Italian Manufacturing Association Conference XVI AITeM

XVI AITeM (Italian Manufacturing Association) Conference
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Edited by
Luigi Maria Galantucci
Luca Settineri

MRF

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XVI AITeM

XVI AITeM (Italian Manufacturing Association) Conference, held in Naples, in the premises of the School of Engineering of the University of "Naples Federico II" on 13-15 September 2023

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Table of Contents

Preface
Committees

Manufacturing processes design, optimization and engineering

A bio-inspired reinterpretation of symbiotic human-robot collaboration in assembly processes
Federico Barravecchia, Mirco Bartolomei, Luca Mastrogiacomo, Fiorenzo Franceschini 2

Addressing idle and waiting time in short term production planning
Erica Pastore, Arianna Alfieri, Claudio Castiglione 10

A numerical methodology for improving the thermoforming process of complex thermoplastic composite components
Antonios G. Stamopoulos, Francesco Lambiase Alfonso Paoletti 19

Study of compostable materials for the production of transparent food containers
Giulia Cappiello, Daniele Rocco, Clizia Aversa, Massimiliano Barletta 28

Manufacturing of a hybrid component in Ti6Al4V-ELI alloy by combining diffusion bonding and superplastic forming
Pasquale Guglielmi, Antonio Piccininni, Angela Cusanno, Gianfranco Palumbo 37

Comparison between two tailored press hardening technologies by means of physical and numerical simulation
Maria Emanuela Palmieri, Luigi Tricarico 45

Workload and stress evaluation in advanced manufacturing systems
Graziana Blandino, Francesca Montagna, Marco Cantamessa 53

Modelling the laser overageing treatment of a 6xxx Al alloy by means of physical simulation tests
Antonio Piccininni, Pasquale Guglielmi, Angela Cusanno, Gianfranco Palumbo 62

An insight into friction stir consolidation process mechanics through advanced numerical model development
Abdul Latif, Riccardo Puleo, Giuseppe Ingarao, Livan Fratini 70

On the role of intermetallic and interlayer in the dissimilar material welding of Ti6Al4V and SS 316L by friction stir welding
Harikrishna Rana, Gianluca Buffa, Livan Fratini 78

Validation of charge welds and skin contamination FEM predictions in the extrusion of a AA6082 aluminum alloy
Marco Negozio, Riccardo Pelaccia, Lorenzo Donati, Barbara Reggiani, Sara Di Donato 86

Additive manufacturing and reverse engineering

Comparison of specific cutting energy in dry and wet post- process turning of Ti6Al4V EBM parts
Ersilia Cozzolino, Stefania Franchitti, Rosario Borrelli, Antonello Astarita 95

Preliminary evaluation of an additive manufacturing procedure for producing patient-specific upper-limb orthotic devices
Francesca Sala, Mariangela Quarto, Gianluca D'Urso, Claudio Giardini 103

Additive foam manufacturing
Luca Landolfi, Andrea Lorenzo Henri Sergio Detry, Daniele Tammaro, Massimiliano Maria Villone, Pier Luca Maffettone, Antonino Squillace..... 111

Exploiting laser-direct energy deposition for customized components: H13 and 316L functionally graded materials
Alessia Teresa Silvestri, Paolo Bosetti, Matteo Perini, Antonino Squillace 118

LPBF process of Zn-modified NiTi alloy with enhanced antibacterial response
Carlo Alberto Biffi, Jacopo Fiocchi, Francesca Sisto, Chiara Bregoli, Ausonio Tuissi 127

Effect of layer and raster orientation on bending properties of 17-4 PH printed via material extrusion additive manufacturing technology
Alessandro Pellegrini, Maria Grazia Guerra, Fulvio Lavecchia, Luigi Maria Galantucci..... 135

Non-Newtonian, non-isothermal three-dimensional modeling of strand deposition in screw-based material extrusion
Alessio Pricci, Gianluca Percoco 143

Influence of the energy density on the Young modulus and fatigue strength of Inconel 718 produced by L-PBF
Michele Abruzzo, Giuseppe Macoretta, Luca Romoli, Gino Dini..... 154

Development of a 3D printer optimized for rapid prototyping with continuous fiber fabrication technology
Matteo Benvenuto, Enrico Lertora, Chiara Mandolfino, Luigi Benvenuto, Alberto Parmiggiani, Mirko Prato, Marco Pizzorni..... 163

Reverse bending fatigue of 316L stainless steel components produced by laser powder bed fusion
Stefano Guarino, Emanuele Mingione, Gennaro Salvatore Ponticelli, Simone Venettacci..... 173

Process parameters optimization in fused deposition modeling of polyether ether ketone
Emanuele Vaglio, Erica Billè, Marina Franulović, Alessandro Gambitta, David Liović, Alfredo Rondinella, Marco Sortino, Giovanni Totis..... 182

