Shape Flow Casting and In-rotating-liquid-spinning Processes for the Continuous Production of Wires and of High-strength and Soft Magnetic Metallic Fibres

Georg FROMMEYER,1) Joachim GNAUK,1) Wolfgang FRECH2) and Susanne ZELLER1)

1) Max-Planck-Institut für Eisenforschung GmbH, Max-Planck-Str. 1, 40237 Düsseldorf, Germany. E-mail: frommeyer@mpie.de, gnauk@mpie.de, zeller@mpie.de 2) Verein Deutscher Ingenieure e.V., Graf-Recke-Str. 84, 40239 Düsseldorf, Germany. E-mail: kunststoffe@vdi.de

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Computer-controlled facilities for continuous casting of metallic fibres and wires performing in-rotating-liquid-spinning (INROLISP) and shape flow casting (SFC) were designed and installed to determine and control the near-net-shape casting processes over an extended production period. In particular, the flow behaviour of the melt jet was experimentally investigated and theoretically described using fluid dynamic equations. The controlling process parameters, such as the velocity of the melt jet, the stable free flight length, the nozzle geometry and cooling rate, were examined and optimised. Several pure metals as well as microcrystalline and amorphous alloys were cast into continuous fibres and wires of high quality. Microstructural features and mechanical properties of rapidly quenched fibres and thin wires were also evaluated. Of great potential application is the production of amorphous softmagnetic Fe base and Co base thin wires with diameters of about 30 to 50 μm. These microwires are used as sensor cores in highly sensitive novel magnetic field sensors based on a magneto-electric effect. Direct casting of wires with diameters up to 3 mm is carried out using the shape flow casting technique. The SFC facility is an highly instrumented modified meltspin facility, performing rapid substrate quenching. The process principles of the SFC technology, which enable a flexible production of steel, nickel base alloy wires and other novel materials are presented. The microstructural features are correlated with the process parameters.

KEY WORDS: continuous casting; rapid solidification; shape flow casting; in-rotating-liquid spinning; fibres; wires.

1. Introduction

Continuous casting and rapid solidification of metallic fibres and wires with final diameters directly from the melt offers many advantages compared with the conventional wire drawing process.1,2) The newly developed shape flow casting technique enables to produce wires with required cross section straight from the molten state. Fine grained, segregation free microstructures or amorphous fine wires and surface quality improvements can be achieved, so affording a high level of strength by finish-drawing of the as cast wires. Microstructural inhomogeneities and material defects produced by rolling and/or drawing will be avoided by using this technology.

The principal idea of ejecting molten material through a round nozzle has been applied for several decades in the chemical industry for the fabrication of polymer or glass fibres. However, continuous casting of metallic fibres or wires has up to now no widespread industrial applications, because of the different physical properties of synthetics, glass and metallic melts. For example, at the process temperature, polymer and glass melts exhibit higher viscosities \(10^5 \text{ vs. } 10^{-3} \text{ Pa}\) and lower surface tensions \(3 \times 10^{-2} \text{ vs. } 1 \text{ N m}^{-1}\) than liquid metals. A metallic free flight jet is mainly controlled by inertia and surface forces, and less by viscous forces. This leads to much lower stability of metallic free flight jets with a short break-up length compared with high viscosity materials.

This paper describes and discusses the physical principles and the controlling process parameters of the shape flow casting technology, as well as microstructural features and mechanical properties of continuously cast wires of selected material systems.

