A Double Wheel Device to Induce a Severe Plastic Deformation in Drawing: a Study for Flexible Manufacturing Systems Within Industry 4.0 Paradigm.

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A DOUBLE WHEEL DEVICE TO INDUCE A SEVERE PLASTIC DEFORMATION IN DRAWING: A STUDY FOR FLEXIBLE MANUFACTURING SYSTEMS WITHIN INDUSTRY 4.0 PARADIGM.

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ABSTRACT

Equal channel angular drawing (ECAD) represents the most successful severe plastic deformation (SPD) technique for continuous industrial manufacturing of longer wires, with a constant cross-section, characterized by smaller diameters and better mechanical properties (i.e. high strain and hardness) mainly due to the grain size refinement. In this paper an advanced innovative concept to impose SPD, on commercial 1370 pure aluminium wires (Al 99.7%), is proposed to improve the flexibility of the classic manufacturing method of ECAD by controlling and regulating process parameters in real time, obtaining several combinations of mechanical properties and increasing productivity. This paper provides an analysis of mechanical and microstructural changes occurring during ECAD process and, preserving the principles of the ECAD method, describes an innovative concept of plastic deformation showing the potential improvements to practice. The proposed manufacturing system has been validated in a digital ecosystem, performing a finite element analysis (FEA); the latter implements a flow stress empirical model, that includes the influence of the grain size change, for the material behaviour and two customized user-subroutines for predicting grain refinement and hardness variation. The study demonstrates the technique potential and, at the same time, how it is possible to mix simulation and reality in the hybrid World promoted by Industry 4.0 paradigm.

Keywords: Industry 4.0, Smart manufacturing, Microstructural changes, Finite element analysis, Severe plastic deformation, digital ecosystems.

NOMENCLATURE

AM	additive manufacturing
AI	artificial intelligence
CDRX	continuous dynamic recrystallization
CPSs	cyber-physical systems
C_x	numerical constant
C_0	numerical constant
C_1	numerical constant
ECAD	equal channel angular drawing
ERP	enterprise resource planning
FE	finite element
FEA	finite element analysis
H-P	Hall-Petch
HV	Vickers hardness
IoS	internet of services
IoT	intelligent and internet of things
I4.0	industry 4.0
M	Taylor factor
M2M	machine to machine communication
PLC	programmable logic controllers
SPD	severe plastic deformation
Φ	die inner angle
Ψ	die outer angle
b	Burger vector
d	average grain size
d_0	initial grain size
d_f	saturation grain size
k_x	numerical constant
k_1	numerical constant
α	numerical constant
ε	equivalent plastic strain
ε_{eff}^{p}	effective plastic strain
ε_{c}^{p}	critical plastic strain
μ	elastic shear modulus
ρ	dislocation density
$\sigma(\varepsilon)$	flow stress
σ_{disloc}	dislocation strengthening stress
σ_{gs}	grain size strengthening stress
σ_0	frictional stress

INTRODUCTION

Industry 4.0 (I4.0), also considered as the fourth industrial revolution, refers to the trend of industrial automation, that integrates some new production technologies, to improve working conditions, create new business models and increase the productivity and production quality of plants. Some authors focused their attention on the smart operators in I4.0 [1] and on smart factory [2]. Ahuett-Garza carried out a wide analysis of the trends of habilitating technologies for I4.0 and Smart manufacturing [3]. Stock et al. considered I4.0 as an enabler for a sustainable progress, developing a qualitative assessment of the paradigm ecological and social potential [4], while Tao et al. were mainly focused on simulation and, in particular, on digital twin-driven product design and manufacturing [5]. I4.0 is strictly related to the concept of smart factory, which is based on three main pillars:

i. smart production: new or reshaped manufacturing technologies that create interaction between all the elements present in the production system and collaboration between operator, machines and tools;

ii. smart service: all the intelligent and internet of things (IoT), cyber-physical systems (CPSs) and internet of services (IoS) techniques that allow systems to be integrated and to connect, in a collaborative way, companies (supplier - customer) with each other and with external structures (roads, hubs, waste management, etc.);

iii. smart energy: careful control of energy consumption, by developing efficient systems able to reduce energy waste.