Experimental analysis of FDM structures in shape memory polylactic acid
Maria Pia Desole, Annamaria Gisario, Franco Maria Di Russo, Massimiliano Barletta..... 191

Dimensional and geometric deviations of parts in PA12 manufactured by selective laser sintering: numerical and experimental analyses
Valentina Vendittoli, Achille Gazzerro, Wilma Polini, Luca Sorrentino..... 198

Mechanical properties and dynamic response of 3D printed parts in PLA/P(3HB)(4HB) blends
Daniele Almonti, Clizia Aversa, Alessandra Piselli, Massimiliano Barletta 206

In-process inspection of lattice geometry with laser line scanning and optical tomography in fused filament fabrication
Michele Moretti, Arianna Rossi, Nicola Senin 216

Effect of process parameters on the thermal properties of material extruded AM parts
Luigi Morfini, Nicola Gurrado, Roberto Spina 225

Robust in-line qualification of lattice structures manufactured via laser powder bed fusion
Bianca Maria Colosimo, Marco Grasso, Federica Garghetti, Luca Pagani 232

Ductility and linear energy density of Ti6Al4V parts produced with additive powder bed fusion technology
Gianluca Buffa, Dina Palmeri, Gaetano Pollara, Livan Fratini, Alessandro Benigno 241

Assembly, disassembly and circular economy

Circular economy strategies at the manufacturing system scheduling level: the impacts on Makespan
Claudio Castiglione, Arianna Alfieri, Erica Pastore 250

Laser welding with and without filler wire of aluminum sheets produced by rolling and additive manufacturing for e-mobility applications
Alessandro Ascari, Erica Liverani, Alessandro Fortunato, Stefano Cattaneo, Marco Franzosi 258

Application of high voltage fragmentation to treat end-of-life wind blades
Marco Diani, Shravan Torvi, Marcello Colledani 266

Process and system simulation, optimization and digital manufacturing

The ranking-aggregation problem in manufacturing: potential, pitfalls, and good practices
Fiorenzo Franceschini, Domenico Augusto Maisano, Luca Mastrogiacomo 276

Digital upgrade of a bandsaw machine through an innovative guidance system based on the digital shadow concept
Federico Scalzo, Davide Bortoluzzi, Giovanni Totis, Marco Sortino 286

The influence of material properties and process parameters on energy consumption in the single-screw extrusion of PVC tubes
Andrea Pieressa, Enrico Bovo, Marco Sorgato, Giovanni Lucchetta 295

Numerical evidence of submerged arc welding at changing of the main process parameters
Francesco Raffaele Battista, Romina Conte, David Izquierdo Rodriguez, Francesco Gagliardi, Giuseppina Ambrogio, Luigino Filice 302

Materials processing technology

Augmented multi-scale instrumented indentation test characterization of complex multi-layered coatings for tribological application
Giacomo Maculotti, Gianfranco Genta, Maurizio Galetto 311

Effect of sub-zero deformation temperatures and rolling directions on the formability of AISI 316 stainless steel sheets
Rachele Bertolini, Enrico Simonetto, Andrea Ghiotti, Stefania Bruschi 318

A novel application of cryogenics in dieless sheet metal piercing
Paolo Albertelli, Valerio Mussi, Michele Monno 326

UV picosecond laser processing for microfluidic applications
Vincenzina Siciliani, Alice Betti, Claudio Ongaro, Leonardo Orazi,
Barbara Zardin, Barbara Reggiani..... 334

Effect of carbon nanotube content on the mechanical behaviour of CFRP composite materials
Marina Andreozzi, Iacopo Bianchi, Archimede Forcellese, Serena Gentili, Luciano Greco,
Tommaso Mancia, Chiara Mignanelli, Michela Simoncini, Alessio Vita 342

Static indentation properties of basalt fiber reinforced composites for naval applications
Chiara Borsellino, Mohamed Chairi, Jalal El Bahaoui, Federica Favaloro,
Fabia Galantini, Guido Di Bella..... 350

Surface micro – texturing of tapping tools with complex geometry
Manuel Mazzonetto, Vincenzina Siciliani, Riccardo Pelaccia, Leonardo Orazi 359

Influence of silica aerogel filler on strength-to-weight ratio of carbon/epoxy composite made by vacuum resin infusion
Luigi Benvenuto, Enrico Lertora, Chiara Mandolfino, Matteo Benvenuto, Marco Pizzorni..... 367

PET foaming: development of a new class of rheological additives for improved processability
Clizia Aversa, Massimiliano Barletta, Annalisa Genovesi, Annamaria Gisario..... 376