2. Theoretical Background

2.1. Stability Criteria of a Metallic Free Flight Jet

Free flight jets of non-viscous fluid are in a state of unstable equilibrium and will break after a certain time interval into droplets. This is a result of radial symmetric surface instabilities caused by differences in the internal jet pressure in the axial flow direction. Four different types of jet disintegration are distinguished.3) These are dropping, varicose break-up, sinusoid break-up and atomization in small melt droplets. Operating in the varicose break-up region results in smooth wires, because of the laminar flow
follows:

where the following expression:

describes the flow behaviour of the jet by the normalized break-up length \( L/d \) and the dimensionless jet velocity, expressed by the Reynold (\( Re = \nu \rho / \mu \)) and Ohnesorge (\( \text{Oh} = \mu^2 \rho \sigma / d \)) numbers. The material parameters are as follows: \( \mu \) is the dynamic viscosity, \( \rho \) is the density of the metallic jet, \( \sigma \) defines the surface tension, \( \nu \) is the velocity and \( d \) is the nozzle diameter. The logarithmic factor takes the ratio of the nozzle diameter to the initial disturbance of the jet at the nozzle orifice into account.

The Ohnesorge diagram, shown in Fig. 1, illustrates the limits of the coexisting regimes which are based on Eq. (1) of the described jet disintegration modes. With increasing Re number and jet velocity the transition from one stage to another occurs. For continuous casting of fibres and wires, the different regimes of jet disintegration, characterized by Re numbers in the range \( 1000 \leq Re \leq 10^4 \) and Ohnesorge numbers of the order of \( \text{Oh} = 10^{-3} \), specifically for the coexisting varicose and sinusoidal break-up stages are of great importance. Jet stability (Rayleigh waves) occurred at defined surface wavelengths.\(^4,5\) The disturbed jet surface can be described by a differential change in the jet radius using the following equations:

\[
\frac{L}{d} = \frac{Re(3\text{Oh}^2 + \text{Oh}) \ln \frac{d}{2\delta_0}}{2\delta_0} \quad \text{.....................(1)}
\]

\[
r(z) = r_0 + \delta(z) \quad \text{with} \quad \delta(z) = \delta_0 \cos \frac{2\pi z}{\lambda} \quad \text{.....................(2)}
\]

Where \( r_0 \) is the radius of the jet, \( \delta(z) \) is the amplitude of the wave-disturbed jet in the flow direction at a given coordinate \( z \), and \( \delta_0 \) defines the initial amplitude. \( \lambda \) represents the wavelength of the jet instability. The inner jet pressure is dependent on the surface tension and the curvatures of the varicose topology which is quantitatively described by the following expression:

\[
\rho(z) = \sigma \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \quad \text{.....................(3)}
\]

where \( R_1 \) and \( R_2 \) are the radii of the sinusoidal jet surface in longitudinal and radial direction. Maximal pressure differences occur in the coexisting relative maxima and minima regimes of the wave-shaped jet surface. Investigations on the free flight jet stability showed that the amplitude of the disturbance increases exponentially in time.\(^6\) This is quantified by:

\[
\delta(z,t) = \delta_0 \exp(\Omega t) \cos \frac{2\pi z}{\lambda} \quad \text{.....................(4)}
\]

where \( \Omega \) is the amplification of the disturbance. \( \Omega_{\text{max}} \) is defined as:

\[
\Omega_{\text{max}} = \sqrt{\frac{\sigma}{8\rho r_0^2}} \quad \text{.....................(5)}
\]

From this expression, the critical wavelength \( \lambda_{\text{crit}} = 2\pi r_0 \sqrt{2} \) can be derived. The break up occurs when the disturbance is comparable to the jet radius and the time interval in which an unstable jet breaks up is given by Eq. (4):

\[
\Delta t = \frac{1}{\Omega_{\text{max}}} \ln \frac{r_0}{\delta_0} \quad \text{.....................(6)}
\]

This was also confirmed by experiments using liquid gallium and water jets.\(^7\) The free flight length in which the jet begins to be unstable is given by:

\[
l_s = \frac{v_s}{\Omega_{\text{max}}} \ln \frac{r_0}{\delta_0} \quad \text{.....................(7)}
\]

In Fig. 2, the normalized exponent \( \Omega_{\text{max}} \sqrt{\text{Re} r_0^2 / \nu_s^2} \) is plotted as a function of the unstable wavelength \( \lambda \) of the jet.

