Agenda

1. Project Purpose and Goals
2. Device Design
3. Models
4. Semester Plan
Problem to Solve

Purpose:
Design a **low-cost** procedure to make **irrigation tubes** from HDPE shopping bags through **heat welding**

Goal:
Maximize the strength to cost ratio of the tubes produced
Irrigation Systems

Krishak Bandhu Family Nutrition Kit: USD$6.00

- Water Height: 1.5 m
- Pressure: 14.7 kPa ~ 0.15 atm
- Irrigates 20 sqm with 20 m of tubes

Source: http://www.ide-india.org
Heat Welding

• Robust

• Low-tech options
  o No training needed for operation
  o Ease of maintenance and fixing if needed

• Resistive Heating: Good control and repeatability

• Other options:
  o Coal: Poor control over temperature
Mechanical Design

Hot Press vs Rollers - Continuous process

Device Design

Spinning Shaft
8020
Resistive Heater
HDPE Films
Free Roller
Adjustable Pressure ↓
AI Rod
Device Design: Heat Transfer
Young’s Modulus $E \approx 180\text{MPa}$
Yield Strength in tension $\approx 4.4 \text{ MPa}$
Diameter $\approx 0.75'' = 1.9 \text{ cm}$
Thickness $\approx 8$ layers of bag $\approx 0.517\text{mm}$
Water pressure $\approx 0.15 \text{ atm}$
Device Design: Concerns

- Efficiency/efficacy of heating
  - Heat loss to environment
  - Power input needed
  - Temperature at contact point

- Discharge of processed pipe

- Constant feed of input bags

- Availability of AC power in regions of implementation
Addressing Some Concerns: Heating

Will temperature at contact point be high enough?

Yes!

Will the heating requirement be reasonable when considering losses?

Yes!

\[
Bi = \frac{hL}{k}
\]

\[
\begin{align*}
h &= \frac{50\text{W}}{m^2\text{K}} \\
L &= 2\text{cm} \\
k &= \frac{235\text{W}}{m\text{K}}
\end{align*}
\]

\[
Bi \approx 0.004 < 1
\]

Heat in

\[
\begin{align*}
q_{\text{rad}} &= \varepsilon \sigma (T_{\text{heater}}^4 - T_{\text{surf}}^4) \\
q_{\text{abs}} \times \text{Area}_2 &= \alpha q_{\text{rad}} \times \text{Area}_2 \\
\alpha &= 0.5 \\
\varepsilon &= 0.7
\end{align*}
\]

Heat out

\[
\begin{align*}
q_{\text{conv}} &= h(T_{\text{surf}} - T_f) \times \text{Area}_1 \\
2 \times \text{Area}_1 &= \text{Area}_2 \\
q_{\text{abs}} \times \text{Area}_2 &= q_{\text{conv}} \times \text{Area}_1
\end{align*}
\]

\[
\alpha \varepsilon \sigma (T_{\text{heater}}^4 - T_{\text{surf}}^4) \times \text{Area}_2 = h(T_{\text{surf}} - T_f) \times \text{Area}_1 \\
0.5 \times 0.7 \times 5.67 \times 10^{-8} \times (398^4 \text{K}^4 - 350^4 \text{K}^4) \times 2 = 50 \times (100 \text{K})
\]

\[
T_{\text{heater}} = 350^\circ \text{C}
\]

Yes!
Weld Quality

• Weld quality (strength) is determined by:
  o Temperature
  o Time
  o Pressure
  o Material Properties

• Max weld strength = Raw material strength
  o Function of processing parameters

• Modeled by Non-Fickean diffusion
Processing Parameters

• **Temperature (T)**
  - Min: 85°C (lowest working temperature\(^1\))
  - Max: degradation temperature (in theory)

• **Time (t)**
  - Min: TBD (based on prototype testing)
  - Max: Depends on cost of labor

• **Pressure (P)**
  - Min: 0.1 PSI
  - Max: Any (in theory)
Non-Fickean Diffusion

**Fig. 1.** Diffusion of polymer chains across weld interface. Diagram shows evolution of minor chains from interface wetting until chains have diffused an average distance equal to the radius of gyration. Adapted from Zhang and Wool [5].
Reptation Model

- Reptation time = avg time for a chain to move a distance equal to its radius of gyration
  - \( t_{rep} \propto M_w^3 \)
  - \( t_{rep} \) for PE of Mw=104 g/mole is in the order of 10 seconds