Study of autoclave process to manufacture thermoplastic composites constituted by PP/flax fibers
Gianluca Parodo, Luca Sorrentino, Sandro Turchetta..... 385

A feasibility study to improve the processability of pure copper produced via laser powder bed fusion process
Abdollah Saboori, Marta Roccetti Campagnoli, Manuela Galati, Flaviana Calignano,
Luca Iuliano..... 393

Mechanical recycling of CFRPs: manufacturing and characterization of recycled laminates
Dario De Fazio, Luca Boccarusso, Antonio Formisano, Antonio Langella, Fabrizio Memola
Capece Minutolo, Massimo Durante..... 402

Miscellaneous

A novel quality map for monitoring human well-being and overall defectiveness in product variants manufacturing
Elisa Verna, Stefano Puttero, Gianfranco Genta, Maurizio Galetto..... 412

Feasibility study and stress analysis of friction stir extruded rods and pipes: a simulative model
Sara Bocchi, Cristian Cappellini, Gianluca D'Urso, Claudio Giardini..... 420

Reinforcement learning for energy-efficient control of multi-stage production lines with parallel machine workstations
Alberto Loffredo, Marvin Carl May, Andrea Matta..... 428

Tool path strategies for a new Agile incremental bending system
Enrico Simonetto, Andrea Ghiotti, Enrico Savio, Stefania Bruschi 437

The effects of dry grinding processing parameters on the electromagnetic and geometrical properties of Nd2Fe14B permanent magnets
Lorenzo Cestone, Erica Liverani, Alessandro Ascari, Alessandro Fortunato 444

Work in progress

Laser welding in e-mobility: process characterization and monitoring
Caterina Angeloni, Michele Francioso, Erica Liverani, Alessandro Ascari, Alessandro Fortunato, Luca Tomesani 453

Development of depositions strategies for edge repair using a WAAM process
Francesco Baffa, Giuseppe Venturini, Gianni Campatelli 467

Measurement and analysis of tooth movements during orthodontic treatment with clear aligners
Marino Calefati, Francesco De Palo, Maria Derosa, Ugo Marco Ferrulli, Andrea Verani, Giorgio Giustizieri, Eliana Di Gioia, Luigi Maria Galantucci 476

A digital solution for slender workpiece turning: the DRITTO project
Niccolò Grossi, Antonio Scippa, Lorenzo Sallese, Lorenzo Morelli, Gianni Campatelli 486

Influence of long and short glass fiber on the mechanical behaviour of a single cell metamaterial
Luca Giorleo, Antonio Fiorentino, Stefano Pandini, Elisabetta Ceretti 495

Keyword index
About the editors

Preface

This book presents selected peer reviewed papers presented at the XVI AITeM (Italian Manufacturing Association) Conference, held in Naples, in the premises of the School of Engineering of the University of "Naples Federico II" on 13-15 September 2023.

AITeM is an officially recognised association dedicated to the academic and industrial world, with a special focus on the young. AITeM is a meeting point for Research and Innovation players – manufacturing companies, universities, other public research institutions, as well as professionals and other experts – discussing the most urgent issues within our industry. It promotes the study, the development of knowledge and the application of manufacturing technologies and systems in all their aspects:

- transformation processes of products, from production to assembly, from testing to recycling;
- mechanical and technological characterisation of the transformed materials;
- methodologies and tools for designing transformation systems (instrumental goods), processes, and components;
- programming, management and control of production, assembly, testing, and recycling systems;
- quality management and environmental safeguard management for sustainable development.

AITeM promotes also events and actions for disseminating knowledge within the manufacturing sector, either autonomously or in collaboration with national and international partners.

Every two years, AITeM organises a national conference: the Association's key moment of vitality is an occasion for meeting and discussing the latest manufacturing topics.

This Conference proposes as a meeting place for the scientific community in the sector of technologies and processing systems. It is aimed at all researchers working on the issues of manufacturing technologies.

The scientific program of the conference is divided into sessions of different nature which can guarantee wide participation in the works of the conference both in the presentation and discussion phases.

The sessions of the XVI AITeM Conference are:

- Manufacturing processes design, optimization and engineering
- Additive manufacturing and reverse engineering
- Assembly, disassembly and circular economy
- Process and system simulation, optimization and digital manufacturing
- Materials processing technology
- Miscellaneous
- Work in progress

The sessions contain the contributions coming mainly from AITeM members. They are designed to enhance different types of papers: the traditional Scientific sessions contain contributions of experienced members who want to share the results achieved with colleagues, the Work in

Progress session contains interventions related to ongoing activities and laboratories that offer new ideas and propositions for collaboration and talk more about future research activities.