### 2.2. Velocity and Pressure Distribution in the Coolant in a Rotating Drum

A circular flow of liquid coolant in a rotating open drum, i.e. rigid body rotation, can be described by the Navier–Stokes equations,\(^8\) considering the acceleration forces in a gravitation field. Therefore, the fluid dynamics are only determined by the primary flow, because a secondary flow component does not exist. The integration of the Navier–Stokes equations by considering the boundary conditions leads to the rotational velocity of the drum being given by:

\[
\nu_i = R \varphi = 2R \pi n \times 60 \quad \text{.....................(8)}
\]

where \( \varphi \) is the angular velocity, \( R \) is the inner drum radius, and \( n \) is the rotational speed in revolutions per minute. The dimensionless velocity in the coexisting regimes of jet disintegration is determined by the primary flow, because a secondary flow component does not exist. Therefore, the fluid dynamics are only determined by the primary flow, because a secondary flow component does not exist. The integration of the Navier–Stokes equations by considering the boundary conditions leads to the rotational velocity of the drum being given by:

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\nu_i = R \varphi = 2R \pi n \times 60 \quad \text{.....................(8)}
\]

\( \varphi \) is the angular velocity, \( R \) is the inner drum radius, and \( n \) is the rotational speed in revolutions per minute.
defines the rotational frequency in revolutions per min.

The pressure distribution in the laminar flowing coolant is defined by:

\[ p(r,z) = \frac{\rho}{2} (r \phi) + \rho g z + C \quad \text{.................(9)} \]

and this expression allows the calculation of the surface shape of the coolant as a function of the angular velocity \( \phi \) and the axial coordinate \( z \).

### 2.3. Jet Velocity in the Nozzle and at the Orifice

A quantitative description of a flow in a cylindrical tube of constant cross-section is given by the Navier–Stokes equations. The requirements to be fulfilled are a stable laminar jet (Re < 2,300) and the friction at the tube wall causes a decrease in the boundary velocity (to \( \theta_b = 0 \)).

From the Navier–Stokes equations it follows that the pressure distribution in the cross-section of the tube in \( z \)-direction is constant. This is the well-known Hagen–Poiseuille flow. The following equation describes the velocity as a function of the radial \( r \) and axial \( z \) coordinates:

\[ v(r,z) = \frac{R^2}{4\mu} \frac{\partial p}{\partial z} \left[ 1 - \left( \frac{r}{R} \right)^2 \right] \approx 2 \left| \bar{\nu} \right| \left[ 1 - \left( \frac{r}{R} \right)^2 \right] \]

\[ \quad \text{..............................(10)} \]

The laminar flow in a nozzle of constant cylindrical cross-section can be described by \( l_s = 0.03d/R \). For Re numbers of the order of 2,000 the run in length is \( l_s = 6d \) (with \( d \) the nozzle diameter). The friction acting in the boundary layer of the tube wall causes a dissipation of the kinetic energy. Consequently, a pressure loss in the jet in the nozzle occurs. This is expressed by the formula:

\[ \delta p = \xi \frac{\rho}{2} \left| \bar{\nu} \right|^2 \quad \text{..............................(11)} \]

where \( \xi \) is the pressure loss coefficient that varies between 0.01 and 0.04. For the carried out casting process of iron or nickel base alloy wires using \( |\bar{\nu}| = 1.5 \text{ m s}^{-1} \), the pressure loss of the jet is about 10–3 MPa. The calculation of the outflow velocity at the nozzle orifice is given by the Bernoulli equation:

\[ v = \left( 2 \left( \frac{\Delta p}{\rho} + gh(t) \right) \right)^{1/2} \quad \text{..............................(12)} \]

where \( \Delta p \) is the pressure and \( gh(t) \) is the specific time dependent potential energy of an incremental flow jet.

