Suppression of Defects in High Productivity Welding

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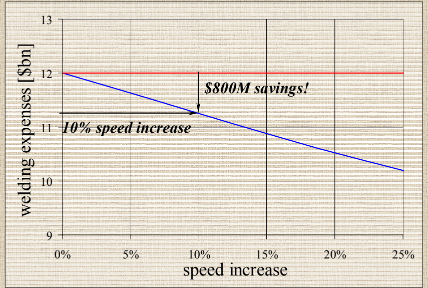
FASTER WELDS SAVE MUCH MONEY

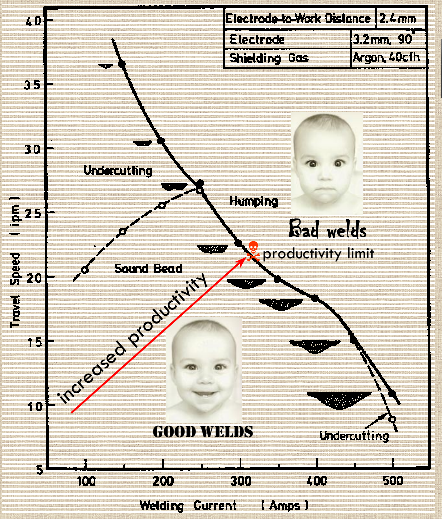
- **$12 billion a year** is spent on automatic welding
- Labor and equipment costs decrease with increasing speed

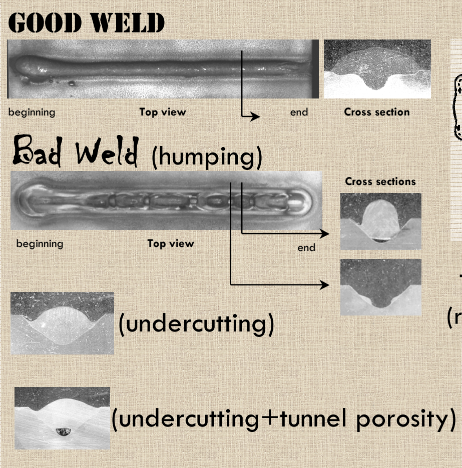


Increasing the ***welding speed by 10%*** *could generate almost* ***$1 billion in savings*** *(1% of the payroll in metal products and industrial equipment)*

- Welding is performed late in the manufacturing process ⇒ **a weld defect ruins all previous added value**
- 300 million tons of metal product are welded each year
- Robotic welding is expanding at 10% per year

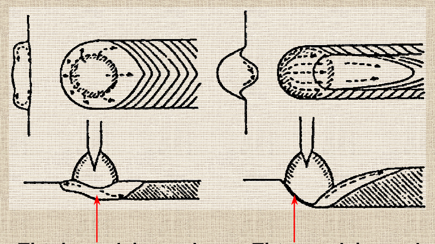
WHY CAN'T WE GO FASTER?





↑speed ⇒ ↑current ⇒ DEFECT

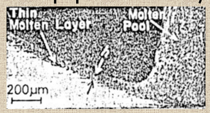
EXPERIMENTAL EVIDENCE



Thick weld pool (recirculating flows)

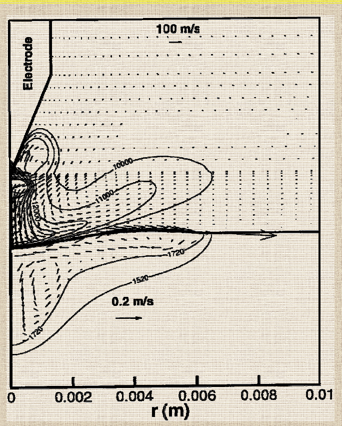
At high current (>250A) the weld pool surface is very depressed. This depression cannot be explained by the arc pressure alone.

Thin weld pool (longitudinal flows, large depression, deep penetration)



thickness<100μm

PREVIOUS STATE OF THE ART



- Thick weld pool with recirculation
- Marangoni*>electromagnetic> gas shear>buoyancy
- ↑current ⇒ electromagnetic *may* dominate (speculation)
- Difficult to model the fully coupled weld, especially with large depression

* Marangoni flows are induced by variations in the surface tension of the liquid-gas interface

OVERCOMING THE LIMITATIONS

- Use the **previous insight** into the problem: we already know that the weld pool is very thin
- Use **orders of magnitude** instead of many digits
- Use **dimensional analysis** to reduce the problem
- Use the information "hidden" in the governing **equations** for the weld pool

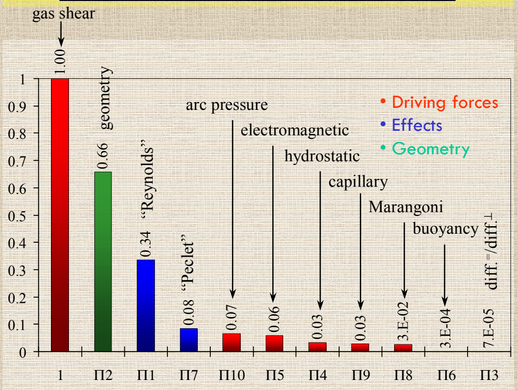
OUR SOLUTION: THE MAGNITUDE SCALING METHOD

Required
- Previous insight into the problem
- Ability to write down the governing equations
- Solution is "well behaved"
- Second order differential equations (or less)
- Second derivatives not large

Not required
- To simplify the equations
- To solve the equations

Provides
- Order of magnitude of solution
- Relative importance of driving forces
- Simple definition of concepts

ANALYSIS OF A THIN WELD POOL



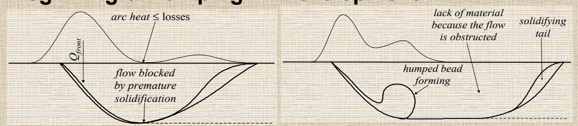
- Gas shear is the dominant driving force
- Marangoni forces are very small
- Thickness of the thin liquid layer:

$$\delta \approx (2\mu V D/\tau_{max})^{1/2}$$

- Thickness thin layer ≈ thickness mushy zone
- The thin layer freezes in ≈1 ms
- The arc acts almost directly over the solid-liquid interface

δ = thickness of liquid layer
μ = liquid metal viscosity
V = welding velocity
D = depth of penetration
τ_{max} = gas shear from arc plasma

MECHANISM OF DEFECT FORMATION



Gas shear decreases towards the tail, therefore the weld pool gets thicker. Heat input also decreases towards the end. When heat input decreases faster than the gas shear premature freezing and obstruction of the flow will occur. A total obstruction causes humping, a partial one at the sides causes undercutting, and at the bottom causes tunnel porosity.

DEFECT SUPPRESSION STRATEGIES

- **"Forehand" torch angle.** This decreases the gas shear, therefore the weld pool gets thick closer to the arc and will not freeze
- **Modify gas shear distribution,** for example by varying electrode to work distance. This requires a deeper study of the arc (in progress now)
- **Modify heat input distribution** from the arc. For example, if the hot zone reaches more to the rear, humping will be delayed.
- Techniques that manipulate Marangoni forces are unlikely to work