The selection of papers was made by the Editorial Committee on the basis of peer reviews. More than 150 reviewers were involved. The reviews considered the coherence of the topic with the AITeM topics, the novelty with respect to the state of the art, the overall scientific quality of the work.

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Feasibility study and stress analysis of friction stir extruded rods and pipes: a simulative model

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Keywords: Sustainable Processes, Aluminium Alloys, Friction Stir Extrusion

Abstract. The traditional aluminium recycling process consumes a lot of energy and adversely affects the metallurgical quality of the secondary alloys produced. With the increasing need for resolving this problem, Friction Stir Extrusion (FSE) has been patented. FSE is a new solid-state recycling process through which parts can be extruded directly from waste. In this research, the analysis was focused on different process parameters, process set ups and geometries of the extruded parts. The traditional setup, where the tool rotates and advances while the chamber remains stationary, was considered, and a new one was introduced. In this configuration, the tool has only an advance feed, while rotation is performed through the chamber. Moreover, for each combination of process parameters the bonding phenomena occurrence, considering both the thermal and the stress conditions generated by the parameters, was analysed. For this purpose, the Piwnik and Plata criterion was chosen.

Introduction

The process of recycling aluminium traditionally involves re-melting scraps, forming new ingots, and reworking them into new billets for extrusion. Unfortunately, this process is highly energy-intensive due to the necessary combustion process, which also negatively affects the metallurgical quality of the secondary aluminium alloys obtained. Moreover, it is very difficult to completely eliminate all impurities from the aluminium bulk, which further compounds the problem [1].

Given the needs of a modern and sustainable industry, traditional recycling technologies have so far proved insufficient. The Friction Stir Extrusion (FSE) is a new solid-state recycling process that enables the direct extrusion of pieces from scraps, bypassing the most energy-intensive phases of traditional recycling. During the FSE process, a rotating tool is plunged into a hollow chamber to compact, stir, and back-extrude the scraps into a full, dense rod.

The FSE process is not limited to aluminium, either; it has been demonstrated in literature that it is also possible to use the FSE process to process magnesium and its alloys, including biodegradable ones [2], as well as dissimilar metals like aluminium and steel [3].

The innovation behind FSE lies in the use of heat developed exclusively through friction between the scraps and the tool: this leads to a reduced energy requirement of approximately 15% compared to traditional recycling technologies [4].

Despite its many benefits, the use of FSE in the industrial field is still limited due to the challenging correlation between process parameters and the final characteristics of the piece obtained, as well as the limitation of extrudable geometries. Currently, only axisymmetric pieces with diameters around ten millimetres can be obtained, because of to the complexity of predicting the behaviour of the chips in contact with each other, which leads to mechanical characteristics that limit the possibility of extruding large pieces.

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As FSE is a relatively new technology, the development of simulative models is very useful for studying the relationship between the parameters and the physics of the process. For this reason, several researchers have developed simulative models using different software.

The thermal, mechanical, and microstructural behaviour of FSEed magnesium chips were analysed using ABAQUS software. The authors demonstrated that the rotational speed of the tool influenced the quantity of heat exchanged more than the descent feed of the tool [5].

A more focused thermal model was built using ANSYS FLUENT, in which only a linear heat flux was considered. This model proved to be able to efficiently simulate the temperature trend reached during an FSE process of a AA6061 cylinder [6].

It is worth noting that almost no model is actually able to predict the integrity of the Friction Stir Extruded products using a unique FEM model considering both the thermal and stress conditions reached during the FSE process [7]. Due to this lack of knowledge, it is important to consider other numerical models to be embedded in the simulation models. One such model is the Piwnik and Plata criterion [8]. This model, traditionally considered suitable for traditional extrusion processes but compatible with the FSE process [9], enables the evaluation of the effectiveness of the FSE process by considering the internal stress generated during the extrusion process.

The purpose of this study is to assess the feasibility of using FSE technology not only for the extrusion of solid rods but also for pipes, taking advantage of the dual configuration of direct and inverse frictional extrusion. To do that, the focus will be on two different process setups and on the extrusion of both rods and pipes. The traditional setup will be considered, in which the tool rotates and advances while the chamber remains stationary, as well as a new setup in which the tool only has an advance feed while the rotation is performed by the bottom of the chamber. Additionally, for each combination of process parameters and setups, the analysis will consider if and how the bonding phenomena occur, considering both the thermal and stress conditions generated by the parameters. For this purpose, the Piwnik and Plata criterion was chosen.

Materials and methods

In order to achieve the investigation of the thermo-mechanical properties of the simulated processes, the implicit Lagrangian 3D simulation software DEFORM 3D was used. To create the simulation model, four distinct objects were taken into account: a tool, a hollow chamber, a bottom, and the material to be extruded.