### 2.4. Heat Transport

The heat transport mechanisms which govern the cooling of the metallic jet are as follows:

- enforced convection in the melt jet inside the run in length of the nozzle;
- convection in the free flight jet caused by the relative velocity between the jet and the surrounding atmosphere;
- thermal radiation of the free flight jet;
- heat transfer between the solidified jet and the substrate (groove profile) of the casting wheel;
- heat conductivity in the melt and the substrate and heat transport due to thermal radiation.

For the performed process parameter variation the heat losses of the free flight jet was estimated to about 0.1 W s\(^{-1}\). The heat transport by thermal radiation of the free jet surface in a time interval was calculated using the following equation:

\[ \dot{Q} = e \cdot A \cdot k_b \varepsilon \cdot \left( \frac{T_s}{100} \right)^4 \left( \frac{T_s - T_{en}}{100} \right)^4 \quad \text{.............(13)} \]

\( A \) is the radiation surface of the wire, \( k_b \) is Boltzmann’s constant, \( e \) defines the radiation number, \( \varepsilon \) is the emission coefficient, \( T_s \) is the absolute surface temperature and \( T_{en} \) is the environment temperature. The heat loss was determined to be about 0.065 W s\(^{-1}\). The important steps of the heat transport are the heat transfer at the liquid–solid interface and the thermal conductivity of the substrate. From melt spinning experiments it is well known that the heat transfer coefficient \( a \) at the interfaces between the molten metal stream and the substrate surfaces is of the order of 5 × 10\(^{8}\) W m\(^{-1}\) K\(^{-1}\) or somewhat higher. The Fourier’s differential equation in cylindrical coordinates is as follows:

\[ \frac{\partial \theta}{\partial t} = a \cdot \left( \frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r} \frac{\partial \theta}{\partial r} \right) + \frac{W_{se}}{\rho C_p} \quad \text{.............(14)} \]

The source term \( W_{se}/\rho C_p \) describes the time dependent heat contributing during liquid solid phase transformation, was numerically solved by computation using the ‘cast’ program.

### 3. Experimental Procedures

#### 3.1. Continuous Casting of Fine Wires and Fibres

An instrumented and computerized in-rotating-liquid spinning facility was built-up for the continuous casting of fibres and thin wires on a semi-production scale (see Fig. 3). The drum is 886 mm in diameter and made of acrylic glass for observing and monitoring the flow dynamics of the metallic jet. The drum was fixed on a high precision driving shaft to maintain the flow stability of the coolant in the velocity range 5–25 m s\(^{-1}\).

For each run, about 250 g of the alloy was melted in quartz or ceramic (Al\(_2\)O\(_3\), ZrO\(_2\)) crucibles in argon atmosphere, using a high frequency induction coil. The metallic jet was formed by a precise boron nitride nozzle, applying an argon inert gas pressure of about 5 × 10\(^{5}\) Pa. The distance between the nozzle tip and the coolant surface was precisely adjustable by a step motor and the injection angle by a tilting device. High resolution cameras monitored the outflow of the jet, the jet impinging on the coolant surface and entering the coolant. Deionized water with small amounts of tensides for reducing the surface tension was used as a coolant. The instrumented facility allows the quantitative determination of the important process parameters, as presented in Table 1.

The stability of the jet is strongly affected by the precision of the nozzle geometry. For the fabrication of high
quality fibres with round cross-sections and smooth surfaces, an optimized nozzle geometry with sharp edges at the orifice was designed.9)

3.2. Jet Behaviour

The wave-length of the sinusoidal jet disturbance was determined for several metallic melts to be \( \Delta = 1.5 \pi d \). This value is in agreement with the theoretical prediction of \( \sqrt{2} \pi d \). The term \( \ln(d/2\delta_0) \) for the initial disturbance was calculated to be about 8. This confirms the results of Liebermann.10)

The jet velocity was calculated using the Bernoulli equation and additional terms, such as the nozzle friction and capillary forces.11) The jet pressure decreases in the run-in length and at the exit of the nozzle. This was taken into account by the additional loss factor \( r_w^2 \). The experimental data agree well with the calculated values for \( \xi = 0.3 \). The optimum ratio of the jet velocity to the tangential velocity of the coolant is \( v_{jet}/v_{coolant} = 0.9 \). Figure 4 shows the linear relationship between the coolant velocity and the jet velocity for a ratio \( \chi \) varying in the range 0.8 ≤ \( \chi \) ≤ 1.0.