The synergy between I4.0 and sustainable manufacturing can reform the current consumption of natural resources and dangerous emissions, implementing sustainable initiatives in monitoring and controlling greenhouse effect, carbon emissions and energy consumption, reducing waste and cost and increasing the prosperity of the environment, economy and society in its complex. Bonilla et al [6] published a scenario-based analysis of the impact and challenges to investigate I4.0 and its sustainability implications; a more detailed analysis was carried out by Oláh et al a couple of years later [7]. On the other hand, other researchers pointed out some criticisms in the implementation of I4.0 paradigm to increase sustainability: Díaz-Ramírez et al discussed an environmental assessment of electrochemical energy storage device manufacturing [8], Duflou et al depicted frame on energy and resource efficient manufacturing [9], Narwane et al introduced their view about the barriers in sustainable I4.0, focusing on the footwear industry [10]. Smart manufacturing represents the core of the new industrial stage, improving manufacturing processes in terms of automation (i.e. robots, Machine to Machine communication (M2M)), vertical integration (i.e. Programmable Logic Controllers (PLC); Enterprise Resource Planning (ERP)), traceability (i.e. raw materials, final products), flexibility (i.e. Additive Manufactuirng (AM), flexible lines), virtualization (i.e. simulation and modelling, Artificial Intelligence (AI)) and energy management [11-13]. For this reason, the fourth industrial revolution is rooted in the concept of smart manufacturing, considering it the beginning and the main purpose of I4.0. Despite the growth of advanced and smart technologies is one of the relevant trends in both industrial and academic research fields, the investigation of barriers related to the implementation of I4.0 represents a central point of view for a number of researchers all over the World [14-18]. Hence, with the aim to give a further impulse to the implementation of I4.0 technologies in industrial production, overcoming part of the literature investigated barriers, the present work describes a preliminary analysis of an innovative concept of SPD system restructuring the classic manufacturing method of ECAD usefulness for continuous production of materials with homogeneous equiaxial microstructure and increased strength for the grain size reduction. After a FEA, the rule of the traditional ECAD die (Fig. 1) was renewed through an advanced technology able to significantly increase the flexibility of the process improving its productivity (i.e. customized components with different mechanical and microstructural properties) and drastically reducing the waste usually generated for manufacturing the ECAD die by the classic machining operations (turning or milling). Experimental tests of the conventional ECAD process, on commercial 1370 pure aluminium (99.7% Al) wires, were firstly conducted. Hence, a corresponding finite element (FE) model of the process was developed including an additive strengthening equation, that considers the influence of the grain refinement on the material flow stress behaviour, and two user-subroutines for the grain size and hardness change prediction. Once validated the effectiveness of the proposed numerical tool and the robustness of the material model under SPD condition, by comparison with experimental data, they were used to study and analyse a new SPD system looking to I4.0.

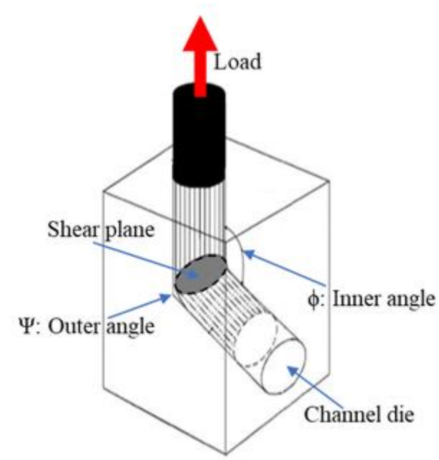


Fig. 1 Schematic illustration of the conventional ECAD die: the sample is drawn through a die, consisting of two channels of equal cross section, preserving its transversal dimension and undergoing deformation by intense shear strain

MATERIAL AND METHODS

Commercial 1370 pure aluminium rods (Table 1) with an initial diameter of 9.50 mm were firstly manufactured by a multiple-pass cold drawing process (15 passes at room temperature with a drawing speed of 25 m/sec) till to reach a wire of 2 mm of diameter with a section reduction of 95.6% and a total drawing strain of 3.11.

Then, on the same manufacturing line, an ECAD process, with an inner die angle Φ=140° and outer die angle ψ=π-Φ, was performed at room temperature preserving the cross section of the wire (Fig. 2).