The first three components were simulated as rigid objects with meshes consisting of 20,000, 27,000, and 8,000 elements, respectively. Meshes were also assigned to the rigid bodies to allow for thermal analysis of the components during the process. With regard to the material to be extruded, even though it was composed of metal shavings, it was included in the simulation model as a single porous object consisting of 61,000 tetrahedral elements. A complete representation of the model setup can be seen in Fig. 1.

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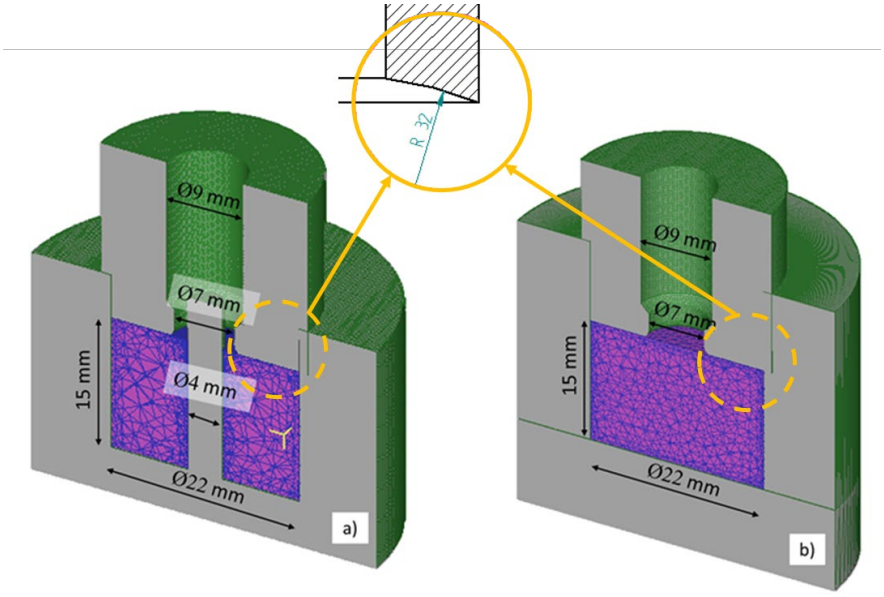

Fig. 1. Models setup for pipes (a) and for rods (b).

This choice was justified by the possibility to pre-compact the metal shavings, demonstrated in previous experimental tests, resulting in a single cylinder with a density of 2.11 g/cm^3, which is 78% of the density of the base aluminium [9]. Additionally, the AISI 1043 material was assigned to the rigid bodies, while the porous workpiece was assigned AA6061 Machining-Johnson aluminium, whose mechanical properties are defined between 20°C and 550°C.

For both the direct and inverse extrusion processes, the setups reported in Fig. 1 were used. In the case of inverse extrusion, the chamber and the bottom remained static while the tool had a rotational and translational movement. Conversely, in direct extrusion modelling, the camera and the tool were kept fixed, and the bottom underwent both a translational movement along Z and a rotational motion.

The simulations were carried out by varying two parameters, namely the rotational speed (S) and vertical feed (F) of the tool/bottom, considering ranges already optimized in a previous work [9] and further analysis conducted by the authors. These parameters were both tested at two levels, as illustrated in Table 1.

Table 1. *Process parameters combinations.*

Combination	S [rpm]	F [mm/s]
1	400	1
2	400	3
3	800	1
4	800	3

To accurately capture the steady state condition of the processed material, the stop criterion for displacement in the Z direction was set at 5 mm for the primary die (either the tool for the inverse extrusion or the bottom for the direct one).

The thermal behaviour of aluminium and steel was held constant throughout all simulations, using the values presented in Table 2, which had been optimized in a prior study [9].

Materials Research Proceedings 35 (2023) 420-427 https://doi.org/10.21741/9781644902714-50

Table 2. *Boundaries parameters for aluminum and steel.*

Parameter	Value
Heat transfer coefficient aluminum-tool [N/s/mm/°C]	11.00
Heat exchange with the environment [N/s/mm/°C]	0.02
Thermal conductivity [N/(s·°C)]	450.00
Steel emissivity	0.70
Aluminum emissivity	0.25
Mechanical conversion to heat	0.80
Friction coefficient aluminum-tool	0.60

Previous researches in literature have demonstrated that relying solely on thermal analysis or density verification at the end of the FSE process is insufficient to ensure the successful extrusion of large pieces [9]. Therefore, it has been chosen to consider necessary to assess the internal stress state of the workpiece using the Piwnik and Plata criterion. According to this criterion, material bonding occurs when the parameter w exceeds a limit value (w_{lim}), which is determined based on temperature. The parameter w is defined as the time integral of the ratio of pressure (p) and the actual stress acting on the material (σ_{eff}), as shown in Eq. 1:

$$w = \int_0^t \frac{p}{\sigma_{eff}} \cdot dt \tag{1}$$

To account for each step of the simulations, Eq. 1 needs to be revised as the total sum presented in Eq. 2:

$$w_{i,n} = \sum_{j=1}^{n} \left(\frac{p}{\sigma_{eff}}\right)_{i,j} \cdot \Delta t_j \tag{2}$$

With n = total number of steps, j = generic *j-th* step, i = generic *i-th* node and Δt_j = time per step of the *j-th* step.

