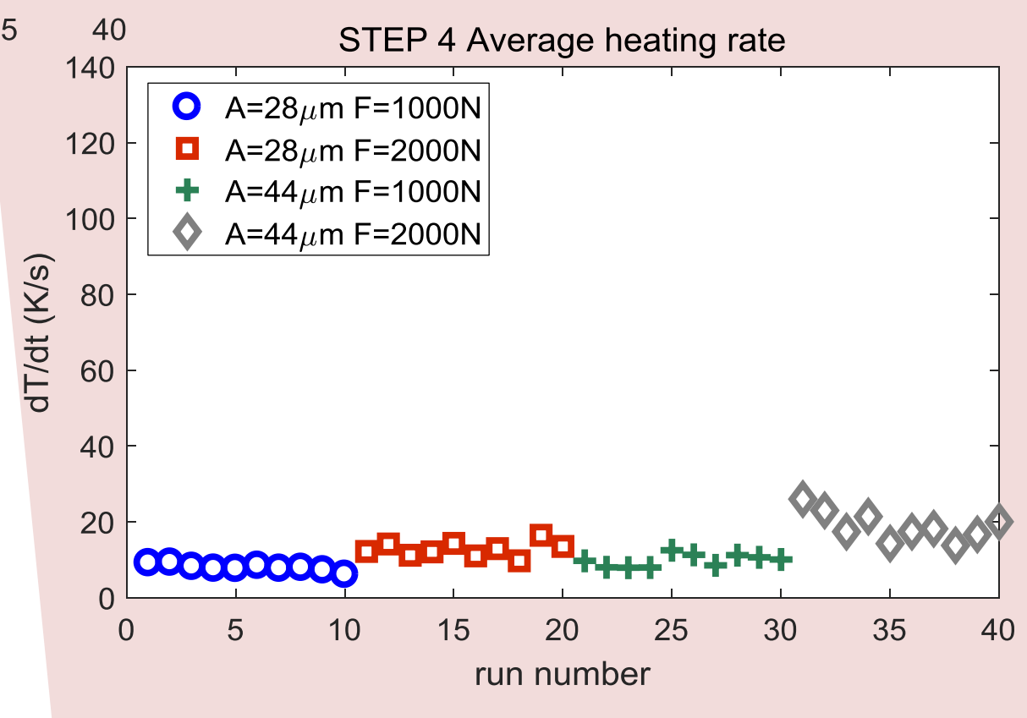




During this step the upper region has a higher heating rate due to the hammering effect.
Moreover, it can be noticed that, in this step, the effect of the force applied is as much important as the amplitude.

STEP 4

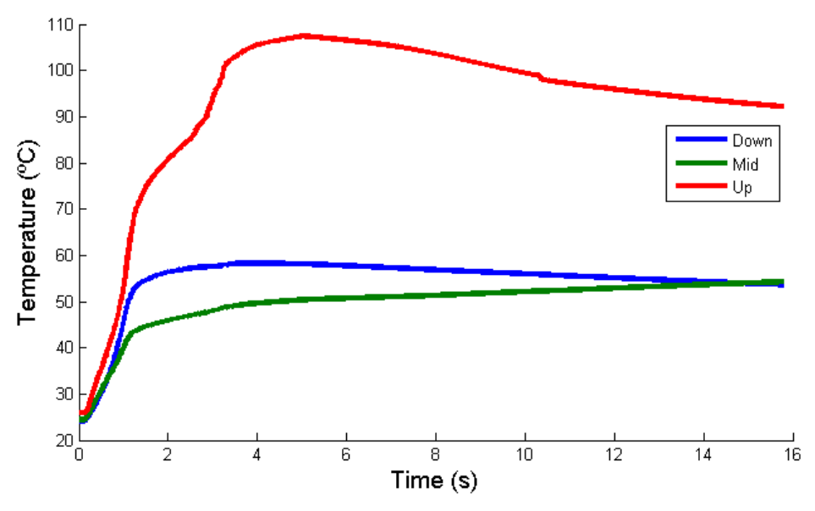
The results from this step are not clear because the cylinder deforms very quickly and the geometric classification of the regions is no longer valid