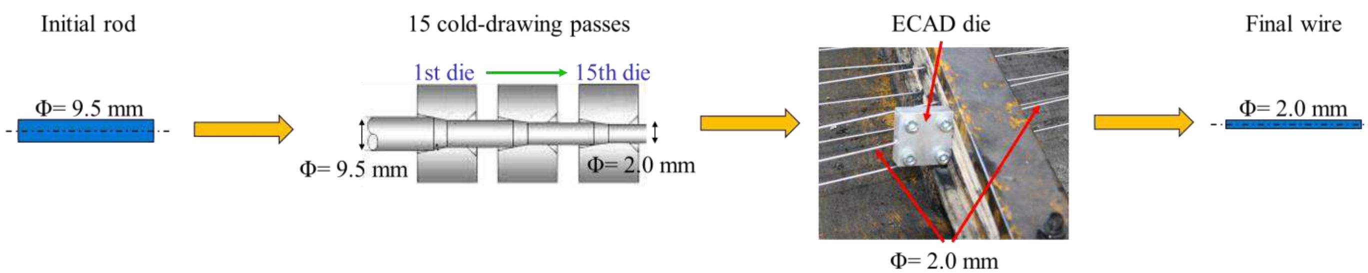


Fig. 2 Schematic illustration of the experimental set-up

By an MTS Criterion Model 45 testing machine, uniaxial tensile tests at room temperature on the aluminium initial rods, drawn wires and ECAD manufactured wires were performed: three replicas per sample were carried out, for a total of nine tests (Fig. 3a). The results reported in Fig. 3 show a material strengthening enhancement, greater than 2 times, after both drawing and ECAD process with a corresponding total true strain reduction of 64% [19]. The flow stress rise was mainly induced by microstructural phenomena, for dislocation density increase [20, 21] and Hall-Petch (H-P) strengthening effect [22, 23] due to the grain refinement (Fig. 4), showing the importance of the imposed plastic deformation in controlling the mechanical performance of the manufactured material.

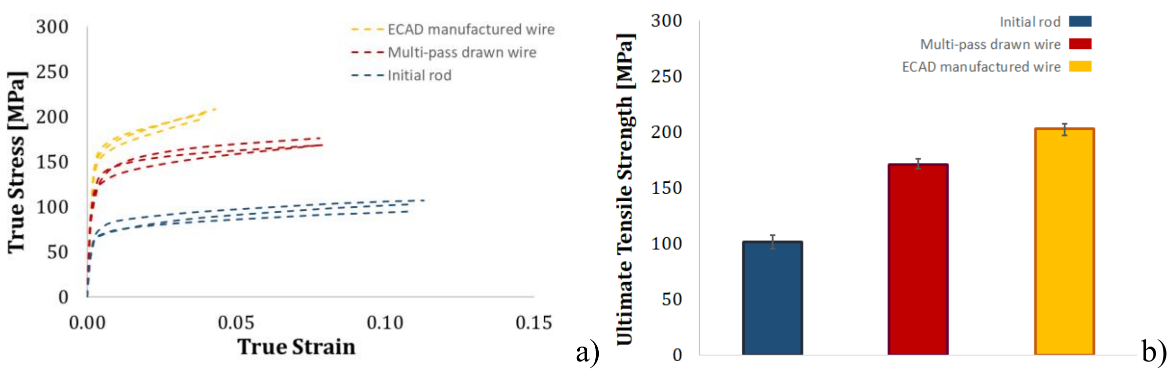


Fig. 3 a True stress-strain curve, **b** Ultimate tensile strength: average value of the three replicas

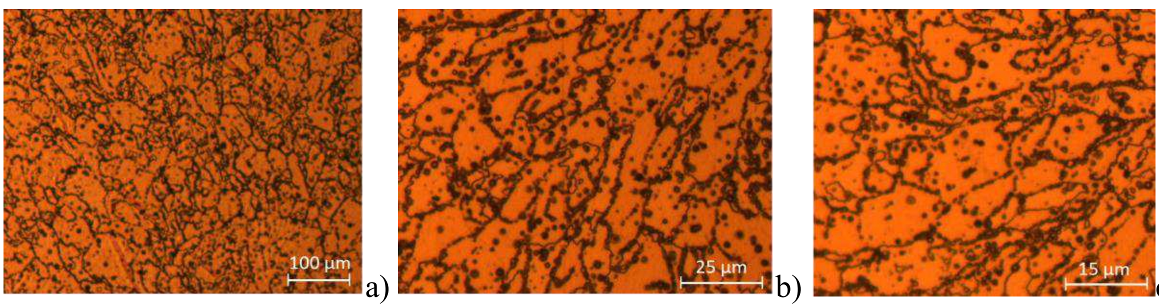
Afterward, 9 specimens (three aluminium rods, three drawn-wires and three ECAD processed wires) were mounted into a resin holder for the grain size analysis and the hardness measurement of the cross section. Mechanical polishing followed by etching (Keller's reagent: 92 ml of distilled water, 6 ml of nitric acid, 2 ml of hydrochloric acid, 2 ml hydrofluoric acid) were conducted before the metallographic analysis. The cross sections of the specimens were investigated by an optical microscope for microstructural analysis, while the micro-hardness measurement ($HV_{0.01}$) was performed by an instrumented CSM micro-nano indenter.