For the Friction Stir Extrusion simulations, the pressure (p) in Eq. 1 and 2 was substituted with σ_{mean}, which represents the average stress acting in the porous material. This choice was made because the workpiece was modelled as a single porous material, making it impossible to calculate the local pressure resulting from interactions between individual chips.

E. Ceretti et al. developed an empirical relationship for determining w_{lim} as a function of the steady-state temperature achieved during the extrusion process [10]. However, the experimental interpolation curve presented in Eq. 3 was only validated for temperatures greater than 320°C.

$$w_{lim} = 4.9063e^{-0.0017\,T} \tag{3}$$

To calculate w and w_{lim} for each node at every step, a specialized Fortran routine was developed and integrated into the simulation model, enabling their automated computation and the relationship between these two parameters.

The data on bonding conditions, torque, energy from axial thrust, and energy from rotational movement were extracted and analysed after the simulations. In addition, the total energy expenditure for machining was calculated by adding the energy from axial thrust and the energy required for rotational movement, calculated as reported in Eq. 4.

Materials Research Proceedings 35 (2023) 420-427 https://doi.org/10.21741/9781644902714-50

$$E_r = \omega \cdot \int_0^t C\, dt \quad (4)$$

With $\boldsymbol{E_r}$ = energy required for rotational movement, $\boldsymbol{\omega}$ = rotational speed [rad/s], C = torque and t = time per step.

Results and discussion

The implementation of a dedicated Fortran routine in the simulation models facilitated the automatic calculation of w and w_{lim} for each node and enabled the relationship between these two quantities to be embedded. The Piwnik and Plata criterion was then graphically represented by introducing a new user-variable called *welding*. This variable color-coded the elements in which $w>w_{lim}$ as red and the regions in which $w<w_{lim}$ as blue, allowing the effective proof of the Piwnik and Plata criterion to be easily identified.

By employing this method, it was possible to demonstrate the feasibility of using both direct and inverse FSE methods to produce sound and completely massive products, including rods and pipes. As already mentioned, it has been already demonstrated that the exclusive thermal analysis of the FSE process are not sufficient to ensure the extrusion of massive pieces [9]. In addition to this, based on the data collected through simulations, it was also possible to demonstrate that not even the verification of the final density of the workpiece can ensure the effective extrusion of massive pieces. In fact, in Fig.2 it is possible to observe that, considering the inverse extrusion with S=400 rpm and F=3 mm/s, although the temperature reached was on average higher than 350°C (Fig. 2a), the temperature at which chip welding begins, and that the density relative reached in the extruded part is equal to 1 (Fig. 2b), the bonding conditions have not been verified (Fig. 2c).