3.3. Principle of the SFC Process

In the SFC process—melt spinning on a rotating profiled substrate surface—pure metals or alloys are melted and superheated in inert gas atmosphere using high-temperature resistant ceramic or quartz crucibles. The surface of the melt is pressurized by argon gas, resulting in a pressure difference between the crucible and its surroundings that causes the melt to accelerate in a round nozzle.

This melt-flux exits the nozzle in the form of a free jet which, after travelling just a few millimetres, strikes the rotating surface of the substrate at a defined angle of immersion (\( \alpha \)). The bottom side of the cylindrical jet is stabilized by the semicircular groove of the substrate and the top side by surface tension. Groove diameters ranging from 1.5 to 3 mm have been used to cast wires close to final dimension, as shown in the schematic drawing of Fig. 5.

SFC technology is a combination of the INROLISP (in-rotating-liquid-spinning) and the PFC (planar flow casting) process.12–14) Due to the achieved high cooling rates of \( \geq 10^3 \text{ Ks}^{-1} \) the SFC process belongs to the realm of rapid solidification technology.

3.4. Influence Variables and Process Parameters

Direct wire casting requires precise coordination of process parameters. Figure 6 shows the basic function of the continuous casting process and a summary of the most important process variables.

The filling of the wire cross section, which is fixed by the geometry of the semicircular groove profile, requires a continuous mass flow (m), which is defined by the circumferential velocity (w) of the melt. The adequate pressure of ejection can be calculated from \( m = \rho w A \) allowing for the continuity and Bernoulli’s equation, Eq. (10), for incompressible fluids. The calculations were supplemented by experiments, in which the ideal mass of a defined piece of wire was calculated from its density and known ideal cross section and compared with the actual mass. By taking measurements on an alloy it is possible to plot an alloy-specific characteristic curve from which the ejection pressure can be read off with allowance for the alloy-dependent viscosity (\( \eta \)) and surface
tension ($\sigma$). Table 2 presents the investigated process parameters and their experimentally determined optimum ranges.

4. Results and Discussion

4.1. Properties of As-cast Amorphous and Microcrystalline Thin Wires and Fibres

A large variety of metallic alloys, such as Pd$_{77}$Cu$_6$Si$_{17}$, Cu$_{98}$Al$_2$, Fe$_{77}$Si$_{10}$B$_{13}$, Fe$_{40}$Ni$_{40}$B$_{20}$, Fe$_3$Si$_{10}$, and Ni$_3$Al, were spun into fibres of 60–300 $\mu$m in diameter. Figure 7 shows a representative scanning electron microscopy (SEM) image of a continuously cast thin Ni$_3$Al wire. The surface is quite smooth and the weak flow pattern in the axial direction on the mantel zone is caused by a thin stabilizing oxide surface layer. The jet diameter was determined to be about 160 $\mu$m and the variation in the diameter was less than 3%. The diameter of the fibres can be reduced of about 5–10% as a result of the relaxation of the jet velocity in the laminar streaming coolant. The flow dynamics of the jet and especially the jet stability correspond well with the theory of Weber.$^{41}$

Table 3 presents some mechanical properties of selected crystalline and amorphous materials. The high strength wires and fibres exhibit tensile strengths of the order of 3 000 MPa and are potential materials for fibre-reinforced composites and high strength ropes. Thin wires of about 250–350 $\mu$m in diameter with ultimate tensile strengths of about 1 200 MPa are also potential candidates for tyre cord in high performance tyres. Functional materials, such as noble metals of high electrical conductivity, soft magnetic high-silicon steel wires containing about 6 wt% Si are feasible for electro-magnetic sensors. Other applications are miniature motors and switching devices. Fine wires of shape memory alloys are used for surgery purposes.