Table 1 Material chemical composition

Al	Si	Fe	Cu	Mn	Mg
99.7	0.10	0.25	0.02	0.01	0.02

Cr	Ni	Zn	B	Ga
0.01	-	0.04	0.02	0.03

Figure 4 shows the microstructure of the initial rod, multi-pass drawn wire and ECAD manufactured wire, all characterized by grains with the same equiaxial shape (grain boundaries represented by black and thicker lines) but different size. In fact, the micrographs report an average grain size of about 58 µm for the initial rod (Fig. 4a), with a reduction of 81% when analysing the cross section of the multi-pass drawn wire (Fig. 4b), featured by a size of 11 µm, and a final reduction to 6 µm when applying the ECAD manufacture (Fig. 4c). The experimental outcomes highlight the effectiveness of the ECAD, by imposing an intense plastic deformation on the material, in achieving microstructural evolution which results in grain size reduction, for the dynamic recrystallization [24], leading to a material strengthening increase with homogeneous equiaxial microstructure.



a) b) c)

Fig. 4 Cross section grain size **a** Initial rod, **b** Multi-pass drawn wire, **c** ECAD manufactured wire

Concerning the micro-hardness, ten indentations per sample were performed, for a total of 90 tests. As a consequence of the grain size reduction (Fig. 4), a material hardness enhancement was observed (according to the H-P effect [25]) with a total increase of 23 $HV_{0.01}$ after performed ECAD process, Table 2.

Table 2 Cross section hardness measurement

Manufacturing step position	Hardness [$HV_{0.01}$]
Initial rod	39
After 15 cold-drawn passes	53
After ECAD process	62

NUMERICAL MODEL

The SFTC DEFORM-3DTM environment has been used to simulate the ECAD manufacture of commercial 1370 pure aluminium drawn-wire by a coupled thermo-mechanical analysis with automatic remeshing. The workpiece was modelled as a plastic object with 52,000 isoparametric tetrahedral elements, while for the die a rigid model with 60,000 elements was considered. An additive strengthening equation, based on the single contribution of the frictional stress, the grain size change and the dislocation density evolution, was implemented for the material flow stress, as reported in the empirical law of Eq. 1.

$$\sigma(\varepsilon) = \sigma_0 + \sigma_{gs} + \sigma_{disloc} \quad (1)$$

Where σ_0 is the frictional stress (a constant which includes contributions from solutes and particles but not from dislocations), σ_{gs} is the contribution from the grain size-related strengthening and σ_{disloc} is the contribution from the dislocation-related strengthening.

σ_{gs} can be written as:

$$\sigma_{gs} = k_1 d^{-1/2} \tag{2}$$

Where k_1 is a constant and d is the average grain size. By this term the material behaviour is influenced by the dynamic recrystallization that significantly modifies the microstructure of the material (i.e. grain refinement, Fig. 4) resulting in material strengthening (Fig. 3) according to the H-P effect.

σ_{disloc} can be written:

$$\sigma_{disloc} = M\alpha\mu b\sqrt{\rho} \tag{3}$$

Where M is the Taylor factor, α is a coefficient, μ is the elastic shear modulus, b is the length of the Burger vector and ρ is the dislocation density.

By Eq. 2 and Eq. 3, the additive strengthening model can be written:

$$\sigma(\varepsilon) = \sigma_0 + k_1 d^{-1/2} + M\alpha\mu b\sqrt{\rho} \tag{4}$$

All the constants characterizing the material behaviour (Eq. 4) are listed in Table 3.

Table 3 Material model parameters [25-28]

σ_0 [MPa]	k_1 [MPa $\mu m^{1/2}$]	M	α	μ [GPa]	b [nm]
11.4	40	3.06	1/3	26	0.286

A regression approach, by considering the tensile tests of both the multi-pass drawn and ECAD manufactured wires, was implemented to determine the value of the dislocation density as a function of the strain [26], Eq. 5.

$$\rho(\varepsilon) = 5.2 * 10^3 * \varepsilon + 235\ [10^{12} m^{-2}] \tag{5}$$

The physical events influencing the mechanical properties of the material were predicted by two customized user-subroutines implementing a continuous dynamic recrystallization (CDRX) model for grain size reduction [20, 29, 30] and H-P relation for the hardness change. Due to the nature of the investigated material, CDRX represents the main physics metallurgical phenomenon [31-33], hence a continuum mechanical model was implemented for predicting the grain size, Eq. 6.