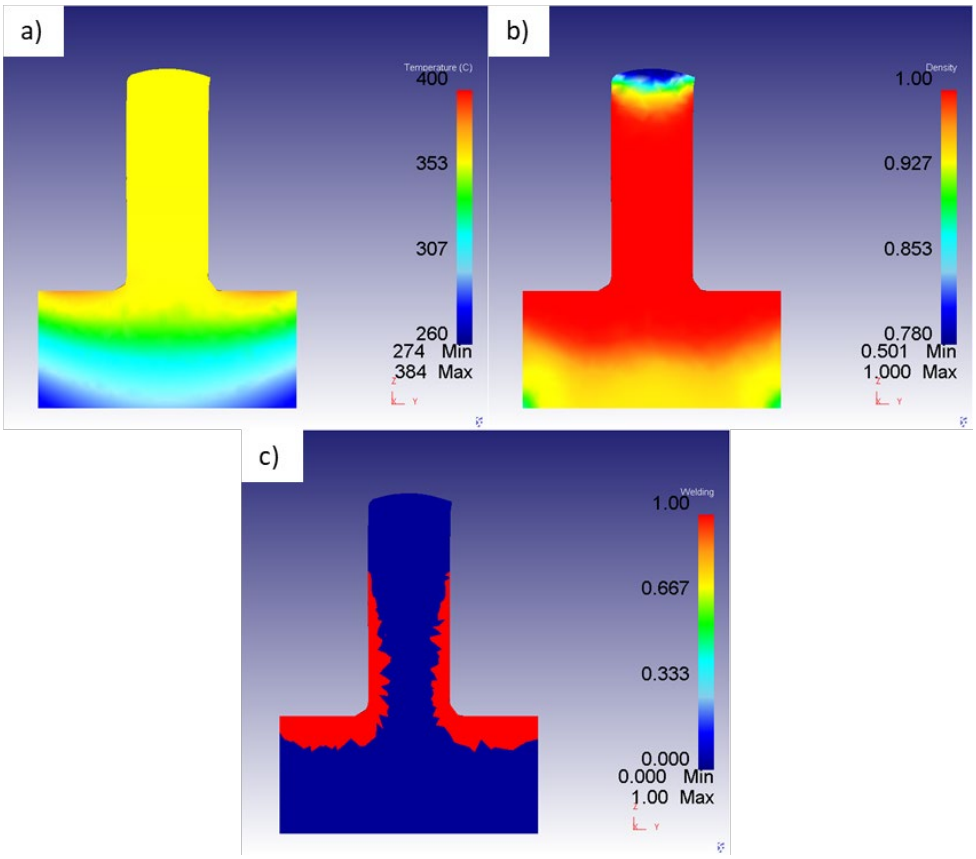

Fig. 2. FEM results: a) Temperature, b) density and c) welding parameter.

Materials Research Proceedings 35 (2023) 420-427 https://doi.org/10.21741/9781644902714-50

By way of example, Fig. 3 illustrates the outcome obtained by considering the direct extrusion of a pipe with S=800 rpm and F=1 mm/s, which enabled both extruded geometries to be produced.

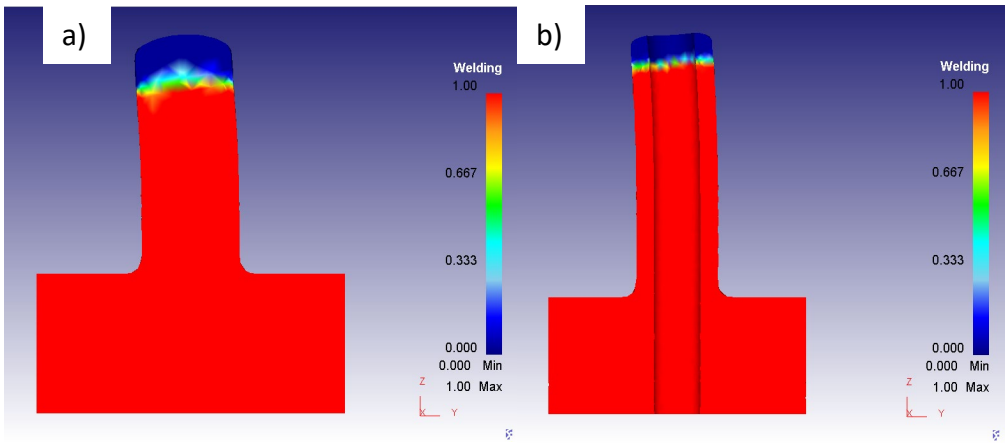

Fig. 3. FEM results obtained: a) rod with direct extrusion and b) pipe with inverse FSE process.

The torque resulting from the different simulations are reported in Fig. 4 and Fig. 5.