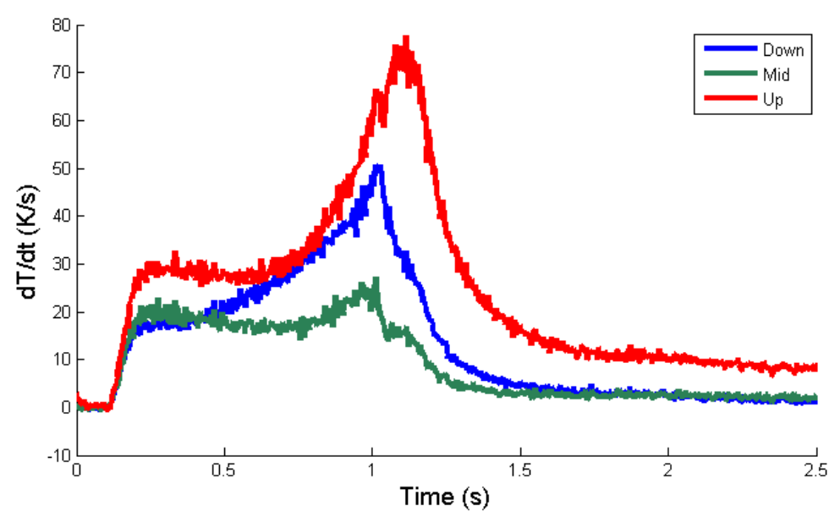


Special case: Low force

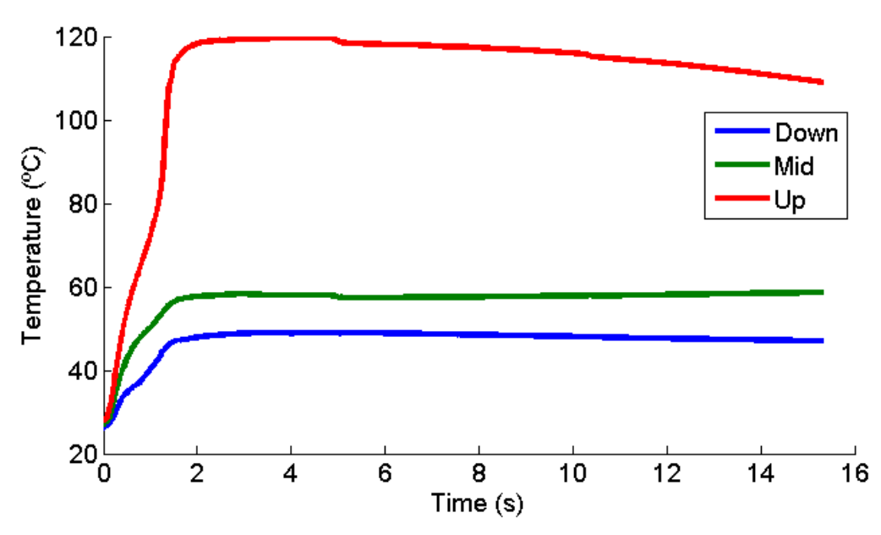
When a force of 500 N is applied to the cylinder, there is no STEP 2 in the heating rate evolution. In this case, the force applied is too low to couple the polypropylene cylinder with the sonotrode. This causes a hammering effect that heats the upper region of the cylinder very fast. This is magnified for high amplitude (experimental runs from 51 to 60)

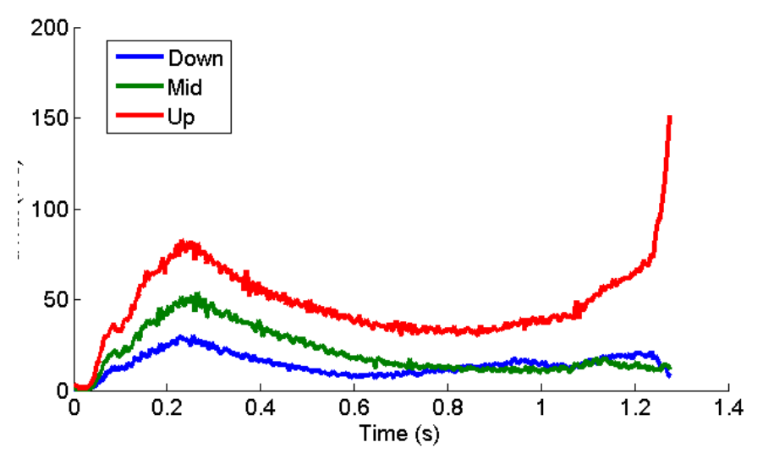
Cycle 43 average temperature and average heating rate in different regions





Cycle 51 average temperature and average heating rate in different regions





The average heating rate only is correct while all temperatures are below 160ºC (the higher threshold of the camera).

With these parameters, some points in the upper region are heated from room temperature to 160ºC in only 1 second .

Conclusions

The results obtained show that the heating of a polypropylene cylinder due to an ultrasonic mechanical excitation is highly inhomogeneous and presents different heating steps during the time. In this study, the different heating mechanisms in each step have been identified and the influence of the main process parameters have been evaluated. From the analysis of the results it can be concluded that both ultrasonic amplitude and applied pressure affect the temperature evolution of the whole polymer although the change in the applied force also modifies the temperature distribution in the polymer and the heating mechanisms present. More experimental measurements will be done in the future to validate the results with other types of polymers.

References

(1) Michaeli, W., Spennemann, A., & Gärtner, R. (2002). New plastification concepts for micro injection moulding. Microsystem technologies, 8(1), 55-57.
(2) Sacristan, M., Planta, X., Morell, M., & Puiggali, J. (2014). Effects of ultrasonic vibration on the micro-molding processing of polylactide. *Ultrasonics sonochemistry*, *21*(1), 376-386.

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