$$d = d_0 - (d_0 - d_f)(1 - \exp(-k_x < \varepsilon^p{}_{eff} - \varepsilon^p{}_c >^{C_x})) \quad d_f \le d \le d_0 \tag{6}$$

Where d is the recrystallized grain size, d_0 the initial grain size, d_f the saturation grain size, k_X and C_X are parameters describing the recrystallization evolution with increasing plastic deformation. The McCauley brackets < > indicate that recrystallization phenomena will occur when the effective strain $\varepsilon^p{}_{eff}$ will reach the threshold value $\varepsilon^p{}_c$. For the ECAD process strain $\varepsilon^p{}_{eff}$ was considered the model developed by Y. Iwahashi et al. [34] (Eq. 7).

$$\varepsilon^p{}_{eff} = \left(\frac{N_{pass}}{3^{0.5}}\right)\left(2\cot\left(\frac{\Phi}{2}+\frac{\psi}{2}\right) + \psi\mathrm{cosec}\left(\frac{\Phi}{2}+\frac{\psi}{2}\right)\right) \tag{7}$$

Where Φ and ψ are the ECAD die angles (Fig. 3) and N_{pass} is the number of ECAD passes. While the parameters k_X and c_X and the critical strain leading to CDRX were set 3.8, 2 and 0.1 according to [31] respectively. Finally, the hardness variation, was calculated as an inverse function of the recrystallized grain size, according to the H-P equation (Eq. 8):

$$HV = C_0 + \frac{C_1}{\sqrt{d}} \tag{8}$$

Where C_0 and C_1 are two material constants while d represents the average grain size. The value of C_0 and C_1, were determined through the previously measured values of the material hardness and grain size of both initial aluminium rods and drawn wires and were set equal to 28.2 and 82.2, respectively.

FE VALIDATION

To validate the robustness of the FE model and the user-subroutines, the predicted hardness change and grain refinement were compared with the corresponding experimental data. Figure 5 shows the numerical results of the grain size and hardness variation during ECAD process. The stable and uniform predicted data confirm the robustness of the customized FE model and user-subroutines in predicting the effects due to the SPD induced by ECAD procedure. In detail, when the effective strain ε^p_{eff} reaches a threshold value, recrystallization phenomena occur in the deformed material resulting in a new fine-grained structure that leads to mechanical and microstructural changes influencing the material behaviour (Eq. 4).

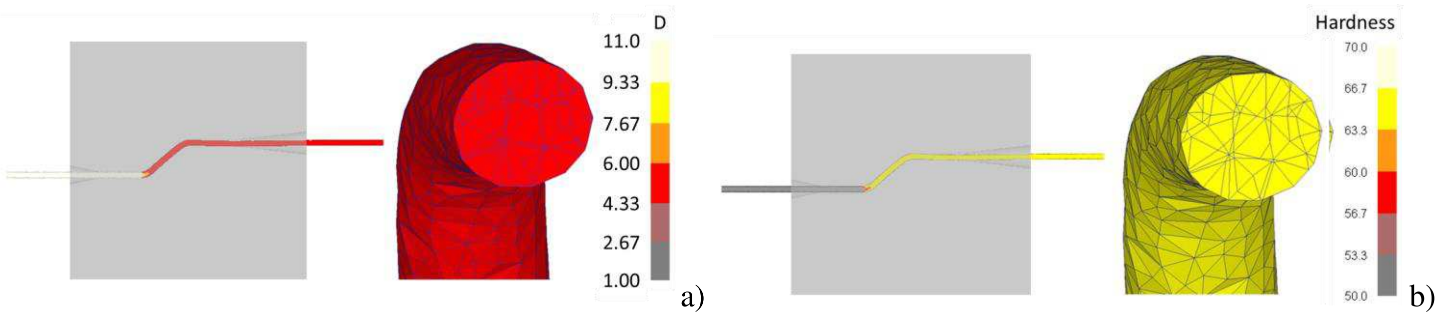


Fig. 5 Numerical simulation of **a** grain size (μm) and **b** hardness ($HV_{0.01}$) variation

In agreement with the experimental evidences, the deformation imposed by ECAD die leads to an average grain size reduction of about 50% which corresponds to a hardness enhancement for the inverse function of H-P relation (Eq. 8), validating the influence of the imposed strain in controlling the mechanical properties modification and the performance of the manufactured components. The comparison with corresponding experimental data shows the effectiveness of the numerical results with an acceptable difference of about 1 μm when considering the grain size reduction and 3 $HV_{0.01}$ for the corresponding hardness increase. This deviation results from the accuracy of both experimental measurements and numerical procedure (empirical laws and equations, setting and calibration of the numerical constants).