- Diffusion scales as \( t^{1/4} \)

\[
\frac{\sigma_w}{\sigma_m} = \left( \frac{t_m}{t_{rep}} \right)^{1/4}
\]

1. Robelin-Souffach et al. 1984
HAZ and Failure Mode

Processing parameters also determine:

- Microstructure of the heat affected zone (HAZ)
  - Crystallinity and spherulite formation
- Failure Mode
  - Chain fracture vs chain slip
Variable Costs per Year

- Cost of labor = (Wage)*(time)
  - Min wage in Ghana: USD$2.19/hr

- Cost of energy = (Energy)*(Cost of energy)
  - Cost of energy in Ghana: $0.20 kWh

- Total Variable Cost per year = ~$900
  - Assume about 1000 pieces (10 m) per year, variable cost per piece = ~$0.90
  - Fixed Cost will be determined after machining final product

Quality-Cost Model

Strength: $\sigma = f(\text{Temperature, Time, Pressure})$
Cost: $C = f(\text{Labor, Energy, Fixed Cost})$

- Optimize: Strength per Cost
  - Taking into consideration the minimum strength required for pipes to be functional
Plan

1. Manufacture initial prototype of heat welding device

2. Heat weld samples for different T, t, and P combinations:
   • Determine weld-strength (peel test on Instron)
   • Characterize weld microstructure:
     o Crystallinity (XRD, FTIR\(^1\))
     o Spherulite formation in the heat affected zone (SEM, Transmitted Light Microscopy\(^1\))

3. Determine parameters that will maximize strength-to-cost ratio

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\(^1\) Structure Evaluation of Polyethylene and Polypropylene Hot Plate Welds, ANTEC 1994
Previous Progress
Elemental Analysis on Scanning Electron Microscope

HDPE Bags
C=25.85wt%, O=48.52wt%

Pure Polyethylene
C=50.3wt%, O=26.16wt%
Previous Gantt Chart

Weeks:  1  2  3  4  5  6  7  8  9  10  11  12  13  14  15

1. Decisions/Designs:
   1.1 Choose Project  [100% complete]
   1.2 Initial Conceptualization of problem  [100% complete]
   1.3 Brainstorming of possible solutions  [100% complete]
   1.3 Picking a heat source  [10% complete]
   1.4 Creation of Final Design  [0% complete]

2. Testing
   2.1 Early "proof-of-concept" testing  [75% complete]
   2.2 Prototype Testing  [0% complete]

3. Design Construction
   3.1 Idea Mock-Ups  [0% complete]
   3.2 Creation of components  [0% complete]
   3.3 Final Prototype  [100% complete]

Last time
Current Gantt Chart

1. Decisions/Designs:
   1.1 Choose Project 100% complete
   1.2 Initial Conceptualization of problem 100% complete
   1.3 Brainstorming of possible solutions 100% complete
   1.4 Picking a heat source 10% complete
   1.5 Creation of Final Design 0% complete

2. Testing
   2.1 Early "proof-of-concept" testing 75% complete
   2.2 Prototype Testing 0% complete

3. Design Construction
   3.1 Idea Mock-Ups 25% complete
   3.2 Creation of components 0% complete
   3.3 Final Prototype 0% complete

4. Documentation
   4.1 Create Website 100% complete
   4.2 Update Website with Progress 0% complete
   4.3 Maintain Lab Notebook 40% complete
   4.2 Final Presentation 0% complete
Questions?
Figure 4. Relaxation times of PE coils in the melt state as a function of the number-average molecular weight. The dashed line has a slope of 3.4.

Thermal Analysis
Thermal Properties

Thermal Analysis via Differential Scanning Calorimetry (DSC)

- Tested 6 different bags
- Average melting temperature, \( T_m = 124.9 \pm 1.3 \, ^\circ \text{C} \)
- Softening point, \( \sim 105-115 \, ^\circ \text{C} \)
- Average heat capacity, \( C_p = 2.1 \pm 0.6 \, \text{kJ/kg}^{\circ} \text{C} \)

Heat Transfer

Resistive Heater

\[ q_{\text{rad}} = \varepsilon \sigma (T_h^4 - T_{\text{surf}}^4) \times A_r \]

Insulation

HDPE Bags

Al Rod
\[ \text{Bi(Al)} = 0.04 \]

\[ r \sim 2\text{cm} \]

\[ q_{\text{conv}} = h (T_{\text{surf}} - T_0) \times A_s \]

\[ T_{\text{surf}} = 125 \text{ C when } T_h = 300 \text{ C} \]