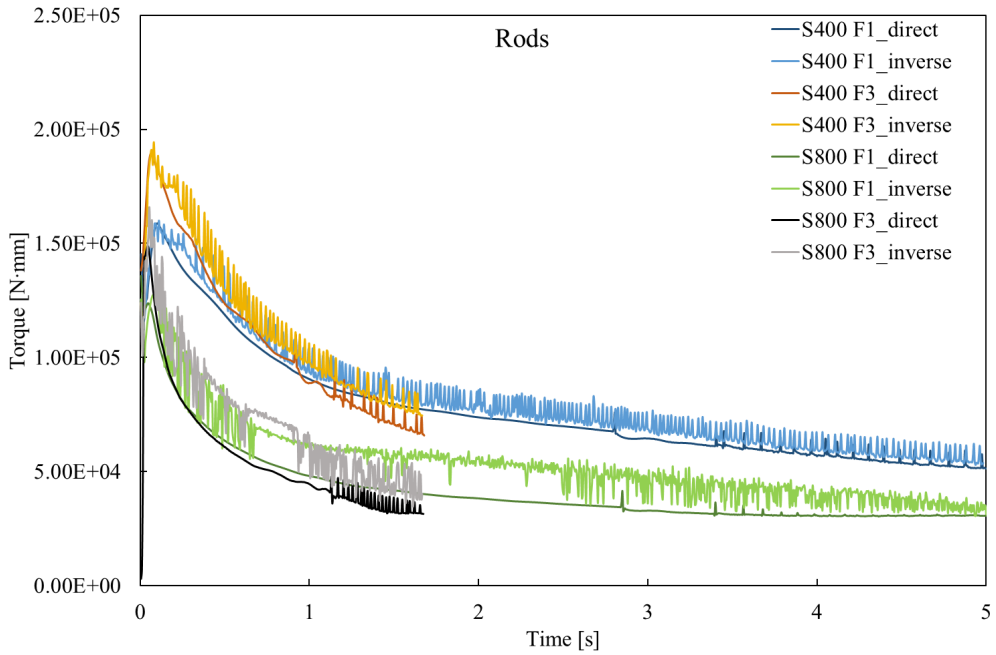

Fig. 4. Torque results from the direct and inverse FSE simulation of rods.

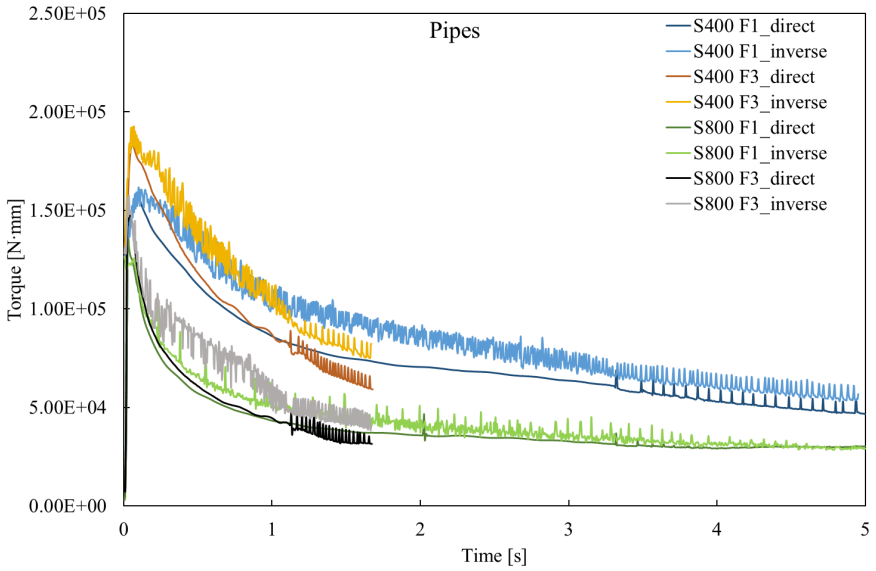

Fig. 5. Torque results from the direct and inverse FSE simulation of pipes.

Starting from these results, by using the Eq. 4, the E_r was calculated for each combination of process parameters. This energy component was added to the energy demand resulted directly from the Deform post-processor, obtaining the total energy demand (E_{tot}).

In Table 3 all the results of the bonding occurrence as a function of both the process parameters and the calculated energy demands are reported. The cells corresponding to the conditions in which perfect bonding was found are highlighted in green, in red where there was no bonding.

Table 3. Simulation results of the energy demands.

		Direct extrusion		Inverse extrusion	
		Rods	Pipes	Rods	Pipes
S [rpm]	F [mm/s]	E_{tot} [KJ]	E_{tot} [KJ]	E_{tot} [KJ]	E_{tot} [KJ]
400	1	16.82	16.15	17.61	18.45
400	3	8.56	8.27	8.81	9.03
800	1	18.2	17.25	22.94	18.92
800	3	8.39	8.37	10.73	10.06

The differences between the direct and inverse extrusion configurations in terms of energy, with the same process parameters, are almost negligible.

However, it immediately became clear that, with the same energy demand -or even lower-, with direct extrusion it was possible to obtain massive pieces also considering the pairs of parameters which did not lead to bonding in the inverse extrusion.

This is due to the benefit of the direct FSE which lies in complete compaction of the chips before the start of extrusion inside the tool cavity. This led to a more thermally uniform starting workpiece, which was ready for fully compacted material extrusion. As a result, the forces required at the interface between the tool and the workpiece were reduced, allowing for bonding even at lower temperatures and creating a state of stress that facilitated the production of completely massive pieces.

Conclusions

The objective of this study is to assess the feasibility of using FSE technology for direct and inverse extrusion of fully dense rods and pipes, by analysing bonding conditions through the Piwnik and

Plata criterion. A robust FEM model was developed to consider the rotational and descent speeds of the tool/bottom, and determine a reliable technology window for FSE. The study demonstrates that both direct and inverse extrusion configurations can be employed, and full dense rods and pipes can be produced with both configurations. Furthermore, it seems that the direct FSE provides a better starting point for the active extrusion phase, allowing the reduction of the energy consumption and limiting, at the same time, the non-bonding technological window.

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