Once validated the robustness of the material empirical law and of the two user-subroutines, and considering Iwahashi's strain principle in ECAD process [34], it is possible to develop and analyse an innovative manufacturing method, to impose SPD in continuous manufacturing processes, more flexible than conventional ECAD die and able to impart on the sample the same equivalent shear strain necessary to achieve grain refined structure for the recrystallization phenomena, Fig. 6.

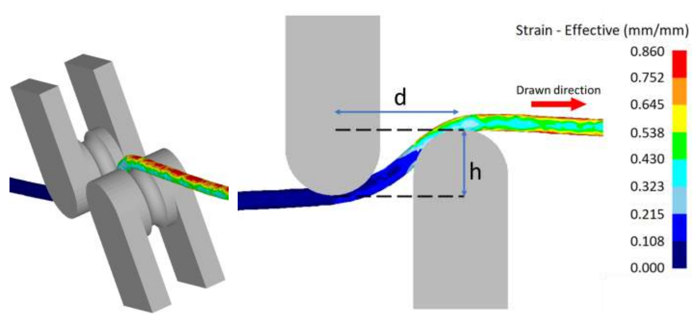


Fig. 6 Induced effective strain by the proposed manufacturing set-up

After simulated both the traditional ECAD technique and the innovative SPD method (Fig. 7), implementing the previously validated numerical tool, the FE analysis demonstrated the possibility of the proposed SPD technique to reach and overcome the strain obtained by classic ECAD approach and to cover a wide range of imposed severe strain by setting the parameters "h" and "d" (Fig. 6). The innovative method preserves the criterion of the conventional equal channel angular process, but renovates its appliance, by proposing a new concept in the manufacturing process able to improve the suppleness of the process and its control giving a potential and advanced contribution towards smart manufacturing and Industry 4.0.

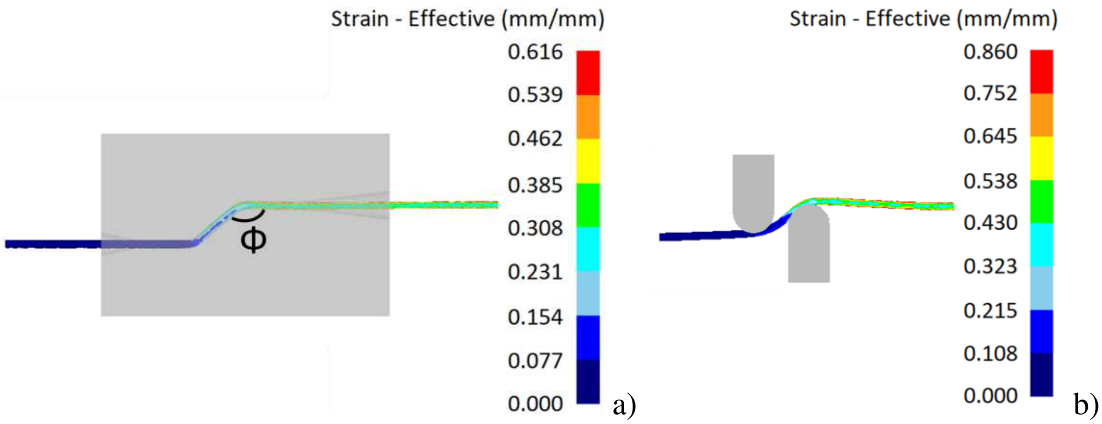


Fig. 7 Effective strain for **a** conventional ECAD process and **b** innovative SPD method

The developed SPD system looks at the old problems of ECAD method, representing a progress to the manufacturing techniques and an advanced solution for improving mechanical material performances. In fact, traditional ECAD die operates as a rigid system offering only one single shape and not allowing the possibility to regulate the imposed strain at varying the material properties (i.e. ferrous-non ferrous material, chemical composition, temperature, hardness, strength) and its geometry: every single ECAD process requires a specific designed die (i.e. cross-section diameter, inner and outer angles, …) manufactured by classic milling and turning machining with a major energy consumption and waste production for chip generation. Moreover, the friction between the sample and the ECAD die, during the draw, not only reduces the regular flow of the process, moving the manufacture towards the material failure, but increases the material temperature leading to the grain grow phenomena instead of the expected grain refinement. Furthermore, it is not possible to control and set the lubrication conditions directly into the die: making inner channels for lubricant/coolant access could create edges that affect the surface integrity of the drawn material and its mechanical performance for the presence of external defects.