4.2. Continuous Casting and Properties of Thicker Wires Using the SFC Technology

For optimizing the casting process parameters video images were recorded and analyzed. A representative one is illustrated in Fig. 8. The jet of the molten metal strikes the guide groove of the rotating casting ring with constant take off angles and jet velocities, but with different wetting behaviour of the substrate by varying its contact temperature.

The jet velocity was calculated using the Bernoulli equation with additional terms, such as nozzle friction and capillary forces, see Eq. (10). The jet pressure decreases in the run-in length and at the nozzle orifice. This was taken into account by an additional loss factor $\xi pe^2/2$. The experimental data agree well with the calculated values for $\xi=0.3$ to...
0.4. The optimum ratio of the horizontal component of the jet velocity and the tangential velocity of the rotating cast ring was determined to be 0.95 in order to keep the momentum component perpendicular to the groove surface minimal.

The heat transfer coefficient and the cooling rates were estimated from on-line temperature measurements of the melt puddle and of the solidified wire section after solidification is finished. The heat transfer coefficient at the melt puddle-groove interface was estimated to about $5 \times 10^5 \text{ W m}^{-2} \text{K}^{-1}$ whereas in the solidified region the heat transfer is decreasing to $5 \times 10^4 \text{ W m}^{-2} \text{K}^{-1}$ or even lower. However, the heat transfer is mainly depending upon the thermal contact between the liquid melt puddle or the as-solidified ribbon and the groove surface at the actual temperature. Figures 9(a), 9(b) show a selected area of the measured and computed temperature distributions in the melt puddle in the longitudinal (a) and transverse (b) sections. The temperature distribution is marked by the isotherms for an as solidifying stainless steel wire. The estimated maximum cooling rate in the contact zone is about $5 \times 10^4 \text{ K s}^{-1}$. The cooling rate on the free surface of the solidified wire is lower than $10^4 \text{ K s}^{-1}$.

After completing the initial parameter studies on a large variety of metallic alloys of different compositions, melting temperatures, cooling rates, and heat transfer coefficients attention was focused on the continuous casting of divers austenitic stainless steel wires, ferritic heat resistant iron-chromium-aluminium alloy and nickel-chromium base material. These alloys are of great importance for industrial applications. Figure 10 shows an as cast and as rolled or as drawn stainless steel wire of about $d=3 \text{ mm}$ in diameter after final dressing and straightening by cold drawing applying a degree of deformation of $\eta=15\%$.

The main task of the performed study was to achieve finer grain sizes by rapid quenching and improved mechanical properties, such as higher strength combined with high production efficiency. Table 4 presents several continuously cast and rapidly solidified materials and some physical and mechanical properties.

### 5. Summary

Continuous casting and rapid solidification enable a low cost production of fibres and wires in the diameter range from 50 $\mu\text{m}$ to 3 mm by performing a high process flexibility. Other advantages are the amorphous solidification and the fabrication of fine-grained microstructures possessing improved mechanical and specific physical properties. The successful implementation of in-rotating-liquid-spinning and the shape flow casting technologies may cut out several forming and heat treatment stages necessary for the production of high quality stainless steel or heat resistant wires of...
up to 3 mm in diameter and thin wires or fibres (30 to 180 µm) of extremely high strength possessing specific soft magnetic properties. The study of the process parameters serve to optimize the continuous casting processes. The actual cooling and solidification rates are high enough to achieve the amorphous state and/or finer grain sizes, and less segregations of alloying and tramp elements in the final fibre and wire products.

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