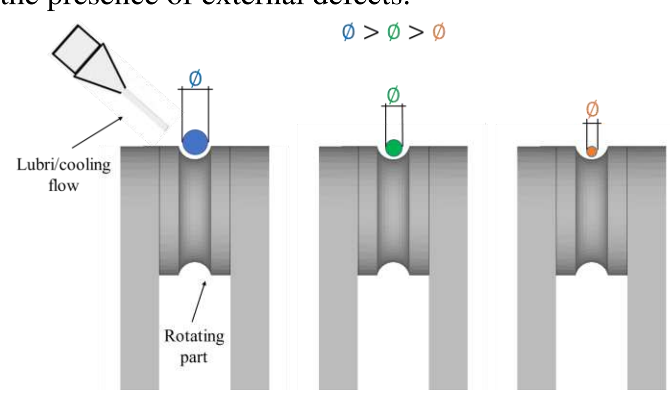


Fig. 8 Fixed set-up at variyng sample diameters and lubrication/cooling delivery at the tool-sample contact zone

The innovative technology represents an important advance in continuous manufacturing processes, giving to the classic ECAD method the flexibility to renew the process in the Industry 4.0 perspective. In fact, the proposed concept, based on two rotating parts, improves the flow of the material during the process, reducing the friction and the possibility of sample failure, and allows to manufacture samples with different diameters by using the same set-up, Fig. 8.Moreover, the new system offers the possibility to control the lubrication conditions at the tool-sample contact zone reducing the process temperature (raising for the high induced strain) and making to occur the recrystallization phenomena that lead to the grain size reduction. The possibility to set different diameters (Fig. 8) and to regulate the parameters “h” and “d” (Fig. 6) allows to control the imposed strain during the process and therefore to obtain different materials microstructures (i.e. grain size). In fact, as reported in Fig. 9, by decreasing only the “h” parameter (from Fig. 9 a to Fig. 9 c), it is possible to impose a different strain on the wire resulting in a different grain size structure and, consequently, hardness value. Hence, at varying the above cited parameters, it is possible to get different combinations of mechanical properties (i.e. material strength, hardness change, threshold stress for crack evolution) increasing the manufacture productivity: materials with different strength, hardness and processability characteristics.

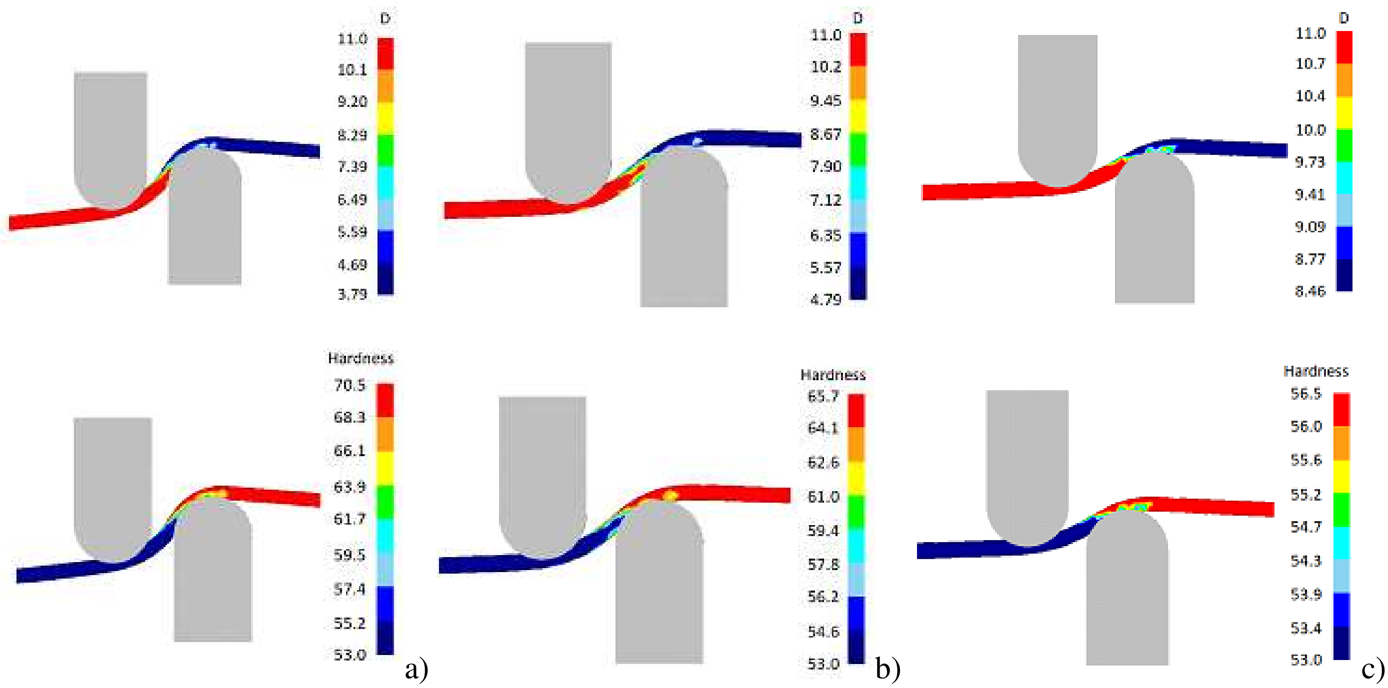


Fig. 9 Grain size evolution and hardness variation at varying the “h” parameter: **a** Φ=130° **b** Φ=140° **c** Φ=155°

Furthermore, Fig. 7 and Fig. 9 show the possibility to get the same strain imposed by classic ECAD procedure and to reach different other deformations highlighting the flexibility of the proposed new SPD procedure. According to the previously shown experimental outcomes, the numerical results reported in Fig. 9 b, characterized by an inner angle Φ=140°, show that after the proposed SPD approach the evolution of the microstructure is similar to that experimentally obtained by conventional ECAD (Fig.

2). The comparison highlights, also in this case, a slight difference of about 1 μm concerning the grain size and a corresponding difference of about 3 $HV_{0.01}$ when comparing the hardness, validating the effectiveness of the procedure. Finally, interconnecting the advanced system with a FE method tool, able to predict aspects as microstructural changes [20], hardness variation, material strength, deformation evolution, process temperatures, etc., it is possible to control and monitor the process sharing the collected data in real-time, creating a proper digital twin. This approach represents an intelligent system able to take decisions in an automated way, setting manufacturing process conditions (i.e. lubrication, drawn-speed, imposed strain) without human involvement and making the operator a supervisor instead of a problem solver.

DISCUSSION AND CONCLUSIONS

In this paper a preliminary analysis of an advanced innovative SPD technique, for continuous production, was proposed demonstrating the possibility for manufacturing to converge to Industry 4.0. In particular, experimental tests of the conventional ECAD process for continuous production of pure aluminium wires were firstly conducted to validate the robustness of a predictive FE model including an additive strengthening equation, that considers the influence of the grain refinement on the material flow stress behaviour, and two customized user-subroutines for the grain size and hardness change prediction. Validated the effectiveness of the proposed numerical tool and the robustness of the material model under SPD condition, by comparison with experimental data, they were both used to study and analyse a new SPD system looking to I4.0. Considering Iwahashi's strain principle and implementing the previously validated numerical tool and user sub-routines, it was illustrated, by a FEA, a new technology for SPD method able to improve the flexibility of the process and its control representing a potential contribution towards smart manufacturing and Industry 4.0. The numerical results validated the presented technique showing the possibility to imprint to the sample the same equivalent strain, usually imposed by ECAD die, leading to the same microstructural changes. The innovative set-up allows to regulate the imposed strain on line, at varying the material properties and its geometry, getting different combinations of mechanical properties, increasing the manufacture productivity in terms of strengthening, hardening and processability, and preventing post manufacturing heat treatments that result energy and time consuming. It was highlighted the possibility of the shown approach to manufacture wires with different diameters by using the same set-up overcoming the rigid set-up of the conventional ECAD die designed only for one geometry and not allowing to regulate the inner angle (Fig. 1). Moreover, the new system lets to control the lubrication conditions at the tool-sample contact zone and to avoid the energy consumption and the waste production to manufacture ECAD die by classic turning and milling operations. By smart services (IoT) it is possible to interconnect the proposed advanced technique with the entire production organization making an automated system able to auto-control and monitoring. The key elements emerging from this study demonstrate a new contribution to practice, steering the classic manufacturing processes to Industry 4.0 by i. adopting new technologies (FE method, flexible lines) to improve productivity and allow smart process, ii. fitting out manufacturing plant with IoT to network humans and technologies, and iii. implementing software algorithms (AI) to collect and analyse data thus providing automated choices and avoiding human intervention.

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Code availability: commercial FE software SFTC DEFORM-3D™

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